DROUGHT AND WATER SCARCITY: ADDRESSING CURRENT AND FUTURE CHALLENGES

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DROUGHT AND WATER SCARCITY: ADDRESSING CURRENT AND FUTURE CHALLENGES

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BRIEF RESEARCH REPORT
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Water Scarcity Communication in the UK: Learning From Water Company Communications Following the 2018 Heatwave

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When communicating about water scarcity, public water companies in the UK operate within a fine balance. There is a legal obligation on water companies in the UK to promote efficient water use, and pressure on water resources means that water companies need to encourage changes in water consumption behaviors. However, there is a lack of information about the way UK water companies communicate with the public. This paper presents the results of research into UK water company practices and perceptions in engaging consumers around water scarcity and water saving and discusses what this means for water scarcity communication. Interviews with 10 water company communication teams (14 interviewees) following the 2018 UK heatwave explored opportunities, innovations and challenges in public communication. Interviewees recognized the need for an ongoing conversation about water in the UK and identified a number of practices which could support a change in public water consumption. The results highlight the perceived importance of trust, timing and community- or group-scale communications, and the need for a cross-sectoral and intergenerational approach to public communication about water resources. This research examines some of the current underlying assumptions of water companies about what influences public water consumption in the UK and offers insights into some of the key challenges and opportunities for the future.

Keywords: drought, water scarcity, science communication, behavior change, social norms, water companies, social comparison, customer communication

INTRODUCTION

Water resources are constrained in many parts of the world and the UK is no exception, with further pressure on water supply expected from both population growth (Office of National Statistics[ONS], 2017) and climate change (Rahiz and New, 2013; Guillod et al., 2018). Globally, by 2050, domestic water use is anticipated to increase by 130% (OECD, 2012). Faced with rising pressure on water supply, water companies use a combination of tools to increase water capacity (e.g., through water reuse schemes) and decrease demand for water (e.g., motivate customers to change behavior). Orr et al. (2018) show that there is a lack of available information about the way UK water companies communicate to the public and how their communication affects outcomes. This study explores the ways in which UK water companies seek to reduce customer demand, focusing specifically on the role of communication as a strategy for demand reduction.

Household water demand can be reduced through legislation and regulatory approaches (such as temporary use bans); technological innovations (water-efficient appliances); information and education campaigns designed to raise awareness of the need for water conservation or to apply approaches such as social norming to reduce consumption; or through financial measures (including metering) (Inman and Jeffery, 2006). These approaches may be temporary, stimulated by a particular drought event, or designed for longer-term changes in consumption (e.g., technological innovations or some information and education campaigns). Waterwise (2013) emphasized that much of the current information provision on water resources in the UK was passive and recommended more proactive provision of information to create a "baseline of understanding," which would encourage pro-environmental activities through normalized behavior. However, Koop et al. (2019) still highlight the reactive nature of water conservation campaigns (i.e., they occur during drought or near drought conditions) and that such campaigns do not appear to have long-term impacts on water consumption. Furthermore, there is growing recognition that information-based campaigns, which may be underpinned by a tacit assumption of a knowledge deficit (also called "deficit model thinking": see Wilkinson and Weitkamp, 2016) may not be effective by itself (e.g., Lu et al., 2017; Lede and Meleady, 2019). In terms of approaches to changing water consumption behavior, Lu et al. (2017) review both information- and norm-based campaigns, and find key factors affecting consumption include water beliefs and environmental attitudes.

CONCEPTUAL BACKGROUND

The information deficit model is predicated on the idea that providing a linear and unidirectional flow of scientific facts and realities from experts to the public will encourage risk acceptance and result in people changing their beliefs, attitudes and behaviors, leading to positive change (Abunyewah et al., 2020). However, deficit approaches to communication, have been shown to be largely ineffective at stimulating reductions in water consumption (see, e.g., Cary, 2008; Adams et al., 2013) and may even lead to increased consumption as individual seek to assert their "right" to consume water (Seyranian et al., 2015). Broader research in science and risk communication (Wilkinson et al., 2011; Stilgoe et al., 2014; Wilkinson and Weitkamp, 2016; Abunyewah et al., 2020) suggests that either upgrading the deficit model with community participation, or moving away from the deficit model entirely – toward bidirectional, dialogic approaches – would be more effective at engaging consumers around water scarcity and water saving.

Science is also a mediated reality within a political context (Scheufele, 2014) and therefore pre-established beliefs about water may affect the efficacy of strategies to reduce water consumption (Jorgensen et al., 2009). In this context, it may be particularly challenging to reduce water consumption in Britain (Weitkamp et al., in review[1]), which is perceived to be relatively wet. Weitkamp et al. (in review) identify groups within the public that may be more amenable to communication about water risks, arguing that those with greater connection to water could act as trusted messengers for water risk messages. Adams et al. (2013) identify a number of factors that positively affected people's willingness to conserve water. In relation to outdoor water use these included: environmental values (e.g., valuing clean water); perception of efficacy (viewing water saving as beneficial to the environment); source of information; interest in community and personal water issues. Regarding reductions in indoor water use, source of information remained important, highlighting the role of trust in the information source. Lu et al. (2017, p. 33) suggest that "norm-based and social comparative feedback are good information-based intervention tools." However, Lu et al. (2017) also point out that social comparative feedback can lead to increases in water use amongst low water users. These studies suggest that approaches which target attitudes and social identity may offer a route to behavior change through prosocial messaging.

Socially comparative feedback may offer means of encouraging reductions in water use. The approach works on the presumption that people want to do better than others, so if they are doing worse than average they will seek to improve their behavior. It can backfire though when people are doing better than the average – so there is a tendency to converge on the norm. Lede and Meleady (2019) suggest that the power of this approach is underestimated. They argue that "Rather than tell people *what to do,* it was more effective to tell them *what other people are doing*" (Lede and Meleady, 2019; p. 2 italics original). Caldiani et al. (2006) suggest two ways of framing messages aimed at encouraging normative conduct: messages that comprise descriptive norms (what is done) and those which comprise injunctive norms (what is approved by society).

We also draw on social identity theory which suggests that attitudes, emotions and behaviors are shaped by the social groups to which you belong. This theory suggests that segmenting people through social categorization relies on a normative cognitive process that exaggerates similarities within a group, and differences between groups (Tajfel and Turner, 1979); social identity arises where these categorizations are used to self-reference. This tendency suggests that ingroup sources are likely to be seen as more trustworthy messengers than those whose group identity is different or unknown. This approach is most salient when the desired behavior forms part of self-identity (i.e., with people who identify strongly with that ingroup norm) (Lede et al., 2019). In the context of water consumers, such social

[1] Weitkamp, E., McEwen, L., Ramirez, P. Communicating the Hidden: towards a framework for drought risk communication in maritime climates. Climatic Change (in review).

identities could include demographic characteristics (e.g., age, family status, race, income level) or behavioral predilections (e.g., money-saving behavior, environmentalism).

Trust is argued to be important for message acceptance. Trust is thought to be composed of a willingness to become vulnerable to another and a belief that others are doing their part (Jorgensen et al., 2009). As we have discussed with regard to social identity theory, trust may be more likely between perceived ingroup sources. In the context of water companies, trust, then, not only involves believing that the water company accurately assesses and reports water related risks (the vulnerability component), but also a belief that the water company is also doing its part in the community to reduce water consumption (e.g., fixing leaks). The need to build trust suggests that water companies need to move beyond communication approaches framed around public knowledge deficits, toward two-way, dialogic and relationship-building approaches (see L'Etang, 2008; Cornelissen, 2017; Autzen and Weitkamp, 2019). In addition, to trusting the water company, when it comes to demand management, individuals also need to trust that their wider community is engaging in water-saving measures (a social component to trust).

METHODS

Publics may be more willing to attempt to reduce water consumption during periods of extreme (dry) weather. However, as extreme weather events go, drought onset is gradual; in fact, droughts may appear so slowly that they "go unnoticed by the public at large" (Weitkamp et al., in review). The summer of 2018, which was declared one of the driest on record (Met Office, 2018), thus provided an opportunity to explore with water companies the strategies they used to communicate with customers about water conservation. Interviews were conducted with 14 water company staff, representing 10 water companies from England (7), Northern Ireland (1), and Scotland (1). The 17 main water companies in the UK were contacted, and the 14 interviewees were those who responded positively to say they would like to be interviewed. Three interviews comprised a group of two or three staff (including both Northern Ireland and Scottish Water suppliers). Interviews were semi-structured, allowing the interviewees to explore issues on their own terms, while ensuring that the broad topics pertinent to this research were covered. Interviews lasted an average of 41 min (ranging from 22 to 71 min). Interviews were conducted by one researcher, via phone call, using a semi-structured interview schedule (see **Table 1** and **Supplementary Material**), and were recorded with the consent of the interviewees.

Data were analyzed using phronetic iterative analysis (Tracy, 2019), which combined close reading of the data with theory-driven models, to uncover the practices and approaches evident in the data. Interview transcripts were first read and discussed between the authors to identify emerging themes. This was followed by review of literature to identify relevant theoretical models that could inform further analysis. Descriptive codes based on these theoretical models were created and formed the initial code book, with broad themes defined from the data through examples and linked to theory. Data were extracted into these broad codes and a sample of coded transcripts were reviewed by the second coder. Following this initial layer of coding, theory was consulted again to identify more nuanced aspects (e.g., within the overall category of trust, data could be subdivided into building trust and trusted sources) and the researchers conferred to agree final codes. Data were then reviewed against these analytical codes, with new emergent codes added as needed and relevant to the research questions. The second researcher again reviewed a sample of transcripts to ensure agreement with coding.

TABLE 1 | Main interview themes.

Question themes	Sub-themes
Past communications with a demonstrable impact on customer behavior	• Type of communication • Evidence or data available to show impact • Future trends
Timing of drought/water scarcity communications	• Effects of timing • Short-term/long-term approaches • Interaction with the media
Groups of customers that are easier/more challenging to communicate with	• Rationale for groups being easier/more challenging • Customer segmentation strategies • Themes, messages, formats and approaches for particular groups
Overcoming communication barriers with customers	• Communications strategies • Use of data/scientific information • Cooperation with partners • UK water risk discourse in general

RESULTS

Timing

All water companies interviewed deployed regular communications about water saving, rather than just focusing on responsive drought-oriented communications. Short-term campaigns around drought events were seen as challenging, and ineffective over the mid-long term, with Respondent (R) 5 reporting "As soon as you stop doing that [a short-term campaign] the intended behavior has gone or the intended awareness has gone." In this context, preparatory communications were seen as very important, and continual preparedness was a consistent theme. Furthermore, water companies also reported that customers wanted this continual communication:

> "*So what we found was that actually a lot of people said most of the time we hear nothing about water resources and then all of a sudden you tell us there is a drought, in terms of, we suddenly need to do something. So what people were saying to us was actually they want that kind of year-round communication about where our reservoir levels are.*" (R10)

Although interviewees reported that they should be communicating about water scarcity issues even if "we are in flood" (R5), there was a recognition that messages might not be well-received at these times. Water-saving messages were perceived to work better when there was a "hook" (e.g., a period of dry weather) and that in the winter "it's really hard to talk about dry weather and there not being enough water." (R4) A further challenge of continuous communications was customer fatigue:

> "*if every year we were to say the same messages about using water wisely... people get to the point where they become quite insensitive to the messaging*" (R8)

In terms of messaging, several interviewees felt that science-led or fact-based messaging was an effective way of overcoming the challenge of finding a "hook" for stories, suggesting that the media like "things like rainfall data, rain charts and anything we can show visually" (R3). This respondent also felt that the public in general "like the stats, they do like the facts, they don't tend to believe us if we don't back it up with facts" (R3).

Trusting the Messenger

Trust was seen as important for effective communication. In England there were concerns that water companies were not sufficiently trusted messengers: "From the eyes of the customers... we might not be the most trusted voice for that message to land" (R5). These concerns were less evident in Northern Ireland and Scotland, as public (governmental) messaging and water company messaging were seen to be better aligned: "we are trusted to deliver a fantastic service" (R1). Companies cited a number of ways in which they could build trust with customers, including communicating about other topics such as plastic pollution, climate change and health. These topics could also be used to engage customers with water scarcity, as explained by this respondent:

> "*We have talked a lot over the last few years around plastic pollution... [to] locally build the trust... that actually we are a decent company, we are doing the right thing so that hopefully when we start to hit messages like we are at the moment around water saving, they are actually being listened to.*" (R11)

Companies also engaged with intermediaries to help deliver messages about water saving and scarcity. Some examples include charities, NGOs or environmental partners (such as river or canal groups) and umbrella organizations, such as race courses as a means of influencing individual horse owners. Four companies felt that the Government, as a trusted messenger, should do more to promote water-saving behaviors. Working together across different sectors came up several times.

Reaching Customers

Building trust locally was seen to be beneficial, and for most interviewees this involved some level of customer segmentation. Customers were often grouped by demographic data such as age, though there were several companies also starting (or wanting to start) to focus on grouping by other factors:

> "*we have very much gone, here is our generic message, this is what everybody should be doing rather than looking and maybe targeting it either to interest groups or to local areas where there is a particular demographic. So we haven't really tried that yet. But again that's something that we want to do.*" (R10)

Understanding customers' cultural background was seen to give insights into their water use context, but one challenge cited was "understanding your customer base well enough to segment them properly" (R5). Identifying customer groups was seen as valuable because different people needed help with particular habits: segmentation allowed messages and services to be tailored to each group. Four interviewees mentioned that it was easier to engage a segment that is concerned about environment, sustainability, or climate. Seven interviewees indicated that it was easier to engage people with money saving messages than other types of messages. However, a couple also mentioned money saving or financial reward being less effective than other messages (e.g., environment) – perhaps because the low costs of water means the financial gains are relatively modest. The low cost of water, therefore, came up several times as a barrier to effective messaging about money saving, as explained by this interviewee:

> "*if you put out a little bit of messaging on gas and electric bills because they are that much higher you have got that much more attention straight away.*" (R4)

Attitudes toward waste or maximizing efficiency came up in several interviews, with older people seen as more likely to hold these attitudes. Older people were generally seen as having more water-saving attitudes, whereas younger people, especially teenagers were seen as less water-conscious. However, this was balanced in part in one case by younger generations being seen as more likely to use water-saving technologies and devices, and one trial where young people responded more to messages involving scientific information than those involving humor or calls to action. Age was seen as a greater factor than cultural diversity in determining water use:

> "*ethnic background and cultural differences lead to different water use, we know that. People use water differently. For a number of reasons, ethnicity, culture or how they cook food and how they use water varies the total consumption or per capita consumption of that particular demographic however when it comes to teenagers we found they all use too much!*" (R4)

Several other segments were also more difficult to reach: time-poor families; people with low digital literacy; and, for three companies, a group who say "why do I care?" (R1) or who "feel aggrieved at being asked to save anything, you know, its water, it falls from the sky, why do I have to pay for it?" (R3). Such customer attitudes were also explored in the context of intergenerational equity. For example, this interviewee considered who should be responsible for paying for increasing water security in the UK:

> "*if you are talking to a retired person, is it fair for them to have their bill go up by £10, £20, £30 to pay for a reservoir or a transfer that they will never see the benefit of?*" (R4)

In terms of reaching customers, interviewees mentioned providing personalized information, using meter readings to tell people how much water they were using. However, it was noted that such information needed to be accompanied by information that would support changes to behavior, whether at the level of personal behaviors or adoption of water-saving technologies. This approach could be extended to provide socially comparative feedback, where customers were told how their water use compared with others in the same area. Eight of the 11 companies represented reported using this approach, which was clearly seen as an effective tool to encourage water saving. A city league table and competitions between families attending a school were other suggestions embedding socially comparative feedback. Funding for communications was also cited as a challenge for reaching customers: "most water companies aren't particularly well-resourced on marketing compared to your typical commercial organizations" (R3). One company mentioned using an AI-supported online facility to help it to become more responsive to customers.

Community-Scale Interventions

Four interviews mentioned conducting community-scale experiments trialing communication approaches to reduce consumption. These approaches focused on specific locations, such as a town served by the water company and were seen as a way of testing "how innovations work together" (R3). In one particularly water-stressed region, a trial was underway to see whether it was possible to reduce average daily water consumption to under 80 l. This trial combined a range of approaches, including personalized reports on water usage; reports on water usage compared to neighbors; and communications about local water resources. The company offered to pay people £50 to read their meter twice during a 2-week trial, to try to stimulate greater engagement with water savings. As the interviewee observed:

> "*We thought that they might really save initially in the first few days and really go for gold and then actually it [water consumption] would rise back up a little bit as they got bored. But actually we found that the savings increased over time. So there was a little bit of getting to grips with it but then once they found the tips that worked for their family and got into their own groove with it, then their savings increased. So it was actually counter to what we thought the outcome would be.*" (R3)

Test communities were also used to assess the impact of the way that socially comparative feedback is provided to customers, for example: "we have called it 'your neighbors,' 'similar properties,' 'properties in your region,' we have put some different language to see what strikes a good cord with customers. What they don't like." (R8) These "testbeds" either fed back personal results or socially comparative information, or produced information the companies were using to inform future communication. Results were mainly measured through metering, though one company used a survey to assess satisfaction. The stated aim was to use a "blueprint" created from the smaller testbeds to roll out well-informed communications over a larger area.

DISCUSSION

In contrast to previous research (e.g., Koop et al., 2019), we found evidence that UK water companies recognized the importance of proactive communication with customers to reduce demand. However, as in previous research with other types of stakeholders, interviewees noted that it was hard to discuss drought and water scarcity issues in the absence of dry weather and particularly in the winter (Weitkamp et al., in review). In this context, our interviewees reported a number of approaches designed to reduce demand and were actively innovating and testing approaches to identify those leading to changes in water-use behaviors. While there was recognition of the challenge of achieving sustained behavior change, examples involving personal feedback and socially comparative data were viewed as the most promising.

From interviewees' perspectives, trust emerged as a major factor affecting their communication and they were acutely aware that as water-selling businesses they were not always the most trusted source to communicate about water scarcity or saving. This need to build trust was a major factor in their recognition of the need for sustained communication about water use and water scarcity and led companies to work with intermediaries that they perceive to be more trusted by the public. It also underpinned the call for a more joined-up approach to water communication, in which government and non-governmental organizations had a significant role to play (see also Waterwise, 2013). Most companies interviewed were at least partially invested in a communications model involving closing informational deficits. Many of the approaches mentioned by water companies were about broadcasting messages to customers and there were relatively few examples of approaches that might be viewed as dialogic or designed to build relationships (L'Etang, 2008; Autzen and Weitkamp, 2019). Where dialogic approaches were mentioned, they were seen as effective but time-consuming, with cause-and-effect impacts on water resources that are very challenging to measure. Therefore, these potentially effective approaches were seen as harder to justify.

Funding for communications was also cited as a challenge for communicating with customers, and one interviewee pointed toward a report showing that the percentage of total water company spending used on water resources and efficiency communications in the UK (0.2%) was much lower than in the EU (1%), the US (1%), or Australia (6%) (Lewis et al., 2018). Public understanding of water resources issues – "how water gets from the sky to your taps" (R3) – and related water risks, was still seen as a general issue, but one that was being addressed with the provision of more scientific or fact-based information in some cases. A lack of recognition for intergenerational fairness in the funding of water infrastructure was cited as an outstanding issue around the communication of risk management; this is a topic the authors recommend for further exploration.

Previous research (Jorgensen et al., 2009; Adams et al., 2013; Weitkamp et al., in review) has suggested that some members of the public are more willing to engage with water savings than others. Our research with water company representatives suggests that many of these businesses rely on more traditional approaches, segmenting customer groups by demographic characteristics (such as age), although there is an emerging trend for segmentation by other types of social identity, such as attitude or underlying values.

There was a mixed response regarding the perceived effectiveness of cost-saving messages. Those who doubted their effectiveness attributed this to the low cost of water, but water companies should also bear in mind Corner and Randall's (2011) research, showing that appealing to cost-saving behaviors does not necessarily make pro-environmental behaviors more likely. Although appealing to cultural and environmental values was perceived as effective, most of the approaches discussed focused on place – e.g., community-based initiatives. Place-based focus may relate to the ways in which water companies typically assess interventions (which could be through comparison of consumption data by postcode). The emphasis on attitude and place aligns with communications approaches that focus on social norms and socially comparative feedback; further work to assess the efficacy of these approaches is needed.

This research sheds further light on the way UK water companies communicate with the public and brings clarity to some of the perceived underlying assumptions in the sector about what influences public water consumption.

Methodologically, combining dialogic, culturally informed approaches with community-scale testbeds could produce a more rigorous understanding of the way that various communications interventions affect outcomes. For policy, our results signal a call for help in building and maintaining an environment of greater trust to discuss water supply issues and risks in the UK: an environment in which long-held beliefs about water may need to be unpicked and challenged, and which creates space and resources for more bidirectional flows of information between consumers and water companies.

DATA AVAILABILITY STATEMENT

The datasets for this article are not publicly available because the nature of the interviews means that it is not possible to provide anonymity to the participants if the full or partially redacted transcripts are made available publicly. As anonymity was a condition of the ethics approval full transcripts cannot be made available. Substantially redacted transcripts can be provided on request to the corresponding author. Requests to access the datasets should be directed to RL, ruth.larbey@uwe.ac.uk.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Faculty of Health and Applied Sciences Research Ethics Committee, UWE. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

RL piloted and amended the interview schedule, carried out the interviews, conducted primary analysis of the data, wrote sections of the manuscript, contributed to revisions, and read and approved the submitted version. EW designed the interview schedule, secured institutional ethics approval, supported data analysis, wrote sections of the manuscript, contributed to revisions, and read and approved the submitted version. Both authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Framing the End: Analyzing Media and Meaning Making During Cape Town's Day Zero

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In this paper, we analyze public discourses in 2018 about water-scarce Cape Town, SA. We investigated the discursive implications of apocalyptic rhetoric such as "Day Zero" by analyzing local and international news media talk ($n = 111$ newspaper articles) surrounding the Cape Town water crisis during pre-, height of, and post-crisis moments, complemented by 12 narrative problem-centered interviews in the height of the water crisis. The analysis led to a focus on the relationship between environmental and communicative developments with a high local impact, and mainly on examples of local engagement, social movements, or resistance as response to changing environmental scenarios and the evaluation of the role of (news) media in raising community concern and commitment. The findings show that the communication around the (twice-postponed) "Day Zero" in Cape Town is a very fruitful example of the digital disrupted, post-truth communication that happens with environmental issues today.

Keywords: water scarcity, water crisis, framing analysis, transformative environmental issues, rhetoric analysis, Day Zero, Cape Town

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INTRODUCTION

Today's societies are dependent on access to clean water. Despite that, one-fifth of the world's population, which corresponds to around two billion people, live in areas facing water scarcity. In total, two-thirds of the entire global population experiences water scarcity at least one month a year (Mekonnen and Hoekstra, 2016), while another 1.6 billion human beings encounter economic water shortages (UN, 2018). An estimated two-thirds of the world's population is expected to face water shortages in the next five years, thus making water supply and water scarcity crucial issues and increasingly urgent problems (UNPD, 2006; UNEP, 2016; European Commission, 2018). As a consequence, communication on water as a risk is considered to be the *key* element in optimizing water resource management (IWA International Water Association, 2019), and plays a major role in the UN's Sustainability Development Goals framework for meeting Climate Change related challenges on an international, national, regional and local level (UN, 2020).

Various meaning making processes focus on water as a resource that is profitable, polluted, threatened, or scarce—again on an interpersonal and community but as well national and international level. Water resources and supply, water politics, and water management are sensitive issues and covering these issues on those levels is a multifaceted challenge—for all kind of organizations and institutions but the media in particular.

This is chiefly due to understandings of water as a "transversal resource," meaning that both water management and water communication are subject to many influences and interests, and the mentioned meaning making has often a certain political or corporate spin (Hervé-Bazin, 2014). Literature shows that water resource management is linked to issues of power and politics, especially in water stressed areas (Trumbo and O'Keefe, 2001; Jöborn et al., 2005; Dolnicar and Hurlimann, 2010; Spinks et al., 2017; Liang et al., 2018). Inadequate or inappropriate water governance—including management practices, institutional arrangements, and intransparent socio-political conditions—as well as economic interests influence mainly the public debate on water as a resource and the risk of scarcity, the degree of problematization of water issues, and the use and abuse of environmental issues like water in political discourses.

Based on this background and with a focus on narratives, frames and metaphors used to express hegemonic frames and the abovementioned spin in public meaning making processes around risks, we analyzed the discourse about water scarcity in Cape Town in 2017/2018 with a specific interest in the *communicative dynamic* of the announced "Day Zero." Therefore, the focus of the paper is centered on water resource management policy; examples of local engagement, social movements, or resistance as responses to changing environmental scenarios; and the evaluation of the role of (news) media.

Introducing "Day Zero": The Case of Cape Town

On January 18, 2018, the mayor of Cape Town Patricia de Lille announced in a press conference that the city of Cape Town had reached "a point of no return" and set an arrival of "Day Zero" —the day when Capetonians taps would be turned off—on April 21, 2018.

However, Cape Town did not run out of water on April 21, 2018. Instead, preventive measures were adopted and "Day Zero" was postponed to June 4, 2018. When June 4 was reached, Capetonians' taps still were not switched off, nor were taps turned off on any of the other predicted "Day Zero" dates (Ma, 2018). Moreover, although "Day Zero" was later pushed to sometime in 2019 (Chutel, 2019), the year concluded with taps still flowing.

Previous research has identified the impact media coverage of drought can have on public understanding of environmental issues (O'Donnell and Rice, 2008). Since the public often uses mass media to gain information on environmental issues and assess risks before enacting policies (Dearing, 1995), it is essential to understand how media communication on environmental crises like "Day Zero" is framed and what kind of public response it seeks to evoke. Indeed, the strategic communication of a "Day Zero" frame with a strong metaphorical character had an impact on how the situation and risk was interpreted locally, nationally and globally. To this purpose, *Part 1* of our study traces back and analyses the media discourse on "Day Zero," while *Part 2* investigates the meaning making process the water crisis aroused in the local community and analyses the role of (news) media in the framing process.

MATERIALS AND METHODS

Understanding Water as a Transformative Environmental Issue

Although "water communication" is not recognized as a specific field of research, communication about water is widely regarded as a sub-discourse of environmental communication and natural resource management (Bennett, 2003; Mäki, 2010; Hervé-Bazin, 2014; Liang et al., 2018; Mitra, 2018). Environmental communication is useful in that it "helps us construct or compose representations of nature and environmental problems as subjects for our understanding" (Cox, 2013, p. 19). The constitutive component of communication implies that when communicating about the environment, specific values and references as well as images and contexts are associated with particular issues. If public discourses are perceived as scripts assembled from the mentioned structural elements (Dryzek, 1997), then frames (Entman, 1993) can be understood as embracing these elements, making them "invaluable tools for presenting relatively complex issues" (Scheufele and Tewksbury, 2007, p. 12). Thus, frames serve as specific interpretative tools that help us understand discourses on complex topics, such as water as a resource and the risk of water scarcity or (mis-)management.

Framing research from an environmental communication perspective mostly focuses on specific topics, such as climate change (Nisbet, 2009, 2010; O'Neill et al., 2015; Brüggemann and Engesser, 2017), and usually involves analyzing news or social media content (Boykoff, 2011; Schäfer and Schlichting, 2014; Newman and Nisbet, 2015). Additionally, some studies have examined sustainability as a master frame in climate change related discourses (Atanasova, 2019; Weder, 2021) and its strategic use by corporations (Schlichting, 2013; Schäfer, 2015; Diprose et al., 2018), political institutions (O'Neill et al., 2015), or organizations in general (Miller, 2012). When viewing water scarcity as a climate change-related problem, issue-specific framing approaches (de Vreese, 2005) appear applicable. However, our focus on communicative problematization processes (in the media or interpersonally) suggests that existing framing research in environmental communication is best complemented by the concept of problematization, which Weder et al. (2019a) has previously introduced as part of sense making processes.

Our paper's use of problematization is rooted in a view of discourse as constitutive processes and the definition provided by Sandberg and Alvesson (2011). We understand problematization to be showing how certain beliefs and opinions about a topic or field are problematic. Following Foucault (1988), problematization means to investigate how an issue is constructed as an issue, as well as how it is classified and contextualized (Deacon, 2000; Bacchi, 2012); in other words, an issue becomes "an issue" due to how it is constructed and/or contextualized by a process that we conceptualize as problematic.

Problematization thus offers a deeper understanding of framing as a process of deconstruction (problematization) and (re)construction [remedy promotion, solution orientation, normativity, with a reference to Entman (1993)].

Problematization involves analyzing the factors that constitute both issue and context (Akor, 2015). Additionally, problematization is discussed as the constitutive part of framing processes, mainly in Entman's concept of framing as problematization and moral evaluation, referring to causal relationships between arguments as well as promoting remedy (1993). Thus, in our paper, framing is considered the process of organizing public communication. As long as frames are considered organizing ideas (Gamson and Modigliani, 1989) they "are contested by journalists and the audience, new ones are selected and others may disappear without the frames themselves undergoing any change" (van Gorp, 2007, p. 64). Using problematization, a certain degree of morality, and different ways of argumentation with a solution at hand, the amount of attention an issue receives and the legitimation or exclusion of its related arguments can be influenced (Newman and Nisbet, 2015).

Water issues are communicated through different interpretive patterns (Shah et al., 2002). If communicative problematization can be characterized as a process, it can also be considered an action that starts by recognizing a situation or idea as problematic and then increasing the level of involvement using various patterns and frames (Crable and Vibbert, 1985). The 2018 Cape Town water crisis stimulated framing processes in political, economic and environmental discourses. Water as a natural resource was problematized and had a relatively high degree of morality in the sense of who or what might be responsible for the drought and which political options or actions should be considered over others (Nisbet, 2009).

In our paper, we trace back the problematization of water as a scarce natural resource and identify the "over-moralization" of the issue with the apocalyptic frame of "Day Zero" in public discourses. Specifically, we aim to identify the exact patterns lying behind the discourse on water scarcity by analyzing the public discourse of the water crisis in Cape Town, SA from a media perspective (*Study Part 1*), as well as the problematization of "Day Zero" and related framing processes from an individual perspective, i.e. the local community's meaning making processes of this crisis (*Study Part 2*). Ultimately, our analytical focus on framing of the water crisis in Cape Town in 2018 offers new insights as to the regularities and irregularities of water communication as a future topic in environmental communication research.

Apocalyptic Rhetoric

Zamora (1982) explains that the term "apocalypse" is used in traditional Judeo-Christian religion to forecast, reveal, or envision the world's annihilation. Apocalyptic rhetoric thus describes a narrative *telos*, or end-point, that implicitly or explicitly predicts when the current world order will be dramatically destroyed and replaced with a new world order (Brummett, 1984, 1991). The common narrative is of a tragic ending, which assumes that the oncoming experience is determined and decided by uncontrolled external forces (Wojcik, 1996). Foust and Murphy (2009) explain this outcome by saying, "Like God's wrath or nuclear war, the apocalyptic scenario is so much greater than humanity (let alone individual human effort), that there seems little hope for intervention" (p. 154).

Following Burke (1984), our paper views apocalyptic frames through two lenses: comic and tragic. A tragic apocalypse is illustrated through humanity's acceptance of a prophesied ending (Burke, 1984) in which the *telos* is catastrophic and unavoidable (Foust and Murphy, 2009). By contrast, a comic apocalypse is ill-defined and considered avoidable if the right human actions are taken (Foust and Murphy, 2009). Importantly, a comic apocalypse is more forgiving and perceives humanity as having made a mistake (Burke, 1984). O'Leary (1993) also differentiates tragic and comic apocalypses as having closed and open-ended interpretations of time, respectively. In environmental communication scholarship, apocalyptic framing has largely been applied to environmental films (Foust and Murphy, 2009; Salvador and Norton, 2011), but these media explorations open the door for other environmental applications, such as the media discourse analyzed in this paper.

Problematization of Water Scarcity in the Media

The effectiveness of news reporting on environmental and resource management issues has led media to play an increasingly key part in the environmental communication field (Jurin et al., 2010). Most importantly, the media informs the public about events and reports information, influences the public's perceived salience or importance of issues, shapes public opinions, and initiates and encourages civic engagement (Moon, 2013).

Previous research on drought around the world—e.g., in Athens (Kaika, 2003, 2006), in California (Nevarez, 1996), and in Sydney and London (Bell, 2009)—reinforces the assumption that media coverage of drought contributes to public awareness and sense-making of not only droughts specifically, but also climate change and environmental issues in general (O'Donnell and Rice, 2008; Bell, 2009). In South Africa, water issues are more commonly assessed from a global perspective, such as Bond and Ruiters (2001) examination of post-apartheid drought and flood discourse. Even though environmental issues are infrequently approached from a local perspective (Marvin and Guy, 1997; Lawhon and Patel, 2013), water discourses in the media specifically present a strong local reference (Weder et al., 2019b) since "the local scale [is] a site of action where change can happen and where ordinary people feel empowered to contribute" (Lawhon and Makina, 2017, p. 240).

In *Study Part 1* we therefore aim to combine these narrow and broad media perspectives by comparing and contrasting local and international discourse(s) of the Capetonians' water crisis. To do so, we conducted a discourse analysis through which different criteria, structural patterns, rules and resources of the meaning making process of water discourses can be identified and analyzed.

Study Part 1

Research Design

In order to understand how public discourse about the 2018 water shortage in Cape Town was constructed, *Study Part 1* explores media discourses surrounding "Day Zero" to gain insight into rhetorical turning points during the Cape Town water crisis. To this purpose we ran a media analysis of $n = 111$ news articles during three different stages of the water crisis: pre-, height of, and post-crisis.

For this study, the term "Day Zero" was considered to have apocalyptic potential due to its reference to a day when Capetonian taps would be turned off and everyday life in Cape Town would cease to exist in its current state. This consideration is supported by the previously mentioned explanation that apocalyptic rhetoric is a useful tool to describe narrative *telos*, or endpoints, and to predict either implicitly or explicitly that the current world order will be dramatically destroyed and replaced by a new one (Brummett, 1984, 1991). This approach to apocalyptic rhetoric is also echoed by O'Leary (1994), who explains: "The tragic and comic frames are interpretative devices for lending meaning to personal and collective human experience by arranging events into a coherent system of signs. As such, they serve as resources for the invention of arguments that enable people to explain otherwise terrifying or anomalous events and incorporate them into a structure of meaning. The comic assumption that human being are free actors and the tragic assumption of divinely ordained fate do not only determine the shape of historical narratives; they also serve as elements of self-definition that constrain and enable arguments for different audiences" (p. 92).

The use of apocalyptic frames is used here to analyze the public discourses on "Day Zero."

Data Collection

Our analysis of the public discourse on Cape Town's water crisis focused on media discourses in newspapers. Newspaper articles referring to "Day Zero" were collected between June 1, 2017 to June 1, 2018. This time frame was selected in order to allow for an analysis of the three stages (pre-, height of, and post-) of the water crisis. A NewsBank search for the keyword "Day Zero" in the headline and "water" in the lead/first paragraph resulted in 251 newspaper results worldwide. In order to allow a comparison between local and international media discourses, results from non-Capetonian South African newspapers were excluded from the final data sample. After data cleansing, i.e., removing newspaper articles duplicated across outlets, $n = 83$ articles in Cape Town-located newspapers and $n = 28$ articles in international and/or non-South African newspaper were included in the final data sample ($n = 111$).

Both data groups (local vs. international news articles) were organized chronologically and divided into three stages: pre-, height of, and post-crisis. The pre-crisis stage was defined as the time frame between June 1, 2017 and January 17, 2018, i.e., any news that occurred before Mayor de Lille's January 18, 2018 press announcement of "Day Zero" as April 21, 2018. The height of crisis stage was defined as the period between January 18, 2018 and February 13, 2018. The post-crisis stage was defined as the lapse of time between February 14, 2018 and June 1, 2018, when data collection ceased.

Data Analysis

After data collection and organization, the newspaper articles included in the final sample ($n = 111$) were analyzed by one researcher and the results compared between local and international newspapers. Following recommendations provided by Strauss and Corbin (1990), data were first analyzed using open coding, or "the process of breaking down, examining, comparing, conceptualizing, and categorizing data" (p. 61). In order to understand and analyze public discourse on news media about Cape Town's water crisis, each data set was first read thoroughly for coherency and understanding. Data sets were reviewed a second time with specific attention being devoted to the identification of recurring apocalyptic concepts and themes present in each of the three crisis stages. Special consideration was given to mention of apocalyptic tropes, including disease, violence, and religion, as well as common crisis descriptions such as "avoid" and "denial." By doing so, we were able to identify the interpretative patterns lying behind the water discourses, i.e., how they were framed, and understand how public discourses about Cape Town's water crisis were constructed.

Study Part 2—Day Zero Meaning Making Processes in Relation to Media Frames

People mainly acquire information about environmental issues from media and news reporting (Schäfer, 2015), which shapes their perceptions of the issues themselves (Adger et al., 2012). Thus, knowledge of environmental issues and related problems is predominantly media-based and can be perceived as a result of mediated debates. Media (debates) shape and construct the public's perception of environmental problems and can therefore enable or inhibit engagement (Lester, 2010; Cox, 2013; Hackett et al., 2017). This assumption led us to investigate what kind of meaning making processes were evoked in the local community by the reporting and framing of "Day Zero" discourse analyzed in *Study Part 1*.

Guimelli (1993) argues that meaning-making processes can work as instructions for individual behavior and direct social practices. As mentioned earlier, we understand problematization as a social construction process that starts with the recognition of an issue as problematic and increases the level of social and/or individual involvement (Crable and Vibbert, 1985). Following Weder, Lemke and Tungarat's (2019a) argumentation, we also understand problematization as a fundamental concept in sustainability and environmental research, because without the problematization of an issue, there is no engagement in finding a solution. Furthermore, problematization—as a core process of permanent stimulation of dissent and legitimization of dominant arguments—allows for the reflection of common knowledge or common-sense issues (Weder, 2017), as well as the development of new viewpoints and critical thinking (Crotty, 1998).

As in *Study 1*, our *Study 2* also applies Entman's (1993) framing approach from a communication perspective, complementing the previously mentioned concepts of problematization. In doing so, we are able to detect the frames, i.e., the interpretative patterns through which issues about the water crisis in Cape Town is communicated. In order to analyze and understand how Cape Town's water crisis and meaning-making process is framed by the local community, we ran a case study in Cape Town in May 2018, just before "Day Zero" was postponed for the second time, addressing the following questions:

- RQ1: Which interpretative patterns construct the local community's meaning making processes of "Day Zero"?
- RQ2: How does the local community respond to the changing environmental scenarios?
- RQ3: What role do the media play?

Research Design

The purpose of qualitative research is to gain a deeper understanding of a phenomena rather than achieve generalizable results. Therefore, to answer RQ1, RQ2 and RQ3, we ran a case study in Cape Town. In May 2018, just before "Day Zero" was rescheduled for the second time, we conducted 12 semi-structured and problem-centered interviews with exponents of the local, urban community (Spinks et al., 2017). We chose semi-structured, guided interviews, since the guidelines serve as a thread in order to structure the conversation. The use of guidelines assures that certain topics are addressed and allows comparability between different cases, as they provide a thematic framework. In addition, semi-structured interviews are suitable to identify and highlight previously unknown qualitative issues and trends, as well as to explore new areas within the scope of the research interest.

The interview partners for our case study were chosen using a system called "critical snowballing," which means finding suitable interviewees based on recommendations from former interview partners (Brodschöll, 2003). In order for the snowball sampling system to work, the identification of the first informant is crucial (Penrod et al., 2003). For our case study in Cape Town, the first interviewee was selected due to the strong local and international media presence of her non-profit organization during the water crisis, which established her as a key actor with a strong and far-reaching network related to our research interest[1]. This way, we were able to conduct 12 interviews with exponents of Cape Town's local community, namely four activists, two journalists, two environmental scholars, and four everyday people directly affected by the water shortage. We concluded the snowballing sample system with the 12th interview, as we had reached data saturation and no new information could be attained (Guest et al., 2006). The 12 semi-structured interviews were fully transcribed and analyzed using the qualitative content analysis by Mayring (2014), following an inductive approach. This type of qualitative content analysis was selected because it allows a systematic, rule- and theory-based analysis of communication, instead of a "free" interpretation of the material. The inductive approach enabled the forming of categories directly from the research material so as not to distort the essence of the written and/or spoken material and its content. In this procedure, the categories were developed inductively based on the text material along a selection criterion determined by theoretical grounds. In addition to the selection criterion, the content analytical rules for inductive category formation required the specification of a level of abstraction, on which categories were phrased (Mayring, 2014). Looking at RQ1, we categorized all text passages in which "interviewees reported on their personal perception of Day Zero and the reasons for it" (selection criterion). Whenever the selection criterion applied to a text passage, a new category was formulated or an existing inductive category was assigned to the text passage. The names of the categories were formulated as "concrete aspects and reasons for Day Zero" (level of abstraction). Using this process, the material was organized into categories and made generalizable, which allowed for its analysis on a higher abstraction level and for a connection to be made between interviews and the building of issue clusters.

The inductive content analysis was performed using the online analysis tool QCAmap. This tool offers the ability to share the project with a second coder through a so-called "inter- coder-agreement" that allows coding processes and results to be compared. The comparison of two analysts coding the same material actually gives a measure of objectivity, since research results are independent from the researching persons (Mayring, 2014).

[1]Due to the anonymization commitment, no further details about the organization and/or the interviewee(s) can be disclosed.

RESULTS

Results Study Part 1—Public Discourses on "Day Zero"

In Capetonian newspapers, discourses related to "Day Zero" were most prominent during the height of crisis stage and least prominent during the pre-crisis stage, peaking in February 2018. In international and non-Capetonian newspapers, the "Day Zero" issue was most prominent during the post-crisis stage, while no articles could be found during the set pre-crisis stage.

Pre-crisis

During the pre-crisis stage, Capetonian discourses on the water crisis were framed as a comic apocalypse. Here, "Day Zero" was framed as a worst-case scenario that could be avoided: for example, Premier Helen Zille was quoted as saying, "Although the drought in the Western Cape is serious, there is no need to panic because the provincial government is doing everything it can to avoid 'Day Zero' and not run out of water" (Measures in place to avoid water doomsday, 2017). Other outlets described Day Zero with potentiality overshadowed by uncertainty that would merely result in a "close call" (Day Zero delayed 2 months, 2017) as long as residents followed prescriptions. Later in the pre-crisis stage, mentions of avoidance were accompanied by clarifying language that explained means of solving the problem, communicated as "whole-of-society" efforts such as "Day Zero can only be avoided if we work together in partnership" (Attempting to push back Day Zero, 2017). Here, media discourses on "Day Zero" were firmly associated with an air of collective responsibility and teamwork.

Height of Crisis

As the water crisis in Cape Town escalated, so too did the media discourse about "Day Zero." During the transition from the pre-crisis to the height of crisis stage, "Day Zero" took on a more concrete meaning, both locally and internationally, and became defined as the day when city taps would be turned off.

News coverage in Capetonian newspapers became more detailed, supported by shared extractions from FAQ documents and concrete explanations of what "Day Zero" would entail, such as water queuing and military oversight of water collection sites, that demonstrated Capetonian media's firm acknowledgment of the crisis. On an international level, the discourse around "Day Zero" consisted of storytelling about Cape Town's daily life, with articles detailing city mandates of two-minute showers, drained swimming pools, or minimal toilet flushing, as well as criticism about the city's ability to transition if "Day Zero" was reached and needed to be enacted.

During the same time that international news coverage about Cape Town's water crisis began, local newspapers reported on Capetonians' confusion related to communication about "Day Zero": "The city has no plans to avoid Day Zero," an op-ed in *The Cape Times* stated, "and they are clueless of what will happen then" (Water Crisis Coalition protest, 2018). This confusion in the reported meaning making process of the local population coincides with a twofold apocalyptic framing narrative in which "Day Zero" was communicated simultaneously as both a comic and tragic apocalypse. As in the pre-crisis stage, some local newspapers continued to frame "Day Zero" as a comic apocalypse that could be avoided through teamwork and commitment, with one article quoting Cape Town's Deputy Mayor Ian Neilson as saying, "[...] it is still possible to push back Day Zero if we all stand together now and change our current path" (Day Zero April 12, 2018). This corresponds with the local community view, which saw Day Zero as something that could still be averted.

Comparatively, others communicated "Day Zero" as a tragic apocalypse. This apocalyptic framing was supported by a narrative climate of fear or anxiety related to potential or existing dangers of "Day Zero's" arrival. In one case, the *Daily Voice* published an article in which a city resident expressed panic at the realization that Day Zero was truly coming: "The worst case scenario is unthinkable. To prevent outbreaks of diseases, schools and businesses will have to close, prices of everything will skyrocket as a result, and desperate people will attack anyone even just suspected of having water. Forget about cash van robberies. There will be water tanker heists and armed robbers will leave cell phones and TVs behind, while making off with bottles of water" (Live as if it's Day Zero already, 2018). Taken together, this kind of news reporting suggests a paralyzing acceptance of an inevitable "Day Zero" disaster scenario.

Our analysis also shows a small but significant local meaning making process related to the framing of "Day Zero": some local news framed Cape Town's water crisis as a hoax and presented conspiracy theories to explain it away, giving "Day Zero" a positive meaning or rejecting "Day Zero's" apocalyptic potential entirely.

Post-crisis

In the post-crisis stage, the framing of "Day Zero" as both a comic and tragic apocalypse continued. On the one hand, local news coverage continued to communicate the need for persistent community commitment in order to avoid and/or overcome "Day Zero," as well as communicate a more general need for environmental changes to avert future crises. On the other hand, even after "Day Zero" was repeatedly postponed, local newspaper coverage continued to mention tragic apocalyptic themes of inevitability and disaster. Some were apocalyptic stereotypes, such as theft, vandalism of water supplies, or mentions of diseases and illness. Still, others persisted with framing "Day Zero" as a hoax "conjured up by the City of Cape Town to intimidate residents into saving water and to cause fear and panic" (Day Zero a Big Con, 2018).

Results show that the post-crisis news coverage of Cape Town's water crisis led to two opposite meaning making processes in the local community: one in which Capetonians were totally aware of and educated about the effects and harms of "Day Zero," and another in which Capetonians were confused about "Day Zero's" origin and shifting temporality. The first group is best identified in a *Cape Argus* article in which school children were interviewed about their awareness of the water crisis—and they clearly were aware: "I know we [sic] running out of water and it makes me scared because water is life and we can't live without it," one of them said fearfully, with another saying, "I get tired when people tell me I must save water every time because I know I must" (Schools produce Day Zero 'water heroes', 2018). By contrast, a separate *Cape Argus* article interviewed ANC Western Cape spokesperson Yonela Diko, who stated frustratedly, "Many people in the Western Cape remain in the dark as to the cause, how did we get here, and who's responsible. Was Day Zero even real?" (No tariff drop, 2018).

Whereas Capetonian post-crisis public discourses were Cape Town-focused, international and non-Capetonian post-crisis news reporting was mostly nation-specific, full of self-comparisons and predictions of which country would and/or could be the next one to face such a water crisis. Although it is impossible to know the specific reason for international media's propagation of the "Day Zero" metaphor, some discourse expressed that using the term "Day Zero" was helpful in visualizing the gravity of water crises: "Cape Town is a really good example of what might happen in the future in many other places," explained University of Cape Town hydrologist and climatologist Piotr Wolski when speaking to *The Australian*, "I hope that other cities will learn a lesson from us" (Steinhauser, 2018). Among many, a sentiment was expressed that water security and accessibility could impact any area, and that little separated their own locations from the Day Zero fate that Cape Town faced. In fact, Australia, Pakistan, Egypt, India, Zimbabwe, the Middle East, and countries of North Africa all disseminated articles contemplating their position and relationship to global water security.

This apocalyptic framing of "Day Zero" was mostly comical and critical of the term "Day Zero" itself due to its sense of finality: "Zero has the connotation that this is the end. It doesn't

TABLE 1 | Public discourses on "Day Zero" —inductive category development.

Public Discourses on "Day Zero"		
Main categories	**Inductive categories**	
Framing "Day Zero"	Day Zero can be avoided	
	Day Zero is unavoidable	
	Concrete information/explanation about causes and consequences	
	Storytelling	
	Narratives of fears/anxiety	
	Day Zero as a hoax	
	Local vs. global	
Meaning making processes	Day Zero can be avoided	Collective responsibility
		"whole-of-society" efforts
		Means of solving
	Day Zero is unavoidable	
	People are aware of environmental issues	Need for change
		Local vs. global discourses
	People are confused by inconsistent communication	

give us hope. But we are responsible. We can do something. We can avert it" (Pellot, 2018). Nevertheless, the minor conspiracy narratives shared by local news coverage also appeared in some international media reporting.

In sum, our analysis of local and international news coverage of "Day Zero" not only shows multiple and at times conflicting rhetorical narratives and frames of the water crisis, but also a multitude of meaning making processes in the local community (see **Table 1**). Results of *Study Part 2* address the latter more thoroughly.

Results Study Part 2—Meaning Making Processes

RQ1 aimed to identify the interpretative patterns that constituted the local community's meaning making process of Cape Town's "Day Zero." The qualitative content analysis of the 12 semi-structured interviews revealed that "Day Zero" is not perceived as an environmental issue, but rather as a vehicle to serve multiple purposes (see **Table 2**).

The first framing of "Day Zero" conforms to the confusion in the meaning making process of Cape Town's water crisis due to controversial and opposite news reporting, as shown by *Study Part 1*, especially in the height of and post-crisis stages. In particular, the framing of "Day Zero" as not an environmental issue is more present in the narratives of the interviewed everyday

TABLE 2 | Interpretative patterns of "Day Zero."

RQ1 - Which interpretative patterns construct the local community's meaning making processes of "Day Zero"?	
Main categories	**Inductive categories**
Day Zero is not an environmental issue	Day Zero as a hoax
	Day Zero as political issue
	Day Zero as economic issue
Day Zero as a way to shift political power	Day Zero as a way to shift political power
Day zero as a way to change people's behavior	Day Zero as a scaring instrument to change people's behavior

people, who seem to adopt the framing of "Day Zero" as a hoax, as found in *Study Part 1*.

Hence, interviewees argue that "*There IS water in Cape Town" (Local Resident 1); "We HAVE [water] resources here. If we look about why the city was founded, it was founded because we have water here" (Activist 3),* and explain their water crisis as a result of economic and/or political decisions: *"One dam is almost empty, but others are full. Those dams that are full don't belong to Cape Town anymore, because they were sold [to multinational corporations]"* (*Capetonian Tourist Guide 1*); *"We've got a complete mismanagement of the water source. [. . .] There isn't even knowledge of what water sources we have" (Environmental Journalist 1); "Day Zero was more a political threat, you know, more than anything else" (Activist 2).*

Framing the Capetonian water crisis as a political issue is also evident from the perception of "Day Zero" as a vehicle to serve diverse purposes. Here, our results show how "Day Zero" is perceived as an instrument to (1) shift political power, as well as to (2) change people's behavior. The former meaning making process is related to the double framing of water as something powerful and as a political issue, which in turn is able to shift political power: *"It's a bit cynical but it is actually the ANC interest to see the DA fail, because they don't control this [water scarcity] problem" (Local Resident 2)*; "*Water is powerful. [...] the water could be a political thing to gain power because now the ANC [...] can be like 'ok, if you vote for us, we will bring you water'"* (*Capetonian Tourist Guide 2*).

Water scarcity and Cape Town's water crisis is therefore problematized and framed as a political issue that is used by political parties to change people's political orientation: "*In the City of Cape Town there was the extra thing [...] province is run by the official opposition party whereas the country is run by the ANC, and it became [...] let's say a political construction. So, national government owns all the water and provincial, local government has to get that water to people. So, in the case of Cape Town [...] municipal government were saying 'well, national government needs to help us more'[...] you know, if one party fails it makes the other party look better or they can use it as an excuse"(Environmental Journalist).*

The perception of "Day Zero" as a vehicle to political propaganda and to shift political power in turn reflects the framing of "Day Zero" as a comic apocalypse in the news media, since it is perceived as being constructed by political parties and therefore resolvable.

The understanding of "Day Zero" as a comic apocalypse is also supported by the second meaning making process of "Day Zero," where it is used as an instrument to (2) change people's behavior. The use of the "Day Zero" scenario is therefore seen as a scaring instrument in order to change Capetonian's water wastage behavior, as mentioned by our interview partners:

"I agree with the'Day Zero Method', because it's an immovable, irrefutable position to say'we will run out of water, you have to cut back to 50 liters a day"' (Environmental activist 1). This, in turn, supports the view of "Day Zero" as being something avoidable through teamwork and commitment: *"I think they were just scaring people, so that they start save water. [...] There has never been a Day Zero" (Local resident 1);* "*They said [...] if we don't start using water sparingly, [...] they would switch your area off, and there would be designated water stations, where you will have to go and full up. This is quite scary, imagine went to line up for water" (Capetonian Tourist Guide 2)*.

In sum, related to *RQ1*, we can assert that the local community's meaning making processes of "Day Zero" is constituted by framing water as powerful and a vehicle to serve multiple purposes, especially political ones, revealing a strong politicization of the "Day Zero" frame. Our results furthermore support the results of *Study 1*, framing "Day Zero" as a comic apocalypse, i.e., constructed and therefore avoidable.

In a second step, we wanted to understand how the local community responds to the changing environmental scenarios (*RQ2*) caused by the water crisis. Our results (see **Table 3**) show that Capetonians' response consisted primarily in trying to find who's responsible for the situation. Furthermore, our analysis shows a split in the attribution of responsibility between less-educated and highly-educated people. The former, which are also the most affected by the water shortage, mostly blame policy: "*Who do you think is responsible for it? The government. No one else*" *(Local resident 2)*; *"So, they're not building new dams and not building storage capacity. So, you're creating a crisis, a water shortage crisis" (Capetonian Tourist Guide 1)*; *"There is no deny here—you know we are in the shit. But still nor, the politicians haven't embrace it" (Local resident 1)*. This responsibility attribution to the political system is consistent with the framing of the water crisis as a political issue. The latter recognize policy's role in the crisis, but see responsibility as a whole of society issue: *"It's political AND that's with the people as well. I feel that, in a way, South Africans we are wasteful as a culture. [. . .] we are wasteful people and also with education, I'm guessing, in school. We don't learn how to use things SPARINGLY. You know?" (Environmental scholar 1);*

"This perception that government [...] are responsible. I think that's wrong. I think it's time that we realize that we have highly complex social structures and cities and outland areas and we need business, and civil society and government, and equal parts to play roles on how we can modify and live our modern life" (Activist 1); "*There are water sources here. Maybe not enough for the kind of quantity that is needed but we have / If we were living more sustainably and more conscious of the fact that we have to [. . .] collect our rain water, recycle our water, not flush our toilets with pure sweet water, those kind of things. [. . .] It's about how do we influence society enough to remember how to live more sustainably, especially with water" (Activist 3)*.

TABLE 3 | Local response to changing environment.

RQ2–How does the local community respond to the changing environmental scenarios?	
Main categories	**Inductive categories**
Attribution of responsibility	Policy and politicians are responsible
	Whole society is responsible
Behavioral change	Awareness for need to change
	Change possible through education
	Change possible only if personal affected

TABLE 4 | Role of the media.

RQ3–What role do the media play?
Inductive categories
Media should educate
Media should create awareness
Media should serve as watchdog

This understanding of responsibility attribution additionally supports the framing of "Day Zero" as a comic apocalypse, which can be avoided through collective commitment. This perception is further confirmed by our analysis. Capetonians respond to the changing environmental scenarios not only by trying to identify who's responsible for the crisis, but also trying to change community behavior through (peer to peer) education: "*I have a lot of friend that came down and they were like: 'I will take like 5 minute shower' And I was like 'NO you can't, you CAN'T do that', so explain them where we are and how we managed with that" (Activist 2)*.

"You get to the school and you talk to the children [...] and say: [...] This is your future. [...] If you brush your teeth in a certain way, flush your loo in a certain way, shower in a certain way [...] If you just do that for yourselves and you monitor the people in your house, that would make a massive impact already. They go home into their community and they talk to their parents and their siblings [. . .] Your goal is community-based solutions" (Environmental scholar 2).

In this context we have to mention another important finding: our interviews have emphasized that behavioral change is only possible if people are directly affected in their everyday life by a situation: *"People don't act unless it actually affects their pocket" (Local resident 4); "But it's not personal if the water is drying and* *you're not feeling it" (Activist 3); "People wait until the taps run dry before they care about it" (Environmental Journalist 2).*

In the last part of our analysis, we wanted to refer again to *Study 1*, by investigating how Capetonians perceive the role of the media in the water crisis (*RQ3*). Results show how local communities perceive media's role as threefold (see **Table 4**): media should educate people to water saving behavior, create awareness related to water scarcity and other environmental issues, and serve as watchdog, especially when it comes to political misbehavior: "*There are so many roles, which can be played by media. They can criticize, they can build and destroy at the same time"(Local resident 3); "Look at Facebook! I mean we had an incredible spread of knowledge [. . .] for the most part it is an incredible tool to get messages out" (Activist 1); "I mean the question is: social media companies are so powerful [. . .]. So get a deeper level on, what's behind what is posted and get more, deeper explanations of what, what the dynamics of the situation are. I think social media is great. [. . .] I think it's an example of a healthy society, when your media can report deeply and truly on an ACTUAL state of affairs" (Environmental Journalist 1); "I think that they should take the gloves off and I think that they should name and shame" (Environmental Activist 2).*

DISCUSSION

The aim of this paper was to identify and analyze discourses about Cape Town's water crisis. For this purpose, we ran two case studies in order to focus on both public as well as local community discourses and framing. In *Part 1* of our study, we analyzed media discourses in local and international newspaper during three stages of the crisis (pre-, height of, and post-crisis). In *Part 2* of our study, we focused on the local community 's meaning making process of "Day Zero."

Our results show that local and international reporting of "Day Zero" relies on different rhetorical narratives. Especially in the height of crisis stage, news reporting produced both comic and tragic apocalyptic narratives. This clearly showcases the apocalyptic rhetorical power of the "Day Zero" term in alignment with previous research (Burke, 1984; O'Leary, 1993; Foust and Murphy, 2009). Unfortunately, the apocalyptic power encased in the term "Day Zero" was strongest during the transition from the height of crisis stage into the post-crisis stage at a local level, and in international discourse during the post-crisis stage itself. In particular, communicating "Day Zero" as a tragic apocalypse in the post-crisis stage led to different interpretive processes of the water crisis that often linked to conspiracy theories. This created confusion for the local community and caused two different meaning making processes. On one side, there were the "aware Capetonians" who perceived "Day Zero" as real and were aware of and scared by its effects; on the other side, there were the "skeptic Capetonians" who perceived "Day Zero" to be a hoax (these two sides can also be seen in the results of *Study Part 2*). In particular, the "skeptic Capetonians" framed "Day Zero" as a hoax and as a crisis constructed by policy in order to serve their own purposes, thus positioning it as a resolvable problem. This shows how environmental issues are used as a vehicle for political communication, or in other words, how environmental discourses are drawn to the political field and abused, i.e. how politicization (Roper et al., 2016) of environmental issues happens.

The communication around the (twice-postponed) "Day Zero" in Cape Town is also a very fruitful example of the digital disrupted, post-truth communication that happens with environmental issues today. The metaphor "Day Zero" as well as the degree of water scarcity behind the concept, is calculated by the amount of water stored in dams and by the daily rate of usage: in other words, the problem of "Day Zero" necessitates public acceptance of variability based on changing environmental facts. Our study shows that even though environmental variance should be expected on a factual level, the use of a term or metaphor of "Day Zero" is operationalized in too many different ways, not all of which are related to the factual situation.

However, it has to be acknowledged that remedial actions taken by the national government, City Council, and citizens to curb water usage ultimately led to the postponement of "Day Zero." Examples of these actions include the limiting of consumption by the agricultural sector by the national government, the reduction in main pressure by the Council, and citizen water saving efforts via a series of well-communicated stages, leading up to Level 6 water restrictions. Since the interviews were conducted after "Day Zero" was postponed for the second time, it is conceivable to assume that these (governmental) measures have influenced the perception of the water crisis as a comic—i.e. resolvable—apocalypse. In fact, the "aware Capetonians" did frame "Day Zero" as a comic apocalypse that could be avoided through community engagement, which can be supported by education mostly spread by the media. Here, however, the use of "Day Zero" as a comic apocalypse, or as an avoidable situation, should be emphasized. The results of *Study Part 2* show that people are willing to change their (water related) behavior only if a certain situation directly affects their everyday life, i.e. in this case, only if they really run out of water. This is particularly true for "skeptic Capetonians" who already doubt the reality of "Day Zero."

Communicating "Day Zero" as a comic apocalypse thus creates a dilemma. On the one hand, this framing can enable the media to do what it does best: act as a warning, create more awareness, and show misconduct so that catastrophe can be avoided. On the other hand, if the catastrophe is avoidable, it means it is not (yet) real. Using this kind of narrative makes early intervention on non-aware people difficult and behavioral effects will probably not be achievable. This problem can also be recognized in the tragic framing of "Day Zero," as communicating an event or a catastrophe as unavoidable may also cause resignation in aware people.

Limitations

The presented analysis does incur some limitations, mostly due to the nature of our two studies as case studies. Related to *Part 1* of the study, we want to address the sample especially related to the data collection. The three analyzed stages —pre-, height of, and post-crisis— were self-defined by the authors and determined independently to the crisis' development. Self-defining these time lapses of course affects the way discourses are viewed and interpreted, and it is possible that differently defined turning points and time periods would lead to slightly different findings. This is particularly true for the pre-crisis stage, where no comparison between international and local news was possible. A different definition of time periods may also lead to a different sample size. Further researchers are therefore encouraged to amplify time periods and sample size.

The same limitation is also present in *Part 2*. As a case study, the sample size is rather limited. Therefore, further research should address a larger group of interviewees. As for this second part of the research project, conducting the interviews at a different time could lead to different results. Running additional qualitative studies could provide interesting comparable data to identify changes and/or similarities in the water crisis' framing.

Nonetheless, our analysis of communication, narratives, and framing of "Day Zero" can be seen as a useful example to point out challenges, dilemmas and difficulties of environmental communication that undoubtedly require further and deeper analysis.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethic committee at the Department of Media and Communications, University of Klagenfurt. Contact: DV. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CB coordinated part 1 of the study. DV coordinated part 2 of the study and wrote the first draft of the paper. All authors have contributed to the conception of the paper, its underlying theories, the methodological approach as well as the discussion and implications of results.

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A 7-Year Lag Precipitation Teleconnection in South Australia and Its Possible Mechanism

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Precipitation teleconnections with large-scale ocean–atmosphere oscillation systems provide useful information for water management. Here, we present a 7-year lag response in South Australia (SA) precipitation to the Southern Annular Mode (SAM) in a positive Interdecadal Pacific Oscillation (IPO) phase. This teleconnection between a positive SAM phase and increased SA precipitation, and vice versa, statistically consists of three sequential steps: a 27-season lag positive correlation between sea subsurface potential temperature (SSPT) to the south of SA and SAM, a zero-season lag positive correlation between sea surface temperature (SST) and SSPT, and a 2-season positive lag correlation between SA precipitation and sea surface temperature. Physically, this teleconnection seems to be associated with a supergyre circulation of the southern hemisphere oceans, which transfers SAM signal via subsurface potential sea temperature in the central south Pacific to the south of SA in 27 seasons during the positive IPO phase. Practically, this teleconnection provides a 7-year-lead drought precursor for rain-fed agriculture planning in SA. However, the teleconnection disappears in negative IPO phases. The oceanic pathway via the supergyre suggested in this study provides a basis to predict when this 7-year teleconnection may resume in the future based on observation and/or modeling.

Keywords: precipitation prediction, southern annular mode, sea temperature, supergyre, drought, Goyder's line

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INTRODUCTION

Precipitation provides water on land to support ecosystem functions and societal development. Drought events, largely associated with precipitation interannual variability, can lead to ecosystem and societal disasters (McDowell et al., 2008; van DijK et al., 2013). Drought impacts on society primarily lie in the water supply and agriculture sectors (Stahl et al., 2016). A reliable prediction of regional rainfall beyond monthly time scale is thus beneficial for water resource management and agricultural planning. In some areas, such as Australia (www.forecasts4profit.com.au), seasonal rainfall prediction has been routinely communicated to farmers and agricultural business operators. Statistical relationships between precipitation of a region and large-scale climate oscillation systems, in addition to atmospheric modeling, provide useful information for drought and its impact predictions, particularly in agriculture (Bonner et al., 2014; Lu et al., 2017).

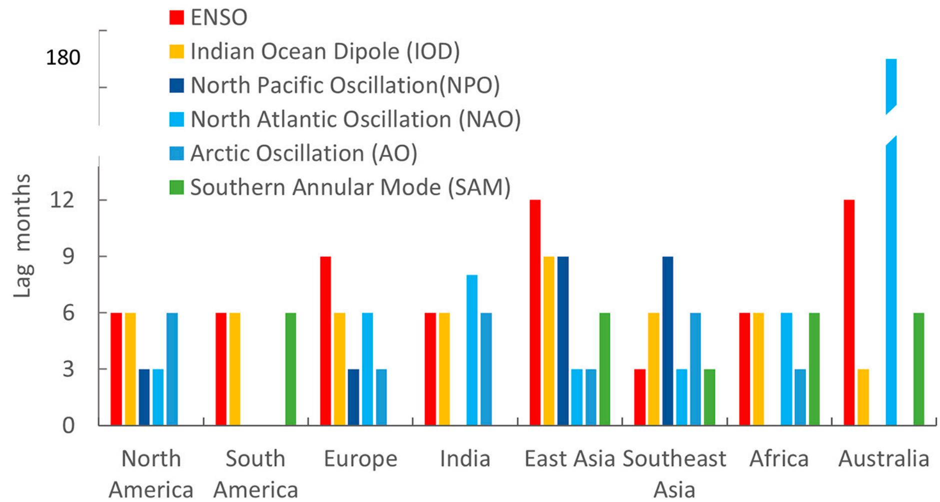

FIGURE 1 | Reported maximum lag (months) response of precipitation to large-scale climate oscillation systems for selected regions based on published studies referenced in the text.

The relationships between large-scale climate drivers and precipitation in different parts of the world have been investigated in numerous studies. While coupled ocean–atmosphere oscillation systems have been shown useful for precipitation prediction, the reported lag structure varies for different climate indices and between regions (**Figure 1**). Most of the reported lags are within a couple of months (Thompson and Wallace, 2000; Saji and Yamagata, 2003; Polonsky et al., 2004; Trigo et al., 2004; Li and Wang, 2005; Hu and Feng, 2010; Kenyon and Hegerl, 2010; Chen and Chung, 2015; He et al., 2017; Tabari and Willems, 2018). Some teleconnections have a lag extending to over 6 months (Kakade and Dugam, 2000; Mistry and Conway, 2003; Saji and Yamagata, 2003; Li and Wang, 2005; Fang et al., 2014; Chen and Chung, 2015; He et al., 2017). In one case, precipitation response lags a climate oscillation system by about 15 years (Sun et al., 2015).

As the driest inhabited continent, Australia has a high hydroclimatic variability (Peel et al., 2001). Rainfall variability poses a big challenge to water resource management and agricultural production (van DijK et al., 2013; Jarvis et al., 2018; Parton et al., 2019), and flood risk management (Liu et al., 2018). Many studies have been carried out to understand rainfall variability in Australia (Nicholls, 1989; Chiew et al., 1998; Saji and Yamagata, 2003; Meehl et al., 2010). El Niño–Southern Oscillation (ENSO) (McBride and Nicholls, 1983; Power et al., 1999; Wang and Hendon, 2007), Indian Ocean Dipole (IOD) (Ashok et al., 2003; Acworth et al., 2016), Interdecadal Pacific Oscillation (IPO) (Verdon and Franks, 2006), Southern Annular Mode (SAM) (Thompson et al., 2000; Hendon et al., 2007; Meneghini et al., 2007; Lim et al., 2016), subtropical ridge (STR) (Drosdowsky, 2005; Timbal and Drosdowsky, 2012), and a combination of them (Ihara et al., 2007; Meyers et al., 2007; Murphy and Timbal, 2008; Pezza et al., 2008; Kirono et al., 2010; Pohl et al., 2010; Cai et al., 2012; Schepen et al., 2012) are documented as having an influence on precipitation in Australia. Generally speaking, ENSO influences precipitation with La Niña (El Niño) associated with a wetter (drier) than normal condition in eastern and northeast Australia (Dey et al., 2019). IOD influences western and southern Australia with negative IOD connected to a wetter than normal condition (Risbey et al., 2009). The influence of SAM varies among season, with positive SAM connected to wetter spring and autumn in Australia, but dryer winter in the western and southeastern coasts (Ho et al., 2012). On interdecadal scales, positive (negative) IPO leads to dryer (wetter) monsoon in northern Australia (Dey et al., 2019).

In South Australia (SA), current skill to predict seasonal and longer time interval rainfall is low, which, however, are critical for the agriculture and water resources management (Drosdowsky, 1993; Risbey et al., 2009; Tozer et al., 2017). Part of this low prediction skill is likely associated with the fact that not all relevant climate indices are considered with an appropriate lag structure (He and Guan, 2013). Most of the teleconnection studies only consider SA rainfall lag responses over a few months—SAM (2–6 months), IOD (3–6 months), and ENSO (3–12 months) (Simmonds and Hope, 1997; Kiem and Franks, 2004; Pezza et al., 2008; Evans et al., 2009; Ummenhofer et al., 2009; Williams and Stone, 2009; He and Guan, 2013; Montazerolghaem et al., 2016; Tozer et al., 2017). These short-lag teleconnections are associated with dynamic ocean–atmosphere interactions and thus more variable and less predictable.

Thus, it is useful to explore teleconnections with lags beyond a year, which can be connected to the so-called "ocean tunnel" (Liu and Alexander, 2007). Should such a teleconnection path exist, it can be less dynamic and more reliable for prediction. Indeed, a recent study reports that subtropical eastern Australian rainfall is likely connected to the North Atlantic Oscillation, with a lag of 15 years (Sun et al., 2015). In the southern hemisphere oceans exists a supergyre that connects subsurface southern Pacific

Ocean and southern Indian Ocean (Ridgway and Dunn, 2007). South Australia sits to the north along the path of this supergyre. If the thermal dynamic conditions carried by this supergyre become explicit on sea surface, they may influence precipitation in South Australia. Thus, there is a possibility to find a long-lag teleconnection for precipitation in South Australia.

In South Australia, rain-fed agriculture is confined to a narrow band in the coast bounded on the north by the so-called Goyder's line (Nidumolu et al., 2012). Goyder's line is a historic rainfall marker in South Australia indicating the margin between reliable cropping environments and those only suited to grazing. It was first drawn by the then Surveyor-General of the colony in 1865, linked with a major drought that occurred in this region during 1864–1865. This line is drawn from Ceduna in the west, across to Spencer Gulf, north to Orroroo, then south and east across the Victorian border at Pinnaroo. It was recently suggested that this line would be better drawn along the growing-season rainfall-to-potential evaporation ratio of 0.26. With projected climate change, this line will very likely move southward, reducing the rain-fed cropping area in South Australia (Nidumolu et al., 2012).

The SAM, a leading mode of variability in the southern hemisphere extratropical circulation, has not been reported with a short-lead predicting skill for precipitation in this region (Risbey et al., 2009; He et al., 2014). Given that the SAM reflects oscillation of a coupled ocean–atmosphere system to the south of 20°S, it is possible to be associated with the above-mentioned supergyre and thus has potential to be a long-lead predictor for precipitation in South Australia, particularly for the agriculture area to the south of Goyder's line. In this study, we examine the possibility of a long-lag SA precipitation teleconnection with SAM. The objectives are to answer the following questions: 1) Does SA precipitation teleconnect with SAM with a long lag? 2) If so, what is the possible underlying mechanism? 3) Is this long-lag teleconnection useful in precipitation and drought prediction for agricultural planning?

METHODOLOGY

Data

The datasets employed in this study include climate indices [SAM, ENSO, IPO, and related Pacific Decadal Oscillation (PDO)], sea surface temperature (SST), subsurface sea potential temperature (SSPT), atmospheric variables, and station-based precipitation data in Australia. The details are given in the following.

Three SAM indices were selected for this present study. They are reanalysis data–based NOAA monthly AAO index (1979–2017) and monthly SAM index (1851–2011), and station data–based Marshall index (1957–2017). The NOAA AAO index, calculated based on 700 hPa geopotential height anomaly poleward of 20°S (Ho et al., 2012), is available at https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/monthly.aao.index.b79.current.ascii.table. The NOAA SAM index, calculated based on the difference of normalized zonal mean sea level pressure at 40°S and 65°S (Gong and Wang, 1999), was obtained from https://www.esrl.noaa.gov/psd/data/correlation/sam.20crv2c.short.data. The Marshall SAM index, also constructed based on the definition in Gong and Wang (1999) but using station data, is available at https://legacy.bas.ac.uk/met/gjma/sam.html. A minor positive trend observed in the Marshall SAM index has been removed for this study. The NOAA AAO index was applied for analyses on data after 1979, and the two SAM indices were adopted for those with data prior to 1979. The monthly Interdecadal Pacific Oscillation (IPO) tripole index from 1854 to present was obtained from NOAA (https://www.esrl.noaa.gov/psd/) (Henley et al., 2015). The monthly Pacific Decadal Oscillation (PDO) index from 1900 to present was obtained from NOAA (https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/pdo.long.data) (Henley et al., 2015). The monthly Niño-3.4 index from 1950 to present was obtained from NOAA (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php) (Trenberth, 1997). Monthly precipitation records of 325 meteorological stations were obtained from Australian Bureau of Meteorology, http://www.bom.gov.au/climate/data/), including 33 sites in SA.

The monthly COBE SST (Centennial *in situ* Observation–Based Estimates of the variability of SST) data were obtained from NOAA (https://www.esrl.noaa.gov/psd/). The COBE data are available from 1891 to present, gridded on a 1.0 × 1.0 mesh (Ishii et al., 2005). Monthly data of reanalysis potential temperature in subsurface were obtained from the ECMWF (European Centre for Medium-Range Weather Forecasts, http://www.ecmwf.int/products/) Ocean Reanalysis System 4 (ORAS4), from January 1959 to present. The data are gridded on a 1.0 × 1.0 mesh (Balmaseda et al., 2013).

Data Analyses

The relationships between pairs of variables are examined by correlation analysis. The statistical significance of these analyses is assessed using the two-tailed Student's t test. For relationships critical to this study, that is, the one between South Australia precipitation and SAM, the statistical significance is evaluated with the t test statistic considering the effect of autocorrelation in time series (Hamed and Rao, 1998; He and Guan, 2013). It is determined by

$$t = \frac{r}{\sqrt{(1-r^2)/(N_{eff}-2)}}, \tag{1}$$

where N_{eff} is the effective sample size taking into account the effect of autocorrelation in the time series. The effective sample size N_{eff} is estimated by

$$N_{eff} = N\frac{1-r_1 r_2}{1+r_1 r_2}, \tag{2}$$

where N is the sample size and r_1 and r_2 are the lag-one autocorrelations of the two time series.

Correlation analysis of anomaly time series is performed between precipitation and SAM indices, between SSPT and AAO index, between SST and SSPT, and between precipitation and SST, with various time lags. These analyses are based on

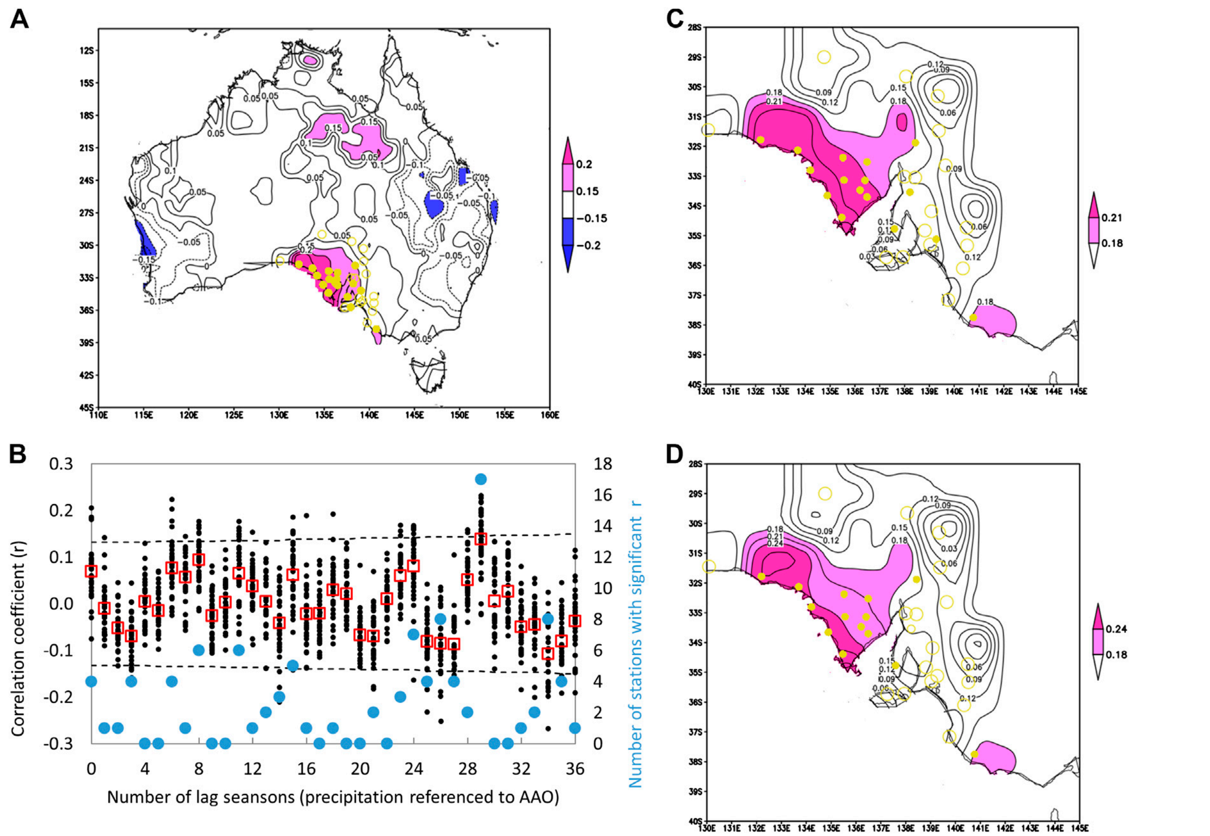

FIGURE 2 | Lag correlation coefficients between seasonal (MAM, JJA, SON, and DJF) precipitation anomalies and the AAO index over the period of 12/1978–11/2017: **(A)** for 325 stations in Australia at a 29-season lag and **(B)** for 33 SA stations with various lags. And partial correlation coefficients between seasonal precipitation at a 29-season lag with the AAO index: **(C)** independent of Niño-3.4 in pace with AAO and **(D)** independent of Nino 3.4 in pace with precipitation. The shaded areas in **(A)**, **(C)**, and **(D)** and dash lines in **(B)** indicate statistically significance exceeding the 95% level. Yellow dots in **(A)**, **(C)**, and **(D)** represent the sites for which correlation coefficients are statistically significant above the 95% confidence level. The red squares in **(B)** are the 33-site average correlation coefficients at various lags, and blue solid symbols show the number of stations with significant lag correlations.

monthly and seasonal anomaly time series. Monthly data obtained from different sources are summed (for precipitation) or averaged (for SST, SSPT, SAM, and AAO) into seasonal time series. The seasons in the study area are defined as spring (September–November), summer (December–February), autumn (March–May), and winter (June–August). Moving average is applied to investigate patterns in variables and relationships between variables at longer time intervals.

It is reported that SAM and ENSO are strongly correlated (Fogt and Bromwich, 2006; Pohl et al., 2010; Lim et al., 2013; Datwyler et al., 2020). Thus, possible ENSO effects on precipitation should be removed when the association between SAM and precipitation is examined. Partial correlation between precipitation and SAM against ENSO is applied to address this issue (Guan et al., 2010). Precipitation teleconnection with a climatic index is often nonsymmetric between the two extreme phases (Power et al., 2006; Ummenhofer et al., 2009; Cai et al., 2011; King et al., 2013). In this study, composite analysis is applied to detect the difference in atmospheric conditions (i.e., water vapor flux and divergence, and atmospheric convective instability) at a certain lag corresponding to positive and negative SAM phases.

RESULTS AND DISCUSSION

Correlation Analysis of South Australia Precipitation Anomaly and Southern Annular Mode

A statistically significant 29-season lag correlation between SA precipitation and AAO is found. **Figure 2A** shows the 29-season lag correlation coefficients of seasonal precipitation anomalies with the AAO index, for 325 Australia sites, including 33 SA sites (**Supplementary Table S1**). For SA sites, common maximum correlations occur at a lag of 29 seasons. The correlation coefficients are statistically significant at a confidence level of 95% or above for 17 sites (solid dots in **Figure 2A**, listed in **Supplementary Table S1**). Distribution of these 17 sites is spatially coherent. They are mostly located in the south close to the coast of South Australia. The other 16 sites, without such a

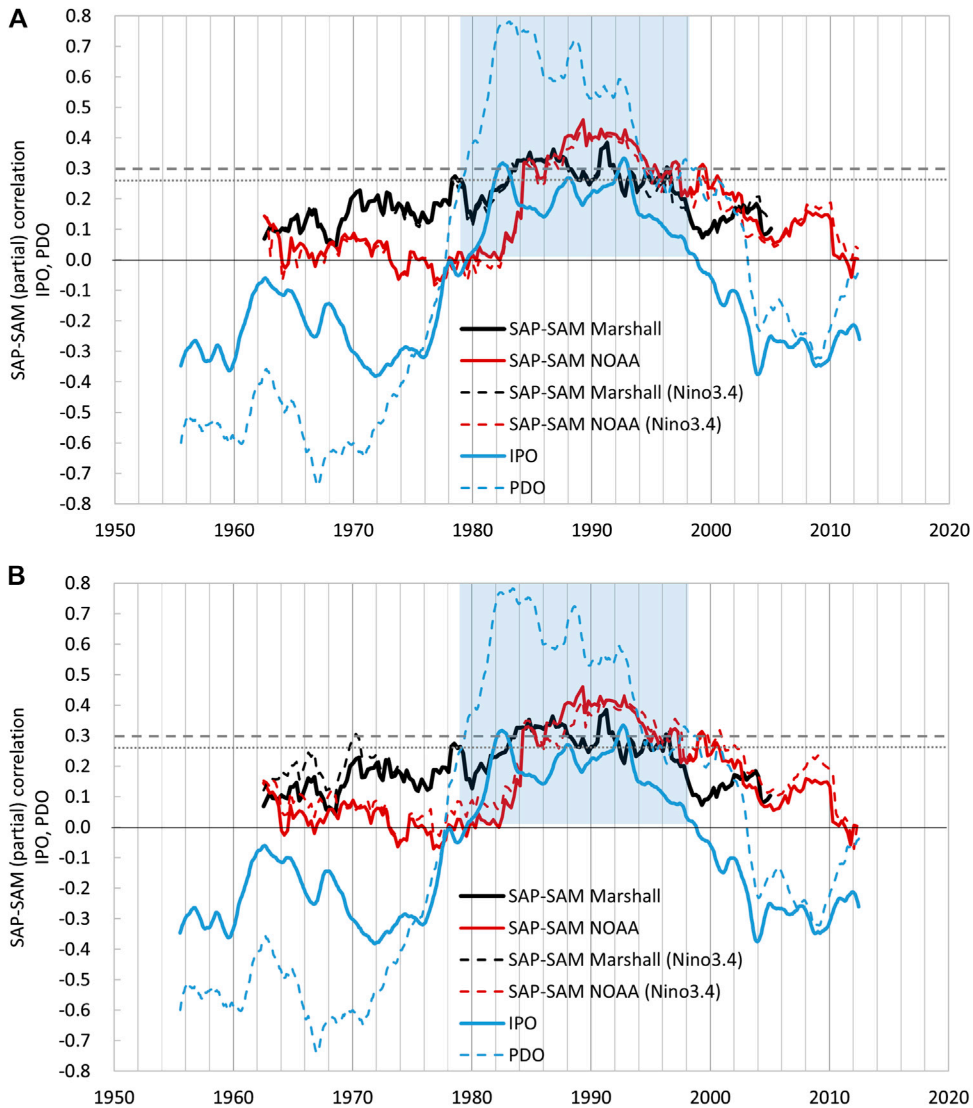

FIGURE 3 | Moving 45-season window 29-season lag correlation between SAP and SAM, and lag partial correlation between them in dependent of Niño-3.4 in pace with SAM **(A)** and in pace with SAP **(B)** (black and red lines, the correlation is shown at the centered season of the 45-season window, referenced to SAM time), compared with the 11-year moving average of IPO and PDO index (blue lines). The dash lines mark the threshold of significant SAP and SAM lag partial correlation at 95% and 90% confidence levels. The light blue–shaded area marks the duration of the positive IPO (PDO) phase.

lag correlation, distribute inland in the north. Such a spatial coherence pattern is common in correlation between spatial distributed precipitation and a large-scale climate driver.

The lag correlation between seasonal precipitation and seasonal AAO index is examined over a wide range of time lags, varying from zero season to 36 seasons (**Figure 2B**). The 29-season lag correlation clearly stands out, with 17 stations with significant lag correlation. At some other time lags (e.g., 8, 11, 24, 26, and 34 seasons), significant correlation exists for six to eight stations. It can be explained by internal cycles in the AAO index (**Supplementary Figure S1**). The result that a much smaller number of stations with significant correlation with the AAO index at these lags than the 29-season lag suggests that the 29-season lag correlation is the primary one and more likely to have a physical basis.

To make sure that this apparent lag correlation between precipitation and SAM is not an artifact from a possible correlation of precipitation and ENSO, partial correlation has been done for precipitation and SAM at a 29-season lag independent of ENSO (represented by Nino-3.4), for two time offsets for ENSO, 0 season with SAM (**Figure 2C**), and 0 season with precipitation (**Figure 2D**). Similar spatial patterns of 29-season lag correlation with SAM, to the original analysis shown in **Figure 2A**, are revealed.

Most of the 17 sites with significant 29-season lag correlation with AAO index are located to the south of Goyder's line, making them an important precipitation prediction target for agriculture planning. The average rainfall anomaly of these 17 sites is thus used as the South Australia SAM sensitive seasonal precipitation

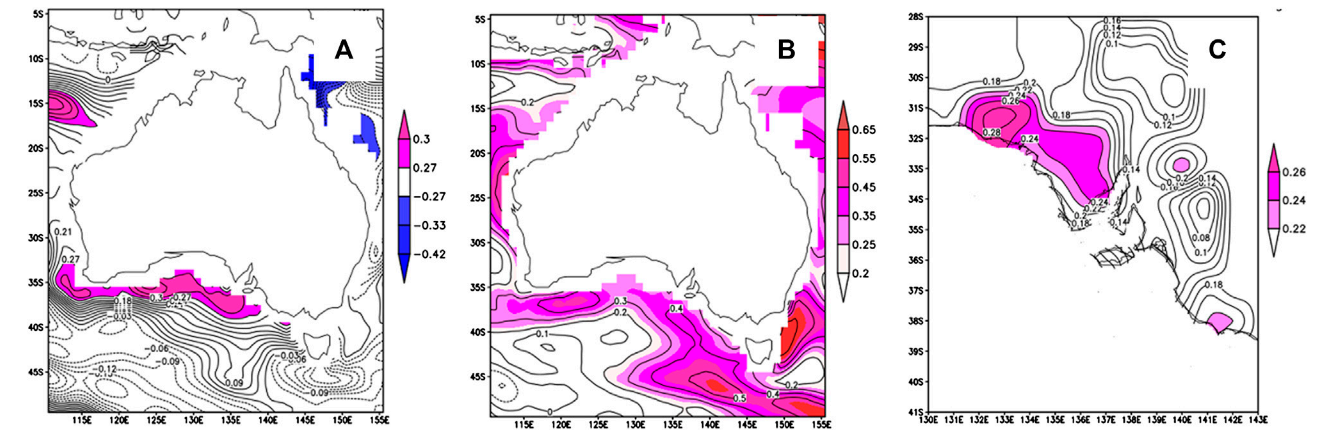

FIGURE 4 | Correlation coefficients during a positive IPO phase (1979–1998) of **(A)** seasonal SSPT anomalies with AAO index at a 27-season lag, **(B)** same-grid seasonal SST with SSPT anomalies at a zero-season lag, **(C)** season precipitation anomaly with SST anomaly index in the Southern Ocean offshore South Australia (120–140°E, 40–35°S) at a 2-season lag. The shaded areas indicate statistically significance exceeding the 95% confidence level.

anomaly (hereafter referred to as SAP) for further analysis. The correlation coefficient of the concurrent NOAA SAM index with the SAP time series during 1957–2017 is insignificant, which is consistent with previous studies (Risbey et al., 2009; Ho et al., 2012). However, at a 29-season lag, the two time-series are correlated with a correlation coefficient of 0.147, which is significant above the 98% confidence level.

To examine how robust this lag correlation varies over time, the 29-season lag SAP-SAM correlation is calculated with a 45-season moving window, based on two selected SAM indices. The size of the moving window is chosen to see if this lag correlation persists across decades. The result indicates that the significant lag correlation started around 1984, lasting for about 15 years (**Figure 3**, referenced to the SAM time). This time window is coincident with a positive IPO (or PDO) (1979–1998) (Salinger et al., 2001; Dong and Dai, 2015; Henley et al., 2015), offset by a half-length of the moving window (~5 years) (**Figure 3**). Beyond this time period, no significant 29-season lag correlation exists between SAP and SAM. Within the positive IPO phase, the lag correlation coefficients fluctuate below the significant threshold in some occasions, which is likely associated with the small moving window size and disturbance from other factors (e.g., ENSO and IOD). This result suggests that the 29-season lag SAP–SAM relationship has a decadal variability, in rhythm with IPO, with the significant correlation occurring only in positive IPO.

Correlation Analyses between Southern Annular Mode, Sea Temperatures, and South Australia Precipitation

If the 29-season lag correlation between SAP and AAO indices has a physical basis, it must be related to ocean processes. Analysis of the relationship between Southern Ocean temperature variations and the AAO index may provide evidence. Given that the lag correlation occurs roughly coincident with a positive IPO phase, this analysis is confined to 1979–1998. A 27-season lag correlation between subsurface sea potential temperature (averaged over the top 1,000 m) near South Australia and the AAO index is found (**Figure 4A**).

In addition, there is an outstanding zero-season lag correlation between SST and SSPT anomalies over the same area where the 27-season SSPT lag correlation with the AAO index appears (**Figure 4B**). The SST anomaly of this area (120–140°E, 40–35°S) is found to have a two-season lead correlation with precipitation in the coastal area of South Australia (**Figure 4C**). The spatial pattern of this lag correlation is in general consistent with that for the 29-season lag correlation between precipitation and the AAO index (**Figure 2A**).

It seems that the 29-season lag SAP correlation with the NOAA AAO index is associated with 1) a 27-season lag correlation of SSPT off coast of South Australia and AAO, 2) a zero-season lag correlation of SST and SSPT, and 3) a two-season lag correlation between SAP and SST to the south of South Australia. These coherent statistical correlations support a physical causal relationship between SAM and SAP. In other words, a 29-season lag SAP teleconnection with SAM very likely occurred during the positive IPO phase (1979–1998).

It would be ideal to test this possible teleconnection using coupled climate models. However, it is difficult to do so because current coupled climate models often do not reproduce observed teleconnection patterns, even for a short time range teleconnection with ENSO (Dieppois et al., 2015). Here, we choose to investigate a possible oceanic pathway via sea water temperature propagation using a statistical analysis, detailed in the next section.

Possible Oceanic Pathway for the 7-Year Lag Teleconnection

If what we deduced from **Figure 4** in the previous section is correct, it suggests that SAM takes 27 seasons to influence SST to the south of South Australia. How does the SAM signal propagate in 27 seasons to arrive offshore South Australia? To answer this

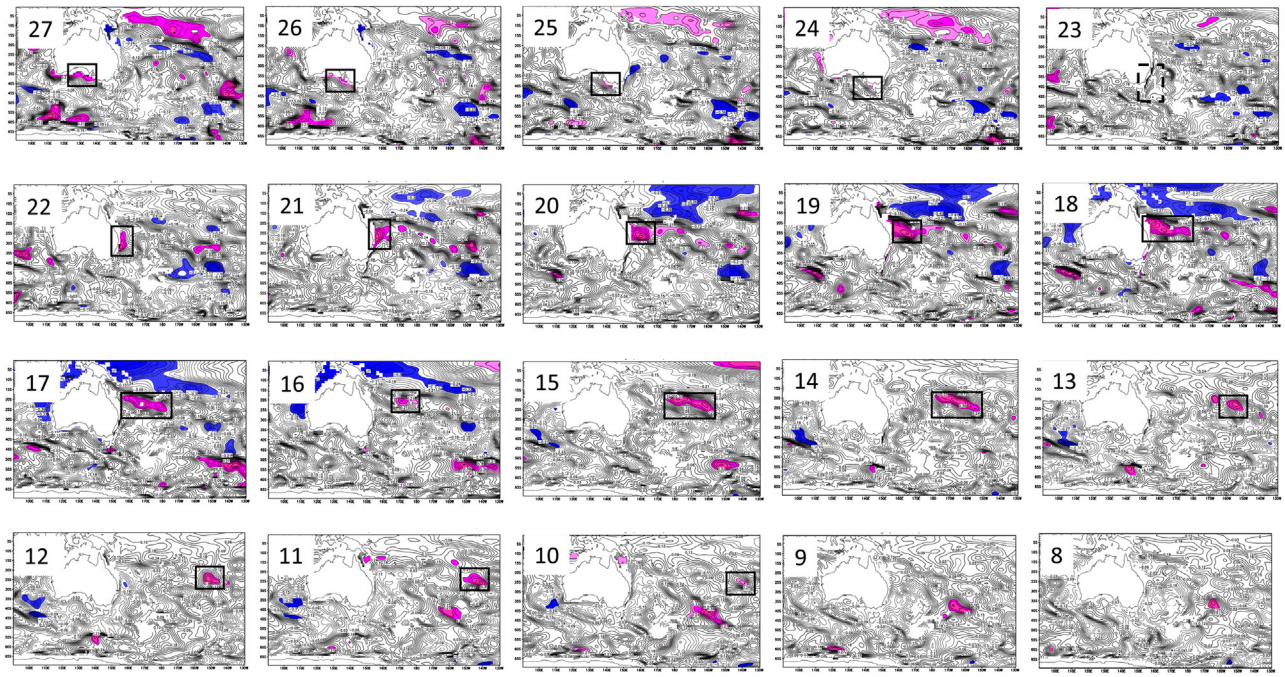

FIGURE 5 | Spatially coherent locations (marked by black rectangles) of significant correlation between subsurface sea potential temperature (SSPT, average of 0–1,000 m depths) with SAM at different lag seasons (numbers in the figure) in a positive IPO phase (1979–1998), showing the track of SAM signal propagation through SSPT starting at 25°S 140°W with a 10-season lag referenced to SAM, arriving at the eastern coast of Australia at a 18-season lag, moving southerly along the coast, emerging in coastal waters to the south of Australia at a 24-season lag, and reaching offshore South Australia at a 27-season lag (**Figure 4A**). The colors indicate statistically significant correlation (red for positive and blue for negative) at the 95% confidence level.

question, we calculate correlation coefficients between the SSPT (averaged over top 1,000 m) anomaly and the AAO index for the Southern Hemisphere Oceans for the period 1978–1998, with lags ranging from zero season to 29 seasons (**Figure 5**). At a 10-season (or 2.5 years) lag, significant SSPT correlation with the AAO index emerges around 25°S and 140°W. The significant correlation area propagates westward, with the front arriving at the northeastern coast of Australia (at 20-season lag) in about 2.5 years. After that, the signal turns southward along the eastern coast. In about one year, the signal passes south of Tasmania (at 24-season lag) and turns west toward the South Australian coast. It finally arrives at the sea to the south of South Australia (at 27-season lag) in about three seasons. The whole path takes about 27 seasons since an SAM episode.

This AAO signal propagation trajectory via SSPT is in a good match with a strong southern hemisphere oceanic supergyre that links the subtropical gyres of the Pacific and Indian oceans (Wang et al., 2014)—a strong East Australia Current passing through the Tasman Sea with a Tasman leakage from the southern Pacific Ocean to the southern Indian Ocean (Ridgway and Dunn, 2007). At the surface level, the Pacific and Indian oceans are connected via the Indonesian Throughflow. In subsurface, the two oceans are connected via the supergyre (Ridgway and Dunn, 2007). Previous studies have shown that AAO is connected to the supergyre. In positive AAO episodes, a poleward intensification of the supergyre occurs as a result of the poleward shift of the westerlies (Wang and Cai, 2013). Thus, it is very likely that the AAO-associated southern hemisphere oceanic supergyre provides an "ocean tunnel," substantiating the 7-year (approximation of 29 seasons) lag teleconnection for precipitation in South Australia.

However, in a negative IPO phase, such an AAO signal propagation via SSPT from the southern Pacific Ocean to Indian Ocean is not found (**Supplementary Figure S2**). It is likely that under negative IPO condition, AAO and the Southern Ocean's supergyre becomes decoupled, or that the depth-varying pattern of the supergyre differs from that in a positive IPO phase. As a result, the 7-year lag correlation between SAP and SAM disappears (**Figure 3**). In other words, the 7-year lag teleconnection holds for a positive IPO phase but breaks down for a negative IOP. Periodic breakdown or weakening of teleconnections is common for other oscillations (e.g., Ashcroft et al., 2016; Zhu, 2018).

Wet-Season Rendering of the Teleconnection

Given the importance of wet season precipitation to natural ecosystems (Xu et al., 2019) and agriculture in South Australia, it is crucial to know how this teleconnection may impact wet season (winter in South Australia) precipitation processes. Composite analysis is conducted to examine the anomaly of atmospheric circulation over SA winters. First, four positive and five negative AAO autumns are identified

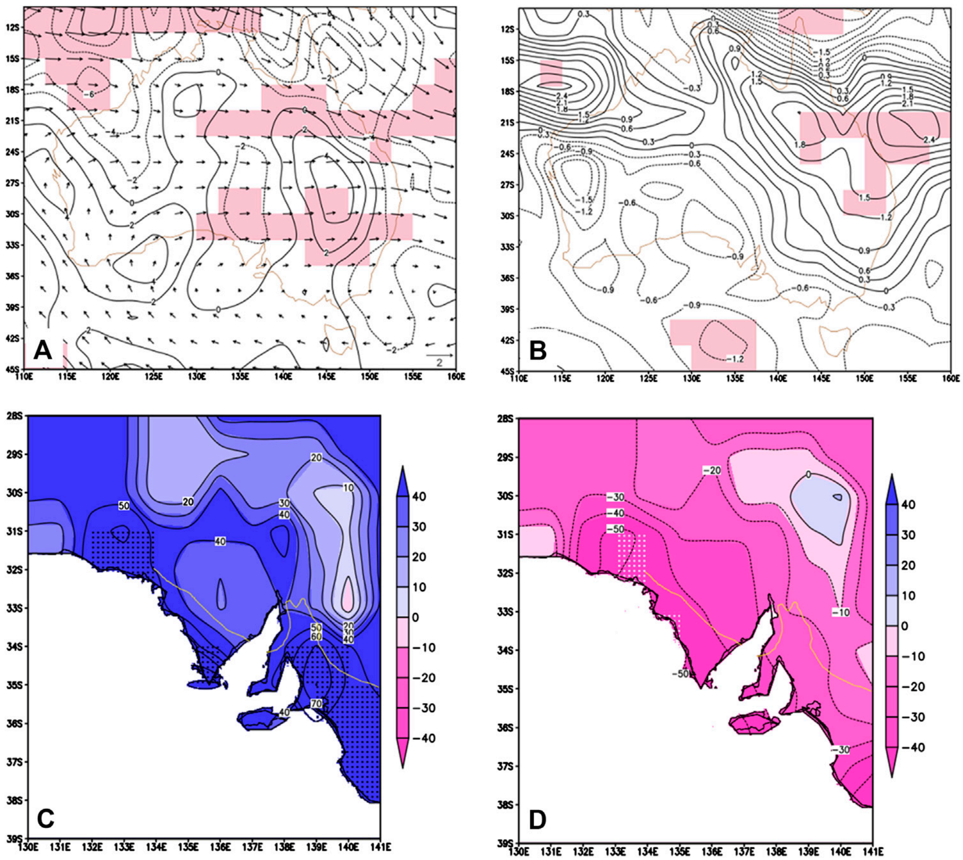

FIGURE 6 | Composite differences of average austral winter (JJA) at a 29-season lag from positive and negative SAM autumns during a positive IPO phase: **(A)** 850 hPa atmospheric water vapor flux (vectors, in g cm^{-1} hPa^{-1} s^{-1}) and its divergence (contours in 10^{-7} g cm^{-2} hPa^{-1} s^{-1}), and **(B)** 700-hPa convective instability (−∂θe/∂p) (contours in 0.3 × 10^{-3} K hPa^{-1}). The shaded areas represent statistically significant above the 95% confidence level. And average winter precipitation anomaly (mm, referenced to the period of 1979–2017) at a 29-season lag from four positive SAM autumns **(C)**, and five negative SAM autumns **(D)**. The abnormal positive AAO autumns occurred in 1979, 1982, 1989, and 1998, and negative AAO autumns in 1980, 1981, 1986, 1990, and 1992 (**Figure 3**A). The anomaly is statistically significant above the 95% confidence level for the dotted areas. The yellow line in **(C)** and **(D)** is Goyder's line, approximating the northern boundary of rain-fed agriculture in South Australia.

during the positive IOP phase (1979–1998), based on 3-month moving average AAO time series (**Supplementary Figure S3**). At a 29-season lag referenced to these AAO autumns, the corresponding winters in South Australia are identified. They are 1986, 1989, 1996, and 2005 and 1987, 1988, 1993, 1997, and 1999, respectively.

Composite differences of winter circulation and water vapor over Australia are shown in **Figure 6A**. At 850 hPa, there is a cyclonic anomaly over SA, combined with a water vapor sink anomaly. The difference of water vapor flux divergence is -2 · 10^{-7} g cm^{-2} hPa^{-1} s^{-1}, statistically significant above the 95% confidence level (**Figure 6A**). Similar composite analysis is conducted for convective instability (**Figure 6B**). It is shown that, although not statistically significant, the convective instability in the coastal SA increases (by 0.6 · 10^{-3} K hPa^{-1}) in winters with a 29-season lag from negative SAM to those corresponding to positive SAM.

These composite analysis results support that the 7-year teleconnection causes an observable difference in mean winter atmospheric conditions in the coastal area of South Australia. And this difference does translate to winter precipitation (**Figures 6C,D**). For SAM-teleconnected wet winters, the seasonal precipitation south of Goyder's line has a positive anomaly ranging from 50 to 90 mm (about 30% of winter precipitation) and is mostly statistically significant. For SAM-teleconnected dry winters, the seasonal precipitation south of Goyder's line has a negative anomaly ranging from 20 to 50 mm (about 15% of winter precipitation). Such a 7-year lead prediction would provide useful information for farmers and other agricultural operators. This is particularly important for low-rainfall farming communities on the edge of Goyder's line which will very likely move southward in the near future.

A 7-Year-Lead Drought Precursor for South Australia

The oceanic pathway (*Possible Oceanic Pathway for the 7-Year Lag Teleconnection*) very likely smooths the SAM signal beyond the seasonal time interval. Additional analysis has been done to

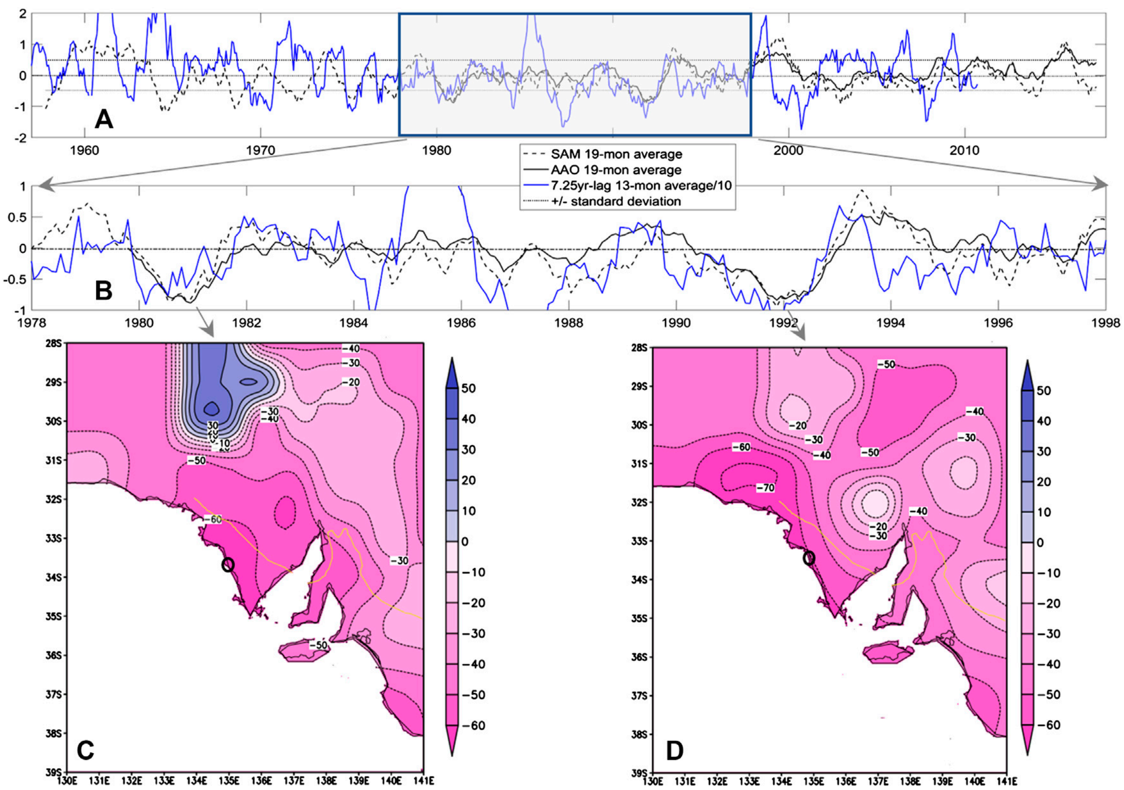

FIGURE 7 | Nineteen-month moving average of SAM (detrended) and AAO monthly indexes and 7.25-year lag 13-month moving average precipitation (unit: 10 mm) at Coulta, South Australia (black circle on the maps) for **(A)** 1957–2018 and **(B)** 1978–1998 (positive IPO). And the distribution of precipitation anomaly (unit: percentage of the mean of 1948–2017) for two selected drought years in the coastal area of South Australia **(C)** June 1987–May 1988 and **(D)** June 1998–May 1999, preceded around 7 years by SAM and AAO low 19-month moving averages. The year numbers in (a) and (b) mark the start of the years for SAM and AAO, with precipitation time shifted by 7.25 years. The yellow line in **(C)** and **(D)** is Goyder's line, approximating the northern boundary of rain-fed agriculture in South Australia.

examine the connection between SAM and annual precipitation at longer time intervals. It is found that during a positive IPO phase, two lows of 19-month moving average of the SAM and AAO indices precede by 29-season two occurrences of reduced annual precipitation (represented by 13-month moving average) at a selected site (Coulta in Eyre Peninsula, **Supplementary Table S1**) (**Figure 7B**).

During the positive IPO phase, there are two such significant negative 1.5-year SAM episodes (**Figure 7A**), and both successfully predict droughts in the coastal area of South Australia with a 7.25-year lead (**Figures 7C,D**). For the drought predicted for June 1987–May 1988, at least 50% precipitation reduction occurs south of Goyder's line, and for that in June 1998–May 1999, precipitation south of Goyder's line reduces by at least 40%.

However, of five negative 1.5-year SAM episodes identified in negative IPO phases (**Figure 7A**), only one (1976) is coincident with a drought in Coulta at a 7.25-year lag. This contrast between positive and negative IPO, in the reliability of using 1.5-year moving average AAO as a 7-year lead drought precursor for rain-fed agriculture in South Australia, is consistent with decadal variation of the oceanic pathway (*Possible Oceanic Pathway for the 7-Year Lag Teleconnection*).

CONCLUSIONS

This study documents a possible 7-year lag teleconnection for precipitation in South Australia, particularly in its rain-fed agriculture region, during a positive IOP phase. This teleconnection is composed of three sequential steps: a 27-season lag positive connection between sea subsurface potential temperature (SSPT) off coast of SA and SAM, a zero-season lag positive connection between SST and SSPT, and a 2-season lag positive connection between precipitation in SA and SST.

The 29-season lag response between South Australia precipitation and SAM is likely related to an oceanic supergyre in the southern hemisphere oceans. It takes 27 seasons for the impact of SAM episodes to emerge in sea temperatures to the south of South Australia. The subsequent influences on the atmospheric conditions likely take about two seasons.

This teleconnection may provide valuable lead information for water resource management and agriculture planning for South Australia. It is found that during a positive IPO phase, a positive SAM autumn tends to be associated with a wet winter 7 year later, and vice versa, south of Goyder's Line in South Australia. A negative 1.5-year moving average SAM can be used as a drought precursor for rain-fed agriculture in South Australia with a 7-year lead time. This relationship successfully hindcasts two drought events with about 50% annual precipitation reduction to the south of Goyder's Line.

However, these conclusions are drawn primarily based on data of 1979–2017, which includes only one positive IPO phase. Nevertheless, the oceanic pathway via the supergyre suggested in this study provides a basis to predict when this 7-year teleconnection may resume in the future based on observation and/or modeling.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. Links to the data can be found in the **Supplementary Material**.

AUTHOR CONTRIBUTIONS

LF: conducted most of the data analysis, found the atmospheric and oceanic evidence to explain the 7-year lag teleconnection, and wrote part of this manuscript. HG: shaped the research idea, coordinated the study, performed part of data analysis, and wrote part of the manuscript. WC: provided advice in data analyses to substantiate the 7-year lag teleconnection, which has led to the important findings in this paper (e.g., IPO-phase dependence, ocean pathway), and wrote part of the manuscript. CR and HG: found the 7-year lag correlation between rainfall and SAM index. JX: provided advice in data analyses to substantiate the 7-year lag teleconnection, edited the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.553506/full#supplementary-material

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Impacts of Droughts and Acidic Deposition on Long-Term Surface Water Dissolved Organic Carbon Concentrations in Upland Catchments in Wales

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Concerns have been raised about rising trends in surface water dissolved organic carbon (DOC) concentrations in UK upland catchments over the past decades. Several mechanisms have been proposed to explain these trends, including changes in climate and declines in sulfate deposition across Europe. Drier summers and wetter winters are projected in the UK, and there is an increasing interest in whether the rising trends of DOC would be continued or stabilized. In this paper, the INCA (INtegrated CAtchment) water quality model was applied to the upland catchment of the River Severn at Plynlimon in Wales and used to simulate the effects of both climate and sulfate deposition on surface water DOC concentrations. We introduced new parameter sets of INCA to explain enzymatic latch effect in peatlands during droughts. The model was able to simulate recent past (1995–2013) rising trends in DOC in Plynlimon. Climatic projections were employed to estimate the future trends on DOC in the uplands and to consider potential impacts on catchment management. The model was run with climatic scenarios generated using the weather@home2 climate modeling platform and with sulfate deposition scenarios from the European Monitoring and Evaluation Programme (EMEP) for 1975–2100. The modeling results show that the rising DOC trends are likely to continue in the near future (2020–2049) and the level of DOC concentrations is projected to stabilize in the far future (2070–2099). However, in the far future, the seasonal patterns of DOC concentrations will change, with a post-drought DOC surge in autumn months.

Keywords: water quality, DOC (dissolved organic carbon), climate change, droughts, enzymatic latch, Plynlimon

INTRODUCTION

While the peatlands cover a relatively small amount of the Earth's terrestrial area, they contain approximately one-third of the world's soil carbon pool (Gorham, 1991; Pastor et al., 2003) and about 40% of the UK's total soil carbon storage (UK National Ecosystem Assessment, 2011). Release of carbon from peatlands includes dissolved organic carbon (DOC) and carbon dioxide (CO_2) in rivers, and direct release of CO_2 and methane (CH_4) to the atmosphere. Rising trends of

DOC concentrations in freshwater system have been reported across northern, central Europe and eastern North America, particularly in the industrial areas (Monteith et al., 2007). The changes in the flux of DOC from the land to surface waters have been attracting much interest from academics (Freeman et al., 2001a, Evans, 2015) and water companies due to the problematic for water treatment (Ritson et al., 2014). Several mechanisms have been proposed to explain these trends including changes in climate and declines in sulfate deposition across Europe (Evans et al., 2005; Monteith et al., 2007). Fluvial DOC export determines a significant proportion of the peatland carbon balance, and widespread increases in DOC fluxes suggest that this carbon balance may be altering, with major implications for terrestrial carbon budgets. These increases appear to be driven by regional or global-scale environmental changes, although the key driving mechanisms have yet to be conclusively identified.

Major DOC increases have been observed over the timescales that have seen reductions in the acidity of precipitation, therefore, sulfur deposition is thought to have a significant effect by altering microbial populations and suppressing the formation of DOC under high deposition loading (Evans et al., 2006, 2012). Monteith et al. (2007) reported that the increasing DOC concentrations are in proportion to the rates at which atmospheric deposition of anthropogenic sulfur and sea salt are declining. As sulfur deposition controls soil water acidity, it leads to changes in DOC solubility in the soil (Evans et al., 2012). A recent study by Kang et al. (2018) investigated biogeochemical linkages between pH increase and DOC production in peatlands and demonstrated that increases of pH stimulate key enzyme activities, which involved the decomposition of peat, resulting in the enhancement of DOC concentrations in the pore water. This experiment supports the hypothesis that the recovery from acidification could cause the increase in DOC concentrations in freshwater ecosystems. Clark et al. (2005) discovered that DOC concentrations and sulfate dynamics in soil solution have a strong relationship under drought conditions in peat soils, which are a major source of DOC to surface waters. Climate-related mechanisms present a particular concern as they would imply that increasing atmospheric CO_2 could lead to an increase in peatland DOC release (Freeman et al., 2004). Conversion of this DOC to CO_2, by microbial or photochemical processes, could therefore create a positive feedback effect, raising atmospheric CO_2 concentrations and stimulating the further release of DOC from wetlands. Other proposed drivers include factors related to the increase of air temperature (Freeman et al., 2001b), changes in precipitation and runoff (Tranvik and Jansson, 2002), and changes in land use (Yallop and Clutterbuck, 2009).

Under future climate conditions, drier summers and wetter winters are projected in the UK (Lowe et al., 2018). Changes in climatic conditions will affect catchment hydrology and river water quality (Whitehead et al., 2009). DOC production rates and mineralisation processes in pore water are sensitive biochemical processes directly affected by these changes (Bell et al., 2018). Drought conditions will consequently affect the carbon storage in peatlands and fluvial DOC concentrations caused by the "enzymatic latch" process (Freeman et al., 2001b, Fenner and Freeman, 2011). Drought events introduce oxygen into the system and change the redox conditions in peatlands, which controls DOC solubility. Organic carbon is not released during the drought, but subsequent re-wetting and re-flooding accelerate carbon losses from the peat to the atmosphere and the receiving waters.

The long-term monitoring of surface water quality networks in the UK has also revealed increasing DOC concentration trends in upland catchments since the late 1980s. DOC may be now stabilizing in catchments where reduced sulfur deposition has reduced ionic strength in soils. However, this would not be the case for peatlands that continue to leak stored sulfur. One upland catchment, Plynlimon, in the upper Severn catchment, is dominated by organomineral soils, with smaller areas of blanket peat so that the upward movement of DOC concentrations could continue for some years. In addition, extreme weather events could trigger occasional releases of DOC, flushing DOC in late summer and autumn storm events (Delpla et al., 2015). A DOC surge could be expected during storm events which could create problems downstream. Peatlands supply over a quarter of drinking water in the UK (ONS, 2019) and higher DOC concentrations in drinking water can cause human health issues as DOC reacts with the chlorine used in some drinking water treatment processes to produce potentially carcinogenic trihalomethanes (Chow et al., 2003). It affects watercolor, transparency, and pH, which all directly link to stream ecology and increases in DOC represent a change in the quality and ecology of streams, thereby creating difficulties from a Water Framework Directive (WFD) perspective (Whitehead et al., 2006). Additionally, the removal of DOC in raw water in the treatment plant is costly for water utility companies (Ritson et al., 2014, Ritson et al., 2016). There has been considerable debate about the changes in DOC concentration in the upland UK, and the Acid Water Monitoring Network report rising trends in many upland peat catchments across the UK.

Several DOC simulation models have been developed for both terrestrial and aquatic environments (de Wit et al., 2016). The INtegrated CAtchments model for Carbon (INCA-C) has been widely used to simulate seasonal and long-term patterns in soil and surface water DOC (Futter et al., 2007). Changes in climate, sulfate deposition and land management contribute to variability in surface water DOC concentrations, and INCA-C is capable of simulating complex, interdependent processes in catchment-scale peatland as a multi-parameter process-based model. The initial model development and application was to catchments in Canada (Futter et al., 2007) and further applications including Norway (Futter and de Wit, 2008), Finland (Futter et al., 2009), Ireland (O'Driscoll et al., 2018) and several UK catchments (Xu et al., 2020).

Whether or not rising trends of DOC in upland catchments will continue, or will stabilize, is an important consideration for peatland catchment responses to future drought and acidic deposition, in addition to the implications for downstream drinking water treatment and supply. The aim of this paper is to present an assessment of potential future climatic and acidic deposition impacts on river water quality in peatland catchments in the upper Severn that has been showing large rising trends of DOC over the last decades. The INCA-C model was first used to simulate current flow and DOC concentrations and fluxes. Here, we introduce new parameter sets of INCA-C to simulate the enzymatic latch effect in peatlands during severe droughts. A large ensemble of climate scenarios generated by weather@home2 project and acidic deposition scenarios produced by Emissions Monitoring and Evaluation Programme (EMEP) were then projected to drive INCA-C model simulations.

STUDY AREA

The study area, Plynlimon sub-catchments, are headwater catchments of the River Severn in the UK. Two sub-catchments are the Hafren and the Hore at between 300 and 700 m above sea level (**Figure 1**). They are 5.5 and 3.2 km^2 in area, respectively. Peatland, semi-natural grassland, areas of plantation conifer forest (mainly Sitka spruce with some Norway spruce), are all represented within Plynlimon catchments (Neal et al., 2011). The upper parts of the Hafren and the Hore comprise hilltop plateau dominated by up to 2 m of deep blanket peat whereas the valley bottoms include areas of seasonally saturated peat and gley soil. The Upper and Lower Hafren represent a single main channel system with a clear divide between the upstream blanket peat and the downstream forested peaty podzols areas. The upper and lower parts of the Hore were harvested in 1985–1988 and 2006–2009, respectively. Logging residue was left on the site after clear-felling, and then the area was subsequently replanted with conifer forest. The catchment soils were plowed and drained by creating ditches in the between harvest periods, so consequently "flashy" catchments were created with rapid responses to rainfall and enhanced sediment transport rates.

According to the UK National River Flow Archive (NRFA), the Plynlimon receives an average annual rainfall of 2,653 mm (computed in the period of 1961–2015, with a minimum of 1,855 mm in 1976 and a maximum of 3,801 mm in 2000). The annual average temperature is 9.2°C (1995–2015, a minimum of 7.9°C in 1996 and a maximum of 9.8°C in 2014). The average summer temperature is 14.7°C, and the average winter temperature is 3.8°C. The land uses of the Plynlimon catchments were categorized as forest (both managed and unmanaged), unimproved grassland (i.e., unfertilised grassland), and peatland. The Hore catchment was divided into two reaches, upper Hore and lower Hore. The land use of Hore catchment is predominantly forest cover with 60% of forest, 31% of unimproved grassland and 9% of peatland in upper Hore. Lower Hore has a similar land use to upper Hore. The Hafren catchment was divided into three reaches, upper Hafren, lower Hafren and Severn at Plynlimon flume where the confluence of Hore and Hafren and an inflow of river Severn and includes Tanllwyth stream. The land use of upper Hafren is 90% of peatland and 10% of unimproved grassland. Forest cover dominates from lower Hafren and Plynlimon flume. **Figure 1** shows the catchment area and land use proportions for the Plynlimon catchments.

The trend of DOC concentrations in the upper Severn catchments is shown in **Figure 2**, showing a gradually increasing trend since the late 1990s with high peak concentrations in 2009 (**Table 1**). The monitoring infrastructure was established initially to investigate the impacts of upland conifer plantations

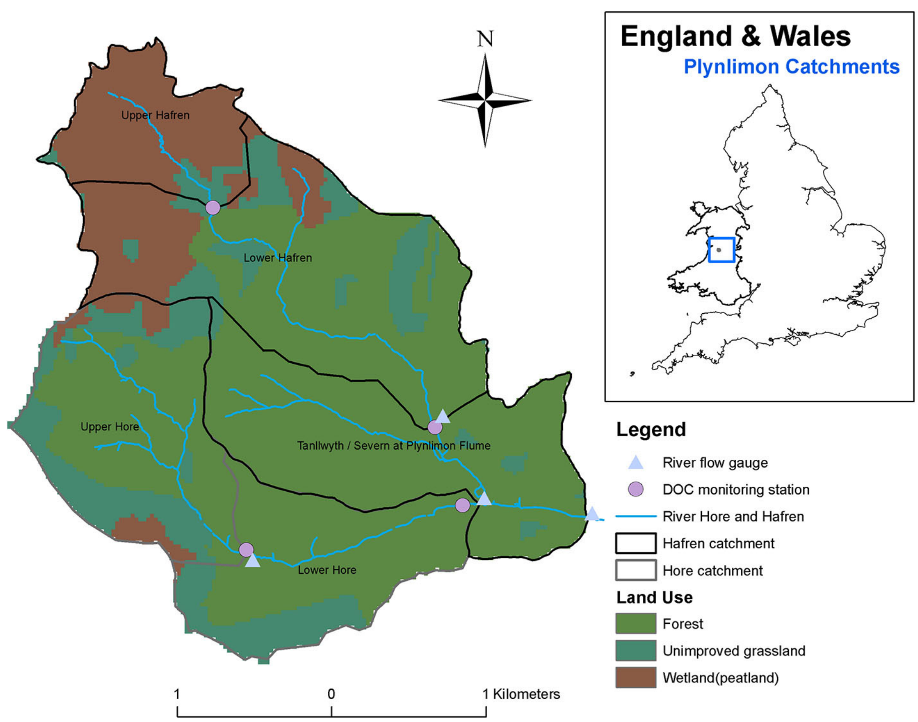

FIGURE 1 | Plynlimon catchment with the Hore and Hafren sub-catchments.

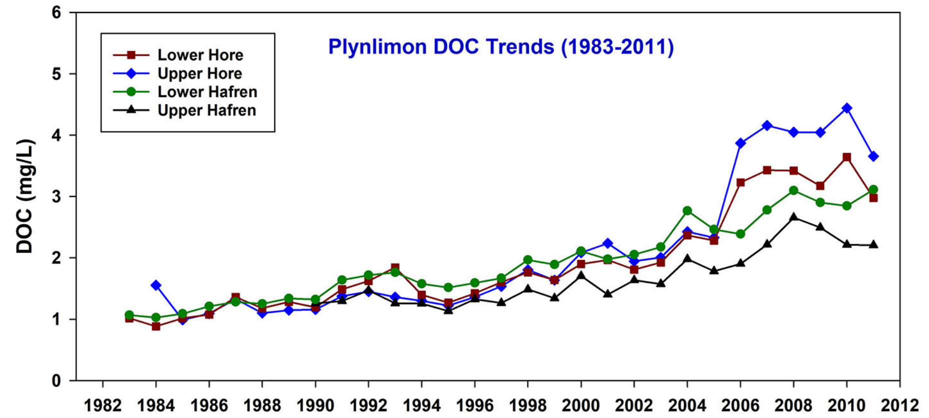

FIGURE 2 | Plynlimon DOC Trends (1983–2011) with annual mean DOC (Neal et al., 2013 and Norris et al., 2017).

TABLE 1 | Plynlimon Mean, Maximum and Minimum DOC concentrations mg/L (1983–2011).

	Upper Hore	Lower Hore	Upper Hafren	Lower Hafren
Mean	2.06	1.87	1.68	1.90
Maximum	21.30	14.00	9.65	11.90
Minimum	0.20	0.20	0.20	0.20
Standard deviation (σ)	1.72	1.30	1.27	1.35
Mean + 1 σ	3.78	3.17	2.94	3.25

on the hydrological cycle in the 1960s. With growing awareness and concern about acid deposition and the effect of forest management practices on river chemistry, hydro-chemical measurements have generated a 30-year uninterrupted record from weekly to monthly which includes pH, alkalinity, nutrients, major cations, anions, trace metals, dissolved organic carbon and dissolved organic nitrogen. The Plynlimon catchment experiment is one of the longest-running studies in Europe, producing extensive environmental data (Neal et al., 2011; Robinson et al., 2013) with several decades of high-quality climate, flow and water quality data. As an extensive data set, it has helped to improve the understandings of many aspects of hydrology, water chemistry and the consequences of changing the land cover in the catchment (Robinson et al., 2013).

MATERIALS AND METHODS

Model Data

Table 2 shows the data used in this study for model application with temporal and spatial coverage. The meteorological data, daily precipitation and temperature, were obtained from the UK Met office (Met Office, 2012). Records of continuous daily water discharge at the Hore and the Hafren were obtained from the National River Flow Archive (NRFA). Discharge records after 2009 were obtained from the Plynlimon experimental site in the UK Center for Ecology and Hydrology (CEH). Weekly water quality data from the Plynlimon experimental site were also provided by CEH (Neal et al., 2013, Norris et al., 2017).

The Integrated Catchments Model for Carbon (INCA-C)

The INCA-C model was employed to reproduce and simulate carbon dynamics in the Plynlimon catchment. INCA-C is a dynamic, semi-distributed catchment scale process-based model of DOC concentrations and fluxes in surface waters (Futter et al., 2007). The INCA model was initially developed to simulate nitrogen (Whitehead et al., 1998a,b) and phosphorus (Wade et al., 2002a) at a catchment scale. Several sub-models were later added, including carbon (Futter et al., 2007), sediment transport and soil erosion (Lazar et al., 2010), pathogens (Whitehead et al., 2016), an organic contaminant model (Lu et al., 2016), and microplastics (Nizzetto et al., 2016).

The INCA-C model simulates daily DOC concentrations, flux and water flow in streams. Fluxes and concentrations of DOC are simulated by solving mass balance equations for terrestrial processes while simultaneously solving flow equations. INCA-C requires a daily time series of soil moisture deficit (SMD), hydrological effective rainfall (HER), air temperature and precipitation as inputs. The latter two input datasets were estimated using a semi-distributed rainfall-runoff model, PERSiST (Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport model, Futter et al., 2014). PERSiST simulates water fluxes in a catchment scale, with a series of user-defined buckets indicating different hydrological processes such as snowmelt, surface runoff generation, soil water storage, groundwater and streamflow. It is particularly designed to provide input time series for the INCA models. In addition, spatial data describing catchment land cover and soil properties, the location of point sources, abstraction and effluent discharge are required to run INCA-C. INCA-C then provides daily time series of flow, DOC and DIC (dissolved inorganic carbon) concentrations at each reach boundary, as well as profiles along

TABLE 2 | Data used in this study for model setup and calibration.

Type	Source	Time coverage	Spatial coverage
Land use	Center for Ecology and Hydrology (UK land cover map)	2007	All the catchment
Meteorology (precipitation and temperature)	Met office	1995–2013	All the catchment, and used for the model calibration and validation
Flows	National River Flow Archive(1995–2009) Center for Ecology and Hydrology(post-2009)	1995–2013 (Different for all the stations)	Hore catchment (reach 1, 2) Hafren catchment (reach 2,3)
Water quality	Center for Ecology and Hydrology	1983–2012 (Different for all the stations)	Reach 1,2 for both the Hore and Hafren catchment

with descriptive statistics of these variables at selected sites. INCA-C is calibrated using the time series of observed and modeled daily discharge and point estimates of in-stream DOC concentrations to minimize the differences between observed and modeled values.

Highlighted Processes for Acidic Deposition and Enzymatic Latch

A detailed description and model equations of INCA-C terrestrial and in-stream carbon processing routines, hydrological routing, and climate controls are well-documented by Futter et al. (2007). The initial version of the model has been further modified, and this section will present the highlighted processes related to the analysis in this study.

In the INCA-C model, all carbon procession in soils and surface waters are modeled as a series of first-order differential equations. All rate coefficients in soil layers are dependent on moisture saturation status and soil temperature. INCA-C simulates in-soil temperature by using observed air temperature. The rate coefficient for soil moisture effect is a linear function of soil moisture content. For example, in-soil carbon transformation operates at a maximum rate when the simulated SMD is at zero, and cease when the simulated SMD is greater than SMD_{max}. SMD_{max} is a calibrated threshold of the maximum soil moisture deficit at which carbon transformations may occur.

The following simplified equations explain the effect of sulfate concentrations and the enzymatic latch on organic carbon sorption and desorption in soil solution. The modification of the sulfate effect to INCA-C has been initially introduced by Futter et al. (2009) and successfully applied to a boreal catchment in Finland. The enzymatic latch process is an innovative additional application in this paper. The same processes occur in the organic and mineral soil horizons with different rate constants.

As mentioned above, the change in mass of DOC is controlled as a combination of soil moisture (k_M, d^{-1}), soil temperature (k_T, d^{-1}) effects and the mass of organic carbon sorbed (c_2DOC, $kg\ C\ d^{-1}$) and desorbed (c_1SOC, $kg\ C\ d^{-1}$). The base rates of the sorption(c_2) and desorption(c_1) coefficients are estimated during the model calibration. To simulate soil water sulfate concentrations ($[SO_4^{2-}]$), atmospheric SO_4^{2-} deposition is used as a surrogate in soil solution. Equations 1, 2 are simplified equations of the changes in the mass of DOC and SOC (solid organic carbon) with functions of soil chemistry controls on organic carbon sorption and desorption rates.

Equation 1

$$\frac{dDOC}{dt} = k_M k_T (c_1 SOC - \left(c_2 + b_1 \left[SO_4^{2-}\right]^{b_2}\right) DOC)$$

Equation 2

$$\frac{dSOC}{dt} = k_M k_T \left(\left(c_2 + b_1 \left[SO_4^{2-}\right]^{b_2}\right) DOC - c_1 SOC\right)$$

The sulfate effect ($b_1[SO_4^{2-}]^{b_2}$) is added on the rate at which DOC is transformed to SOC. At high sulfate concentrations, the transformation from DOC to SOC will be more rapid. Increasing sulfate concentrations should increase the rate at which DOC is transformed to SOC, and hence lower the mass of DOC in solution (Equation 1). The equation for the change in mass of SOC is effectively the reverse of that for DOC (Equation 2). When b_1 is at zero, the effect of $[SO_4^{2-}]$ is turned off in simulation where organic matter changes from the dissolved to the solid phase.

The "enzymic latch" mechanism (Freeman et al., 2001b) has been proposed as a mechanism to explain an increase of DOC concentrations observed following a severe drought in peatlands (Worrall and Burt, 2004). The mechanism is simulated in INCA-C as an increase in the rate of SOC to DOC transformation when the soil moisture deficit drops below a critical threshold.

The enzymatic latch effect is triggered by a drought event by increasing the rate at which SOC is transformed to DOC. Drought is defined in INCA-C when simulated SMD is exceeding a critical threshold (l_2, mm). The maximum effect of the enzymatic latch is immediately following a drought event and gradually declines to zero. The decay in enzymatic latch effect is simulated as a linear function of the number of days (n) since the drought threshold was crossed (t_{Crit}) divided by the duration of the latching effect in days ($365\ x\ l_0$). l_0 indicates a return period (years) of the enzymatic latch. In the event that another drought event occurs in which the SMD exceeds the critical threshold (l_2), the number of days since crossing the drought threshold (t_{Crit}) is reset to 0. The enzymatic latch multiplier (l_{Mult}) is defined in Equation 3. It should be initialized to a value of 0.

Equation 3

$$l_{Mult} = \begin{cases} \left(1 - \frac{t_{Crit}}{365 \times l_0}\right), & SMD_{t-n} > l_2 \ \& \ t_{crit} \leq 365 \times l_0 \\ 0 \quad , & all\ other\ conditions \end{cases}$$

Since both sulfate effect and enzymatic latch effect are associated with the same process, the changes in the mass of DOC and SOC, Equations 1, 2 can be updated accordingly to Equations 4, 5, respectively. The rate of production of DOC from SOC is controlled by the desorption(c_1) coefficient and the enzymatic latch effect ($l_{Mult}l_1$), where l_1 (d^{-1}) is the enzymatic latch rate coefficient. The rate of DOC transformation to SOC is controlled by the sorption(c_2) coefficient and the sulfate effect ($b_1\left[SO_4^{2-}\right]^{b_2}$). The range of parameters is achieved during the calibration process.

Equation 4

$$\frac{dDOC}{dt} = k_M k_T ((c_1 + l_{Mult}l_1)\, SOC - \left(c_2 + b_1\left[SO_4^{2-}\right]^{b_2}\right) DOC)$$

Equation 5

$$\frac{dSOC}{dt} = k_M k_T \left(\left(c_2 + b_1\left[SO_4^{2-}\right]^{b_2}\right) DOC - (c_1 + l_{Mult}l_1)\, SOC\right)$$

Model Parameterisation and Generalized Sensitivity Analysis

The Calibration Procedure

The INCA-C model has been applied to the whole upper Severn Catchment at Plynlimon using a long run of data from 1995 to 2013 to calibrate and validate the model. The period was split in two: 2000–2013 for calibration, and 1995–1999 for validation. The period of model evaluation was set according to the availability of daily meteorological inputs. Given that the two catchments have quite a different land uses, separate INCA-C models were set up for the two catchments to compare catchment responses under a changing climate. Reach boundaries were drawn at Plynlimon experimental monitoring stations where long-term flow and water quality data were available. Manual calibrations were carefully conducted in which land phase hydrology and carbon processing parameters were allowed to vary so as to observe the correspondence between modeled and observed stream flows and DOC. The initial values of parameters and those ranges were found from the literature (Futter et al., 2007). The manual calibration was repeated and conducted until the Nash-Sutcliffe (NS) statistics (Nash and Sutcliffe, 1970) showed a reasonable agreement between simulated and observed values of flow and DOC. The parameter sets derived from manual calibrations were used as the starting point for a Monte Carlo analysis in which selected carbon processing and hydraulic parameters which could affect modeled DOC concentrations were allowed to vary by ± 20%. The Monte Carlo simulation produced an ensemble of 10,000 model runs, and those results were assessed to find the best performing parameter sets. Model performance was assessed using the sum of Nash-Sutcliffe statistics representing correspondence between modeled and observed DOC in upper and lower Hafren and upper and lower Hore, respectively. Best performing model runs were selected and used for further analysis.

General Sensitivity Analysis

A General Sensitivity Analysis (Hornberger and Spear, 1980; Spear and Hornberger, 1980) using Monte Carlo Simulations was applied in order to investigate model complexity and understand parameter influence on model simulations. The method is also conversely to inform those parameters that appear to exert little influence on model results as well. The main strategy is to incorporate uncertainty in the model simulation by specifying the parameter values from probability distribution functions, rather than point values. The Monte Carlo simulations are employed with chosen parameter values from the specified distributions, which should reflect the feasible parameter ranges. The results of Monte Carlo simulations are classified into those that are considered behavioral and non-behavior with respect to the pre-defined criteria set. The definition of behavior and non-behavior is problem-dependent, and the criteria can be for general trends or extreme events. The each of model results from the Monte Carlo parameter sets is compared with the observed values via the pre-defined behavior criteria algorithm (in this study, increasing trends in DOC concentrations) in order to determine the occurrence or non-occurrence of the required behavior. Then, the parameter sets will be classified to the one associated with the occurrence of behavior (B) and one with the non-behavior(N). Similar methodologies have been applied to provide a probabilistic procedure for model calibration and to identify critical parameter uncertainties in phytoplankton models (Whitehead and Hornberger, 1984), in a model application of phosphorus and macrophyte dynamics in River Kennet (Wade et al., 2002b), and in new model development of dissolved oxygen, Q^2 (Cox and Whitehead, 2005).

The Hornberger and Spear's generalized sensitivity analysis looks for the difference between the behavioral and non-behavioral sets for each parameter. It does so by comparing the cumulative distribution of that parameter in each set. Where there is a strong difference between the two distributions for a parameter, it may be concluded that the simulations are sensitive to those parameters. If the two distributions are very similar, it may be concluded that the simulations are not very sensitive to those parameters. A quantitative measure of the difference between two distributions can be calculated using the non-parametric Kolmogorov–Smirnov d statistic ($d_{m,n}$). The Kolmogorov-Smirnov two sample test is computed as following Equation 6:

Equation 6

$$d_{m,n} = sup_x \left|S_n(x) - S_m(x)\right|$$

where S_n and S_m are the sample distribution functions corresponding to the behavior(m) and non-behavior(n) values of a given model parameter and this statistic is the same as that used in the Spear and Hornberger (1980). The value of $d_{m,n}$, d statistic, can be used as an index of relative difference for model parameters. The highest $d_{m,n}$ value among all parameter set is the most influent model parameter. This approach is a nonparametric method of sensitivity analysis in that it makes no prior assumptions about the variation or covariation of different parameter values, but only evaluates sets of parameter values in terms of their performance.

In this paper, the aim of the behavior analysis is specific to understand which particular parameters will have a significant influence on the rising trends of modeled DOC concentrations. The general sensitivity analysis was applied to the Hore and Hafren INCA carbon models, respectively. Based on a prior general sensitive analysis of the INCA Carbon model (Futter et al., 2007, Futter and de Wit, 2008), following carbon and non-carbon processing parameters were identified as the most significantly influential on model behaviors and considered to the analysis:

- In Forest cover, organic layer: DOC mineralisation rate, the rate of change in mass of DOC to SOC, the rate of change in mass of SOC to DOC, retention volume of organic layer, minimum organic layer flow
- In Forest cover, both organic and mineral layer: soil temperature rate multiplier, the rate of change in mass of SOC to DOC
- In Peatland cover, organic layer: retention volume of organic layer, minimum organic layer flow
- In Peatland cover, mineral layer: the rate of change in mass of DOC to SOC
- In Peatland cover, both organic and mineral layer: the rate of change in mass of SOC to DOC, and maximum SMD at which carbon processing can occur.

In addition, parameters related to the enzymatic latch process and sulfate multipliers were also included in the analysis. The feasible space of model parameters was drawn and sampled randomly to generate 10,000 different parameter sets. The calibrated INCA-C model was then run with each of these parameter sets. The 2000 best performing model runs were retained for further sensitivity analysis. Model performance was assessed using the sum of the NS statistics representing correspondence between modeled and observed DOC in the Upper and Lower reaches for the Hafren and Hore.

Projected Future Climate

In this study, climate scenarios generated by the weather@home system (Massey et al., 2015, Guillod et al., 2018) were applied to explore the potential impacts of climate change on hydrology, the carbon in catchments. The modeling system- weather@home (hereafter, w@h) consists of a global climate model (GCM) with a nested regional climate model (RCM) driven by sea surface temperatures as well as other forcings. It enables the production of a large number of ensembles of weather events with the help of volunteers distributed computing across the world. In this model application, weather@home2 (hereafter w@h2, which includes an improved land surface scheme) was used to generate 30-year-long weather time series of rainfall and temperature projections for three different periods. The data set is specifically designed to support a risk-based approach for the study of extreme events such as drought and heavy precipitation, both of which require the spatial consistency of hydro-meteorological data sets (Guillod et al., 2018). The scenarios in each future time slice all follow the Representative Concentration Pathway 8.5 (RCP8.5) and sample the range of sea surface temperatures and sea ice changes from CMIP5 (Coupled Model Intercomparison Project Phase 5) models. A number of daily and (or) monthly output variables are available from the RCM including temperature, precipitation, surface air humidity, mean sea level pressure, and potential evaporation. To assess the worst possible future condition of water quality, the RCP8.5 was selected as it is the most severe scenario among the current available future scenarios. Of particular relevance for water quality modeling is the changes in intense rainfall, which can affect leaching and drought, which influences chemical retention times and river flows.

From a 25 × 25 km grid over Europe, 100-time series are available for each of time slices which represent baseline (BL, 1975–2004), near future (NF, 2020–2049), and far future (FF, 2070–2099) climatic scenarios. Outputs from grid cells include Plynlimon catchment in Wales were averages to generate input time series for water quality modeling application (**Figure 3**).

The precipitation data was bias-corrected in order to reproduce the patterns and distributions of observed data better, and a linear approach was applied (Guillod et al., 2018). The bias correction method was conducted by using spatially-variable monthly bias-correction factors, obtained by the ratio of the modeled and observed monthly average precipitation. However, very little bias was observed from temperature, so temperature bias was not explicitly corrected. More details about weather@home2 data and bias-correction method can be found in Guillod et al. (2017) and Guillod et al. (2018). **Figure 4** shows the comparison of bias-corrected precipitation (purple) and raw precipitation from w@h2 (gray) with observed precipitation. A dry bias during summer months on precipitation was well-corrected.

Sulfate Deposition Scenarios

Deposition scenarios from the Emissions Monitoring and Evaluation Programme (EMEP) were applied for this study to include the impacts of historical, present, and future acidic deposition. Historical sulfate deposition time series from 1970 to 2010 on a 50 × 50 km grid resolution was taken from the output of the EMEP/MSC-W model, as well as the future projection on the depositions until 2030 was also provided under the Gothenburg Protocol Currently Legislated Emissions (CLE) scenario (Posch et al., 2007). The chemical transport model developed at the Meteorological Synthesizing Center–West (MSC-W) is called the EMEP/MSC-W model. After 2030, the deposition is assumed to remain constant until 2090. More information on EMEP data can be found in Schöpp et al. (2003).

Reduction in acidic depositions is believed to have helped acidification recovery of European rivers and lakes (Skjelkvåle et al., 2003). As explained in the previous section, organic matter solubility in the INCA-C model is controlled by the concentrations of strong acid anions in soil solution (Futter et al., 2009, 2011). As soil solution data are not readily available, sulfate deposition data are assumed to be a reasonable surrogate for soil solution strong acid anions concentrations. Deposition for the

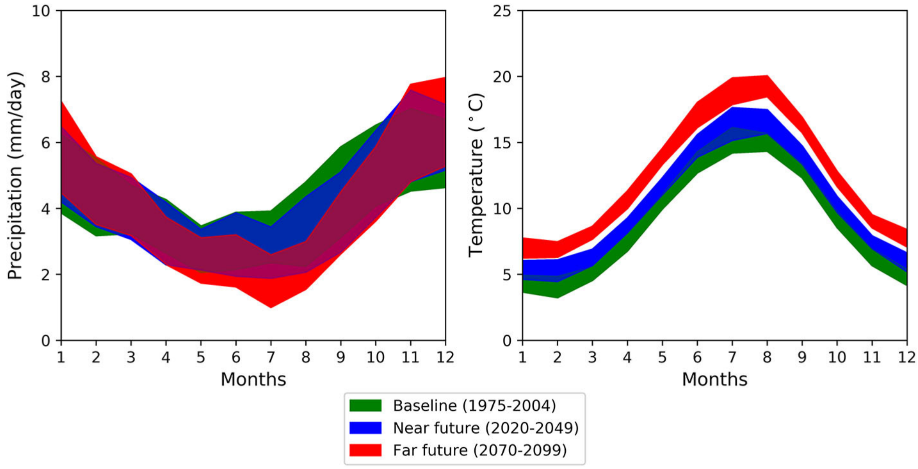

FIGURE 3 | Precipitation and temperature projections (w@h2) for the Plynlimon catchment.

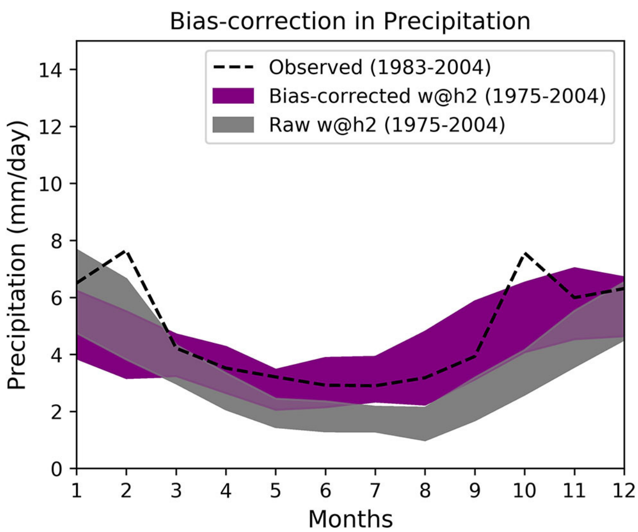

FIGURE 4 | Comparison of Bias-corrected and raw w@h2 in precipitation in Plynlimon catchment.

forest land cover type was applied as an input to the modeling study. A smoothed sulfate deposition time series was created using estimates of average monthly wet sulfate deposition. The linearly interpolated monthly sulfate loadings were multiplied to daily precipitation depth to produce monthly average deposition values. These monthly deposition estimates were then assumed to be representative of the soil solution concentration throughout the soil profile. Estimated deposition showed that the peak was in the 1980s and rapidly declined since then. For the calibration, a single deposition series was provided. For the climate projections, 300 deposition time series were produced according to each input precipitation for each climate realizations for each of w@h2 time slices (baseline, near future and far future).

RESULTS AND DISCUSSIONS

Model Evaluation

The Monte Carlo simulation produced an ensemble of 10,000 model runs and those results were assessed based on observed values of flow and water quality (DOC) at reach two for both the Hore and Hafren catchments (Lower Hore and Lower Hafren). The best model parameter set was selected for the Hore and Hafren model and used for the rest of the study. A combination of model evaluation measures was used to determine the best performance model including (a) visual assessment of time series, (b) model performance statistics and (c) total DOC loads estimation, and selected model performance was described.

Figure 5 shows the calibration and validation results of flow and DOC concentrations at Lower Hafren and Lower Hore. It is seen that the models are successfully representing a temporal pattern of DOC concentration and flow. The model simulations did not always capture the magnitude of peaks in DOC concentration. However, the models were able to capture the timing of peaks and seasonal patterns of DOC concentrations.

Table 3 shows the performance indices of the INCA model in Plynlimon catchments (1995–2013). The performances were measured by Nash-Sutcliffe Efficiency (NSE), log NSE for streamflow and percent bias (PBIAS) for DOC concentration. Perfect matching was represented by the value of one for NSE. A negative value of NSE means that the average observed value is a better predictor than the simulated values of model simulation. NSE is one of the most popular indices for evaluating models, but it is sensitive to high or low extreme values. Therefore, log-transformed discharge (log NSE) was evaluated to consider the variability balanced at low values (low flows). The NSE values of daily simulated streamflow in both the Hore and Hafren catchments show acceptable ranges for a whole period of model evaluation (1995–2013), 0.68 and 0.66, respectively. The log NSE values were improved from the values of NSE in this study, which is 0.73 and 0.68, respectively, for the Hore and Hafren catchments. The simulated daily flow provided

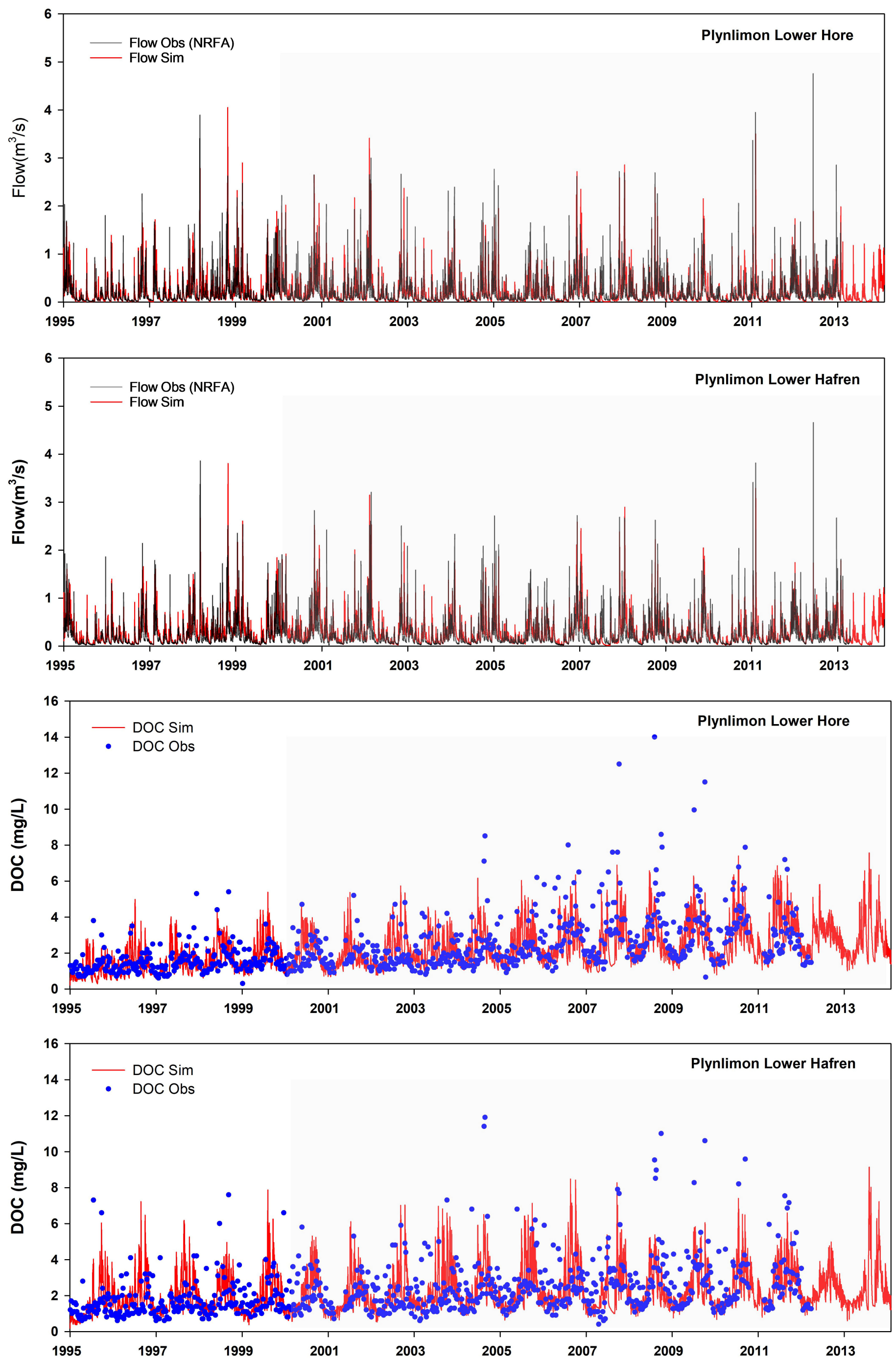

FIGURE 5 | INCA-C calibration and validation results (Flow and DOC) at two locations in Plynlimon catchment. The gray-shaded area is the time period used for calibration. The unshaded area is used for validation.

an acceptable reproduction of the observed flow, including a low flow period, particularly given the flow in Plynlimon is generally small.

Concerning the DOC simulation, PBIAS is <10% bias for both catchments, and INCA-C results can be considered satisfactory. PBIAS measures the average tendency of the modeled values to be larger or smaller than observed counterparts. The optimum value is 0, and negative values indicate a model overestimation bias while positive values mean an underestimation of modeled values. As suggested by

TABLE 3 | Performance indices of INCA -C calibration and validation.

	2000–2013 calibration			1995–2000 validation		
	Flow		DOC	Flow		DOC
Reach	NSE	*log*NSE	PBIAS	NSE	*log*NSE	PBIAS
Lower Hore	0.68	0.69	8.94	0.67	0.80	4.96
Lower Hafren	0.67	0.68	8.93	0.61	0.72	−7.77

NSE, Nash and Sutcliffe index; PBIAS, Percent bias.

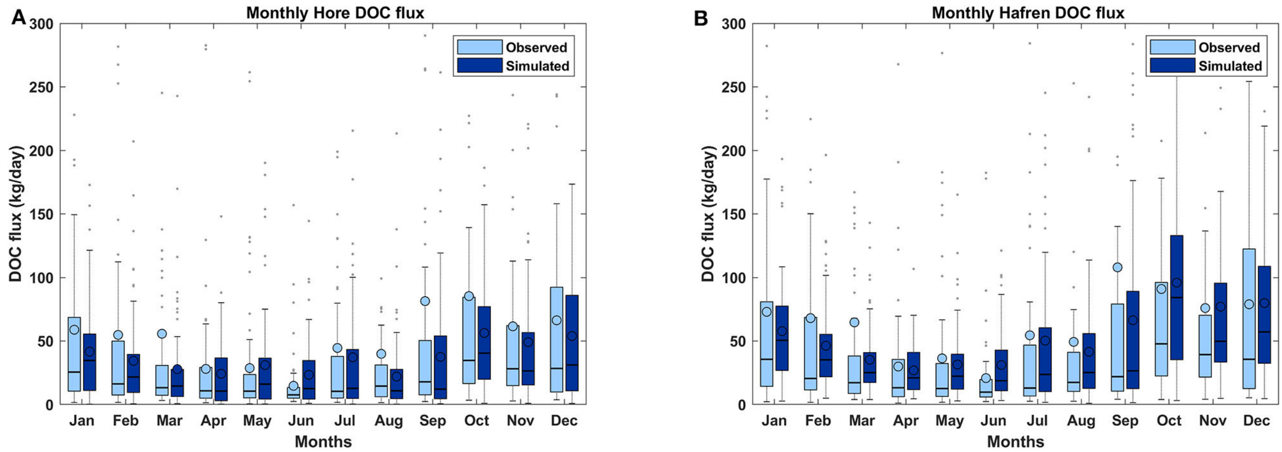

FIGURE 6 | Simulated and Observed Monthly (in-stream) DOC load (kg/day) at Hore **(A)** and Hafren **(B)** catchments.

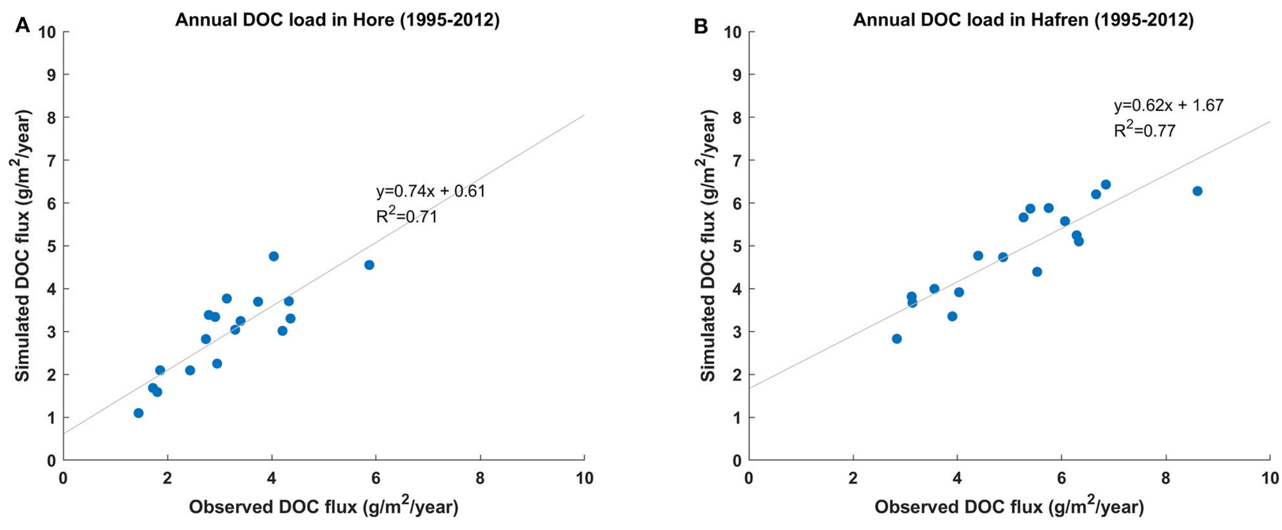

FIGURE 7 | Simulated and Observed Annual DOC load at Hore **(A)** and Hafren **(B)** catchments.

Moriasi et al. (2007), satisfactory simulation can be indicated by PBIAS from ±25% up to ±70% for water quality variables. The sulfate deposition data application was helpful to the model calibrations. Model calibrations without the sulfate deposition data were shown −42% and −16% of PBIAS values for the Hore and Hafren, respectively.

The monthly in-stream DOC flux (kg/day) was calculated to demonstrate whether the model reproduced similar seasonal loads. **Figure 6** showed the simulated and observed monthly DOC loads, which yielded similar results and well-reproduced seasonal patterns. The precipitation-driven annual DOC fluxes showed a great agreement between observed and simulated DOC fluxes (**Figure 7**). The degree of fit in terms of fluxes load with an R^2 of 0.71 (for Hore catchments) and 0.77 (for Hafren) are acceptable.

The many measures used for evaluating model performance showed generally satisfactory simulations, in terms of reproduction of the seasonal patterns of both streamflows and DOC concentrations over a long period, given the uncertainty that characterizes both model results and measurement data values. It suggests the model can be used with confidence in predicting future projections.

Model simulations were forced by a combination of gridded data for sulfate deposition and daily weather inputs and calibrated against point observations of streamflow and water chemistry. The gridded data used here provided complete, gap-free time series, which is a prerequisite for INCA modeling. The EMEP gridded data are widely used when modeling future trajectories of recovery from acidification (e.g., Posch et al., 2007, Futter et al., 2009). Within a region, e.g., the Severn River catchment, long-term temporal variation in sulfate deposition is higher than spatial variation. Thus, it was considered appropriate to use gridded EMEP data as an input to the model. Ledesma and Futter (2017) showed that gridded climate products could give as good or better simulations of streamflow when compared to observational weather data. This finding, combined with the difficulties in obtaining gap-free observational weather data and the need for consistency when applying model parameterizations based on the present-day to future conditions motivated the use of gridded climate data throughout this study. Point observations of streamflow and water quality are also spatially-integrated values as they are the result of processes occurring throughout the catchment.

Sensitivity Analysis –Sensitive Parameters

The criteria for behavior were defined by examining the observed data and identifying a range of values for monthly mean and maximum DOC concentration from 1995 to 2013. Behavior criteria were set to include an increasing trend of DOC concentration and reasonable ranges of monthly mean and maximum DOC concentrations for selected years and months. Summer months (August, July) were chosen and year of 1996, 2002, 2004, and 2008 were all selected to demonstrate increasing trends of DOC concentration. The top 2,000 model runs were retained to proceed with the general sensitivity analysis. Each simulation result consists of the parameter vector itself and the behavioral outcome, i.e., whether the particular parameter vector gave rise to the behavior or not. The criteria used to separate behavioral and non-behavioral parameter sets. Once the parameter set space was partitioned into two groups, the degree of difference between the two groups identified the model parameter influence. If the distribution of non-behavioral values of a model parameter does not separate from the behavioral one, this indicates that the parameter does not have a significant influence on model results. The Kolmogorov-Smirnov two-sample test was used to evaluate model parameter sensitivity. Following refinement of the parameter ranges, the 2,000 simulations for the Hore and the Hafren produce a mixture of behaviors (m) and non-behaviors (n) as expected.

TABLE 4 | Kolmogorov-Smirnov Statistics (significant at 95% level or greater) in the GSA of parameters influencing model behavior.

Rank	Parameter	Land cover type	$d_{m,n}$
Hore catchment ($m = 305$, $n = 1695$)			
1	Organic layer DOC mineralisation	Unimproved grassland	0.25
2	Soil temperature response	Unimproved grassland	0.25
3	Organic layer retention volume	Unimproved grassland	0.25
4	Organic layer b_1, sulfate multiplier	Unimproved grassland	0.18
5	Soil temperature response	Peatland	0.12
6	Organic layer b_1, sulfate multiplier	Forest	0.11
7	Organic layer residence time	Unimproved grassland	0.10
8	Soil temperature response	Forest	0.10
9	Organic layer b_1, sulfate multiplier	Peatland	0.09
10	Organic layer residence time	Forest	0.09
11	Mineral layer retention volume	Forest	0.08
Hafren catchment ($m = 132$, $n = 1,868$)			
1	Soil temperature response	Unimproved grassland	0.57
2	Organic layer enzymatic latch rate	Forest	0.25
3	Soil temperature response	Forest	0.25
4	Organic layer SOC to DOC	Peatland	0.22
5	Organic layer residence time	Unimproved grassland	0.19
6	Organic layer retention volume	Unimproved grassland	0.14
7	Organic layer residence time	Forest	0.14
8	Organic layer critical SMD threshold	Unimproved grassland	0.13
9	Organic layer b_1, sulfate multiplier	Peatland	0.13

In this study, 15 parameters for each type of land cover were applied to the sensitivity analysis, including parameters related to carbon processing, microclimate, hydraulic, enzymatic latch, and sulfate effects. As three land types (Forest, unimproved grassland, and peatland) were employed in this study, forty-five parameters in total were examined in the whole sensitivity analysis. The parameters and corresponding statistics ($d_{m,n}$) that are significantly above the 95% level are ranked in order of importance and listed in **Table 4**. Eleven out of forty-five parameters are significant at the 95% level or greater in the Hore catchment. Nine for the Hafren catchment are found influential, and the relatively large separations denoted by the K-S test $d_{m,n}$ explains that these parameters are important for obtaining the correct behavior in a simulation. In this research, nine parameters contribute significantly to simulate an increasing trend of DOC concentrations in Plynlimon. Among the important parameters, the soil temperature response, sulfate effect (b_1) multiplier, and organic layer hydraulic parameters (residence time and retention volume) have a significant impact on both catchments. It is not a surprise that the temperature effect has ranked as the most

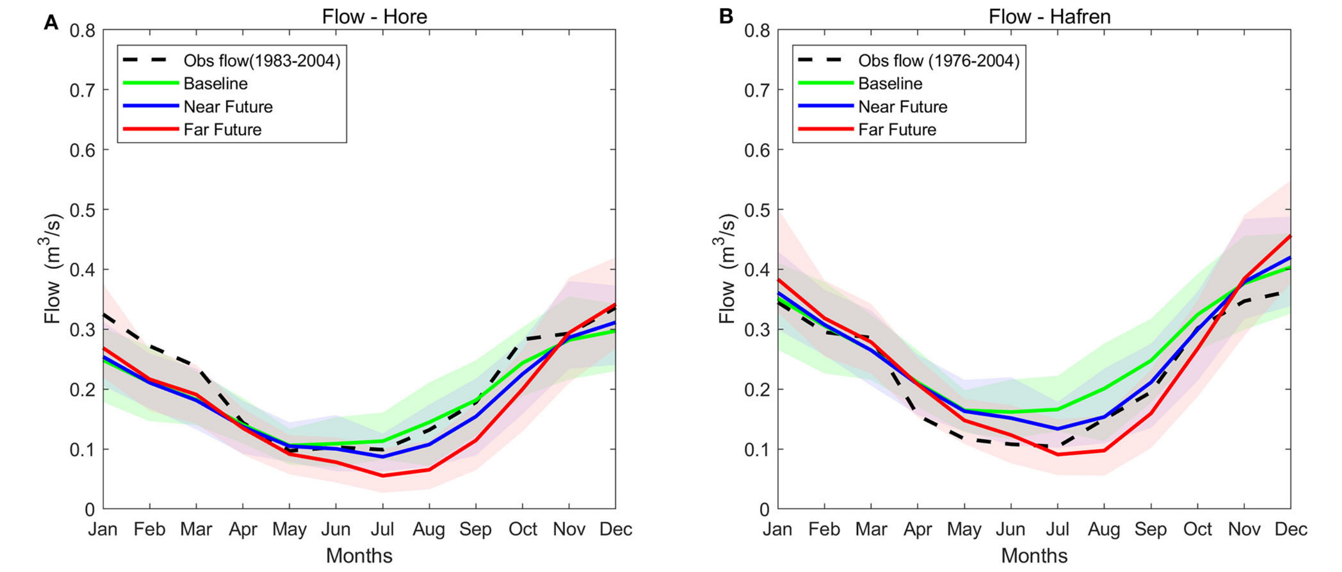

FIGURE 8 | Impact of climate change on flow at Hore **(A)** and Hafren **(B)** catchments.

important parameter to influence model behavior and DOC concentrations. In soil process, sorption and desorption rates of organic carbon are dependent on soil temperature and moisture status, which decide the total mass of DOC and SOC in soil layers and in-stream DOC concentrations. Parameters associated with the effect of sulfate and enzymatic latch revealed to the influential parameters in Plynlimon (**Table 4**).

Climate Change in Plynlimon

According to the results of w@h2 climate scenarios, Plynlimon precipitation is expected to show a slight increase in winter months and a clear decrease in summer months (**Figure 3**). The trends are gradual from the near future to the far future time period. In the far future, the average increase of December precipitation is about 15% whilst a 43% average decrease is expected in July. The total annual average precipitation of the Plynlimon is expected to decrease by 3% in the near future and 6% in the far future. Projected changes in the seasonal patterns of precipitation are more significant than the total annual average precipitation. The average daily air temperature is projected to increase for all months for both future time periods (**Figure 3**). The mean temperature changes are from 9.01°C (8.76°C–9.28°C) as the baseline to 10.22°C (9.94°C–10.44°C) for the near future and to 12.28°C (12.02°C–12.48°C) for the far future scenario.

Simulated Flows and DOC With Projected Future Conditions

The calibrated INCA Carbon model was run with w@h2 climate scenarios and acidic deposition scenarios for the baseline, near future and far future for both Hore and Hafren catchments. The flows in Hore and Hafren show a clear seasonality, with low flows in summer months and high flows in winter months (**Figure 8**). The results of w@h2 driven by the INCA model, future climatic change will enhance this seasonal flow patterns. In particular, summer flows will decrease significantly, while changes in winter flows will be mild. This is probably because the projected lower summer rainfall and increased air temperatures in the Plynlimon area contribute to decrease flows, up to an average of 51% in July under the far future scenario. In winter months, projected flows are expected to increase the range of 1–5% in the near future, and 3–15% in the far future compared to the baseline. However, Plynlimon is a small stream with an average flow with 0.234 m^3/s and 0.205 m^3/s for Hafren and Hore, respectively (average between 1973 and 2009). It is quite difficult to represent in the model simulation, so the range of each future time slices is overlapping with the range of observed flow period. However, the median lines are showing the degree of changes in each time period (**Figures 8A,B**).

The INCA model results show a substantial increase in DOC concentrations in the near future and the far future from the baseline for both catchments. The DOC concentrations in the far future are stabilized and slightly reduced in the summer months after the near future. **Figure 9** shows the DOC monthly average and maximum concentrations driven by the w@h2 climate scenarios. For the Hore catchment, the simulated baseline values slightly overestimate DOC concentrations from April to July compared to the observed values (**Figures 9A,C**). The rest of the months are represented in a reasonable range. It is worth noting that the time series of baseline condition started in 1975 and DOC monitoring has started since 1983, which may cause a slight discrepancy between baseline and observed values. The Hafren catchment, observed values lie within the range of the simulated values of baseline (**Figures 9B,D**).

In the near future for both catchments, there is a significant increase in later summer to autumn (August, September, and October). In the forest-dominant catchment at the lower Hore

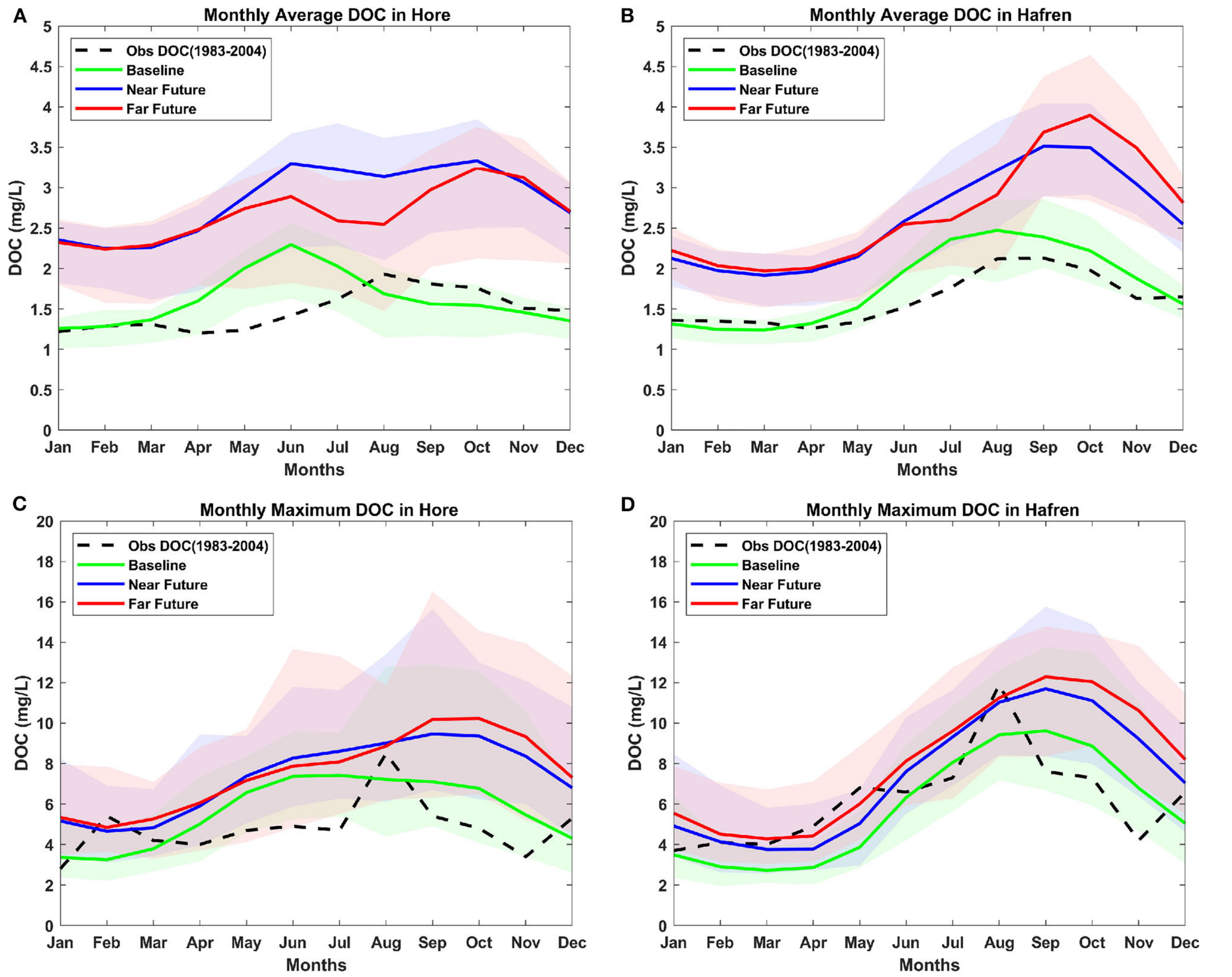

FIGURE 9 | Impact of climate change and acidic deposition (up to 2030) on the Upper Severn catchments; the simulated mean monthly DOC concentrations at the Hore **(A)** and Hafren **(B)**, the simulated monthly maximum DOC concentrations at the Hore **(C)** and Hafren **(D)**.

(**Figure 9A**), there is a slight reduction in DOC concentration the summer months in far future compared to the near future. However, there is still a big surge from the baseline level. Hafren (Peatland-dominant) catchment shows a different trend (**Figure 9B**). From September to November, there is an even greater increase in DOC in the far future than the near future while the summer months of DOC concentrations are slightly decreased.

Several droughts and associated low flows in summer months and subsequent re-wetting in early autumn in peatlands could destabilize peatland carbon stocks and enhance in-stream DOC production rates. This process is greatly affected by the combination of temperature and water availability in pore water as well. The w@h2 analyses projected less summer precipitation with warmer temperatures, which seems to cause an enzymatic latch effect in peatland soils. In the model simulations, the soil moisture deficit is a surrogate measure of soil dryness, and it is representative of the difference between the water currently in the soil and the water-holding capacity of the soil. The SMD is a key driver of INCA-C results as in-soil all carbon transformation rates are assumed to be soil moisture dependent. Additionally, in the INCA-C model application presented here, SMD is compared to a drought threshold below which an enzymatic latch effect is triggered. The SMD threshold of 31 mm was applied for this study in Plynlimon, and if SMD values were >31 mm depth, the enzymatic latch effect was triggered. The threshold was achieved from the calibration process, and it is consistent value with a measurement from Plynlimon experiment site (Hudson, 1988). **Figure 10** shows the changes in the frequency and duration of soil moisture droughts (when SMD > 31 mm) for the two future scenarios that the enzymatic latch effect was triggered. The w@h2 future scenarios suggest a substantial increase in the duration of each soil moisture droughts (**Figure 10B**) than its frequency. It can be explained that during the drought, organic carbon is not mobilized. However, subsequent re-wetting after a long and severe drought, DOC production rates are accelerated

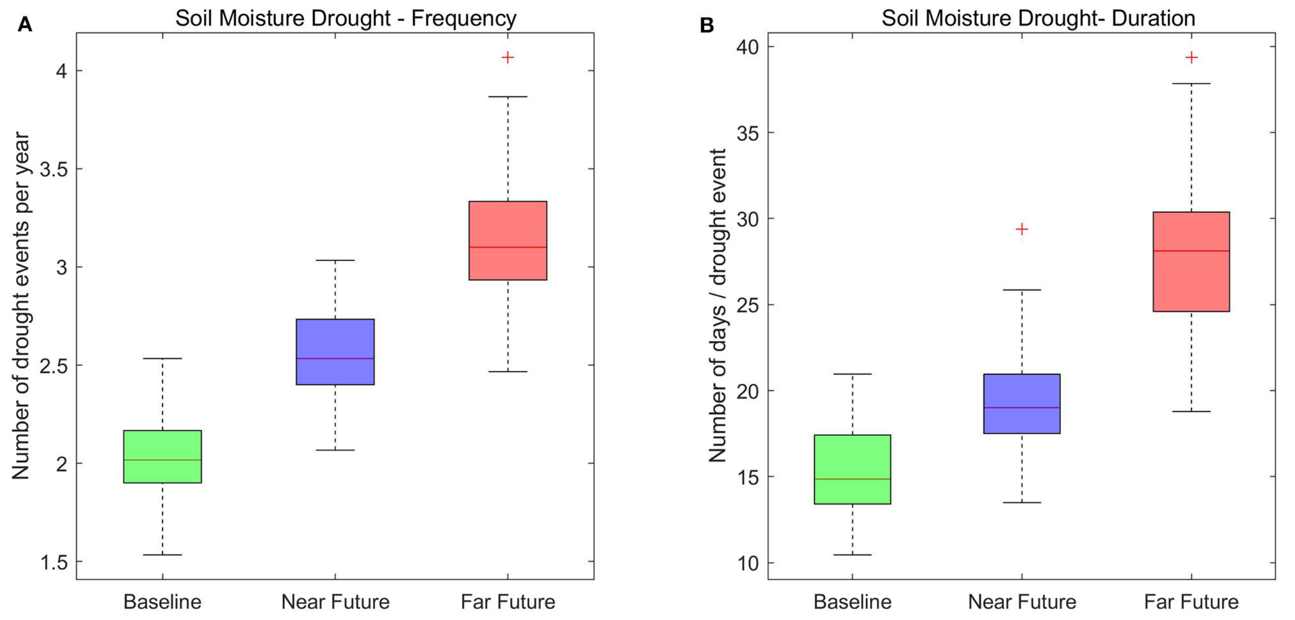

FIGURE 10 | Changes in frequency **(A)** and duration **(B)** of soil moisture droughts in Plynlimon.

from the peat. When the peatland soils become saturated and are mobilized, they flush DOC into the stream. Therefore post-drought surge of DOC concentrations become visible in autumn months (**Figure 9B**).

Maximum DOC concentrations show a substantial increase in the wet season, while a small increase in the summer months is projected at around 20% (**Figures 9C,D**). The projected sulfate deposition continues to decline until 2030 and remain constant after. The projected changes have inter-annual variability, but no intra-annual variability. Therefore, the sulfate decline could affect the stabilization of DOC concentrations in the far future period. However, the changes in seasonal variability of DOC concentrations are most likely driven by climatic changes and enzymatic latch processes during droughts. While this paper has only presented results for the Plynlimon in Wales, enzymatic latch simulations in peatlands can also be extended to understand the other peatlands catchments in the UK.

CONCLUSIONS

In this study, the impact of climate change and acidic deposition on flow and water quality was analyzed for an uplands catchment, Plynlimon in Wales, UK. This paper focused on the dynamics of droughts and sulfate deposition in peatlands by including those mechanisms in water quality modeling. Our study is the first to model enzymatic latch mechanisms in the UK catchments to explain a complex biochemical process in a multi-parameterised process-based model. The main findings are focused on assessing whether the rising trends of DOC concentrations would be continued or stabilized in the future. Taken across from our future climate, sulfate scenarios and the identified enzymatic latch parameters, the projected DOC concentrations in Plynlimon will continue to increase in the near future and then will be stabilized in the far future. However, in the far future, the seasonal patterns of DOC concentrations will change, with a post-drought DOC surge in autumn months.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article. Publicly available datasets were analyzed in this study and this data can be found here: Land use map 2007 (UK Centre for Ecology and Hydrology, https://www. ceh.ac.uk/services/land-cover-map-2007#obtain), meteorology data (Met Office, https://catalogue.ceda.ac.uk/uuid/dbd451271eb04662beade68da43546e1), flow data (UK National River Flow Archive, https://nrfa.ceh.ac.uk/), and water quality data (UK Centre for Ecology and Hydrology, https://catalogue.ceh.ac.uk/documents/0392bf93-62b2-49f7-8c85-10038f22f0c0). The weather@home2 climate simulations are also available online (The Centre for Environmental Data Repository, https://catalogue.ceda.ac.uk/uuid/0cea8d7aca57427fae92241348ae9b03).

AUTHOR CONTRIBUTIONS

All authors designed the research together. JL and MNF collected the data and set up the modeling. JL analysed the data. JL, PGW, MNF, and JWH wrote the paper.

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The Resilience of Inter-basin Transfers to Severe Droughts With Changing Spatial Characteristics

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Faced with the prospect of climate change and growing demands for water, water resources managers are increasingly examining the potential for inter-basin water transfers to alleviate water shortages. However, water transfers are vulnerable to large-scale spatially coherent droughts which may lead to water shortages in neighboring river basins at the same time. Under climate change, increasingly severe droughts are also expected to have greater spatial extent. We have integrated climate, hydrological and water resource modeling to explore the resilience of new transfer schemes between two neighboring water companies in Southern England. An extended historical record of river flows and large ensemble of future flows derived from climate simulations were used to explore the effects of spatial and temporal drought variability. The analysis examines meteorological, hydrological and water resource drought events and how the spatial characteristics of these droughts may change with different transfer arrangements. Results indicate that all drought types examined are expected to increase in frequency and intensity throughout the twenty-first century, but a new transfer has the capability to increase the resilience of water supplies. The analysis also highlights the importance of testing new water infrastructure against drought events that are more extreme and have different spatial patterns to those in historical records, demonstrating the value of scenario-based approaches to adaptive water resource planning.

Keywords: drought, water management, hydrology, water transfers, climate resilience

KEY POINTS

- Methodology to test resilience and performance of transfer infrastructure to meteorological and hydrological drought events in future climates.
- Without adaptation, probability of severe water restrictions on any given day is projected to increase by 266% in the receiving region by 2099.
- Some transfer infrastructure alleviates the impact of climate change, but this depends upon available storage in the receiving region.

INTRODUCTION

The changing climate and growth in water consumption poses new threats to water resource systems (Intergovernmental Panel on Climate Change, 2013), affecting the management of water resources (Ehsani et al., 2017) and increasing the risk of water shortages (Borgomeo et al., 2014). Notwithstanding large uncertainties in climate models, climate change is projected to alter the global hydrological cycle and transform the balance between evapotranspiration, runoff and precipitation (Liu et al., 2012). Precipitation trends and interannual variability have been shown to strongly control the water-balance (Ukkola and Prentice, 2013). Changes in precipitation patterns are therefore likely to impact the amount of water available for human use, with the potential to exacerbate droughts and associated water scarcity in water stressed areas throughout the twenty-first century (Connell-Buck et al., 2011). Previous studies suggest that drought frequency and severity are important for water supply (Marsh et al., 2007), but that historical droughts provide a poor basis for future planning because the historical record is restricted to a handful of drought events with specific spatial and temporal characteristics (Watts et al., 2015). Feedbacks between water management operations and drought are also considered important for maintaining reliable water supplies (He et al., 2017), with studies revealing that human activities influence the probability of extreme hydrological drought (van Loon et al., 2016), and manipulate the characteristics of drought along river networks (Tijdeman et al., 2018; van Oel et al., 2018; Wu et al., 2018). However, these studies are also limited to drought periods that exist in the historical record.

To ensure the resilience of water supply systems in an uncertain future, it is necessary to test the performance of water systems against a range of climatological, hydrological and socio-economic scenarios. This is particularly important for inter-basin water transfers, which rely on a reliable supply of water from one region to another. Inter-basin transfers are defined as the "transfer of water from one geographically distinct river catchment, or basin to another, or from one river reach to another" (Davies et al., 1992), and have been widely used in an attempt to artificially improve water security in water scarce areas. In 2008, ∼14% of global water withdrawals were transported via transfers; a statistic which is estimated to increase to 25% by 2025 (Gupta and van der Zaag, 2008). The design of water transfers can vary considerably depending on the needs of the importing and exporting regions, with the principal transfer types classified as permanent, short-term, temporary, reclaimed, water bank, or "wheeled" (Lund and Israel, 1995b). The focus of this study is on system capacity expansion through permanent inter-basin transfers, which are designed with the aim to (i) increase capability to meet demands, and (ii) improve long-term water system reliability.

Several efforts have been made to understand the value of inter-basin water management in alleviating water supply shortages during historical drought events. Cooperative transboundary management of water resources in the Blue Nile Basin has been shown to improve water security during drought events, but careful coordination is required to avoid harmful impacts to downstream water users (Wheeler et al., 2018). In the western US, transfers have played an important role in managing water resources, with short-term emergency water transfers providing rapid response to emergency conditions during the 1991 and 1992 Californian droughts (Lund and Israel, 1995b), and cost-effective spot-market water transfers contributing to California's pool of traditional water supplies (Lund and Israel, 1995a). At a continental scale, India's National River Linking Plan aims to resolve national water scarcity issues by creating an interconnected water grid that transfers water between 37 rivers (Purvis and Dinar, 2020). The ambitious plan has received mixed reviews, with concerns raised regarding the geomorphological response to infrastructural changes and forced displacement of local communities (Gupta and van der Zaag, 2008). As with other capacity expansion options, large scale transfers offer trade-offs between cost, revenue and reliability for the water managers (Zeff et al., 2014), with different inter-utility transfer agreement mechanisms offering risk reduction for both the water buyer and seller (Lund and Israel, 1995b; Caldwell and Characklis, 2013). Careful consideration of the impact of contractual transfer agreements on the environment is also key, with licensing agreements potentially benefiting consumers at the expense of increased risk to riverine habitats (O'Keeffe and De Moor, 1988; Wildlife Countryside Link, 2016; San-Martín et al., 2020).

Permanent inter-basin water transfers incur costs and benefits, the balance of which differs for the water exporter and the water importer (Gupta and van der Zaag, 2008). As indicated above, these can include large financial costs incurred from construction and operation of transfer infrastructure, adverse ecological impacts, sustainability issues, and uncertain economic efficiencies afflicting existing transfer schemes (Purvis and Dinar, 2020). Whilst they are designed to improve security of supply, there are inevitable limits to the reliability of water transfers as well as potentially negative impacts. For this reason, water planners must test proposed transfer infrastructure and operating policies against a wide range of water supply, demand and socio-economic scenarios that contain conditions beyond what has been observed within historical records.

When designing transfer schemes, it is imperative that water planners understand the spatial coherence and intensity of drought events in neighboring basins, ensuring that adaptation in one region does not lead to water shortages in another. This is important because transfers from a source location vulnerable to the same extreme drought events as the receiving location are more likely to fail than transfers between locations that have a low probability of coincident drought (Rahiz and New, 2012). For example, analysis of climatic-hydrological relationships in the headwaters of the Tagus River in central Spain revealed that over-use of the Tagus-Segura Water Transfer in periods containing severe climatic droughts resulted in declined natural flow and lower reservoir levels in the transfer source region (Lorenzo-Lacruz et al., 2010). Further mismanagement of the transfer during critical periods affected economic activities in the transfer source region (Hernández-Mora and Del Moral, 2015), altered the downstream river environment through reduced hydraulic connectivity, and fuelled socio-political conflicts between the donor and recipient basins (San-Martín et al., 2020).

Previous work has examined the reliability of small treated transfers in the eastern United States against (i) historical observations (Palmer and Characklis, 2009) and (ii) stochastic streamflow data created using historical records (Kirsch et al., 2013; Zeff et al., 2016). For the purpose of exploratory modeling, artificial streamflow time series with increased frequency and intensity of droughts have also been used, generated by modifying streamflow generators (Herman et al., 2016). This research incorporates some aspects of potential future climates into transfer reliability assessments, relying on extreme events in the historical record to "stress test" adaptation options. More recent work examined the influence of within-basin raw water transfer (RWT) schemes on reliability and financial objectives when simulated against the future hydrologic conditions, with analysis revealing that RWT can reduce requirements for demand management interventions and inter-basin treated transfers, and contribute to lower regional financial risk (Gorelick et al., 2018). However, the eastern US-based studies do not fully account for spatial characteristics of drought types that may help to explain the ways in which transfers can prevent (or aggravate) water resource droughts during periods of extreme climate conditions and increased demand pressures. As Gorelick et al. (2018) hypothesize, the utility of raw water transfers are likely to depend on many features of the transfer regions, including available water storage, infrastructure, demand growth rates, and spatial correlation of hydrologic events. Furthermore, the studies only investigate transfers that move small volumes (<100 Ml/d) of water, the conclusions of which may not be scalable to larger, inter-basin untreated water transfers. There is therefore considerable scope to investigate the operation of high-volume inter-basin transfers under future scenarios of change, and the impact these transfers have on water system performance in both exporting and importing regions.

The new large ensembles of climate model simulations used in this study, along with extended series of historical observations and demand growth scenarios, provide the opportunity to test the joint probability of coincident droughts more thoroughly than has hitherto been the case. We combine this with simulation modeling of the operation of water transfers, including a variety of strategies for how risks may be shared between neighboring water utilities. This study aims to (i) explore the resilience of new high-volume inter-basin water transfer infrastructure with different operating agreements to severe meteorological and hydrological drought events, and; (ii) evaluate the level of risk and reliability of a given version of transfer infrastructure during drought events and water demand pressures not present in the historical record. The novel methodology proposed here demonstrates the importance of using large climate ensembles containing a wide range of climatological extremes in long term water resource planning, providing a mechanism to explore the joint occurrence of different types of drought events and associated consequences on transfer operation, cooperation and reliability.

The following analysis focuses on new unidirectional transfer infrastructure in south east England, connecting two private water companies, Severn Trent Water and Thames Water, who together supply more than 18 million people a year (Severn Trent, 2019; Thames Water, 2019a).

STUDY AREA, DATA, AND MODELING FRAMEWORK

Study Area

This study investigates the spatial characteristics of meteorological, hydrological and water resource drought in Southern England (**Figure 1**). Meteorological and hydrological drought are calculated for the Severn to Deerhurst and Thames to Kingston catchments and are consistent with the basins used in the UKCP09 climate projections (UKCP09, 2009) and the Severn Thames Transfer Study area (Rudd et al., 2018).

Climate characteristics in southern England vary between regions, with a gradient of precipitation from west to east caused by prevailing westerly weather systems (Fleig et al., 2011). This is reflected in observations of average annual precipitation, which was 724 mm in the Thames catchment to Kingston and 793 mm in the Severn catchment to Deerhurst from 1961 to 1990 (NERC CEH Wallingford, 2018). Historical precipitation records reveal that meteorological droughts commonly occur in both the Severn and Thames basins, but the impact of droughts vary depending on the duration, severity and management of the event (Vidal and Wade, 2009). In south east England, drought events are attributed to southerly weather fronts bringing warm air from continental Europe (Fleig et al., 2011). Droughts in the west can be explained by severe rainfall deficiencies (Marsh, 2007; Marsh et al., 2007) and circulation anomalies in the North Atlantic Oscillation (Rahiz and New, 2012).

Several studies have explored the spatial and temporal patterns of projected twenty-first century meteorological droughts in the UK (Fowler et al., 2007; Vidal and Wade, 2009; Burke et al., 2010; Rahiz and New, 2013). Whilst estimations of future precipitation at regional scale are considerably uncertain (Hawkins and Sutton, 2011), general patterns of change can be inferred from ensembles of climate projections. For example, the UK Climate Projections 2009 (UKCP09; Murphy et al., 2009) ensemble estimate median decreases in summer precipitation in southern England of −40% (confidence interval of −65–6%). Likewise, results from the Weather@Home modeling experiment by Guillod et al. (2018) reveal large decreases in summer precipitation across the UK for time periods in the middle and end of the twenty-first century. Rahiz and New (2013) present an analysis of twenty-first century droughts in the UK using monthly precipitation projections from the perturbed-physics ensemble, HadRM3-PPE-UK, to estimate a drought severity index. Results show an ensemble-mean increase in drought intensity, drought covariance and frequency of drought months for the Severn and Thames regions in the second half of the twenty-first century. The findings support earlier work by Vidal and Wade (2009), Fowler et al. (2007), and Fowler and Kilsby (2004) who also report increased drought risk in south east England. Overall, future projections suggest that by the end of the century droughts could be more spatially coherent, with large meteorological droughts in south east England affecting multiple catchments and threatening both existing and proposed water supply infrastructure.

Analysis of historical flow records reveal few changes in the pattern of hydrological drought and low flows in the UK in the twentieth century (Hannaford and Buys, 2012; Watts et al.,

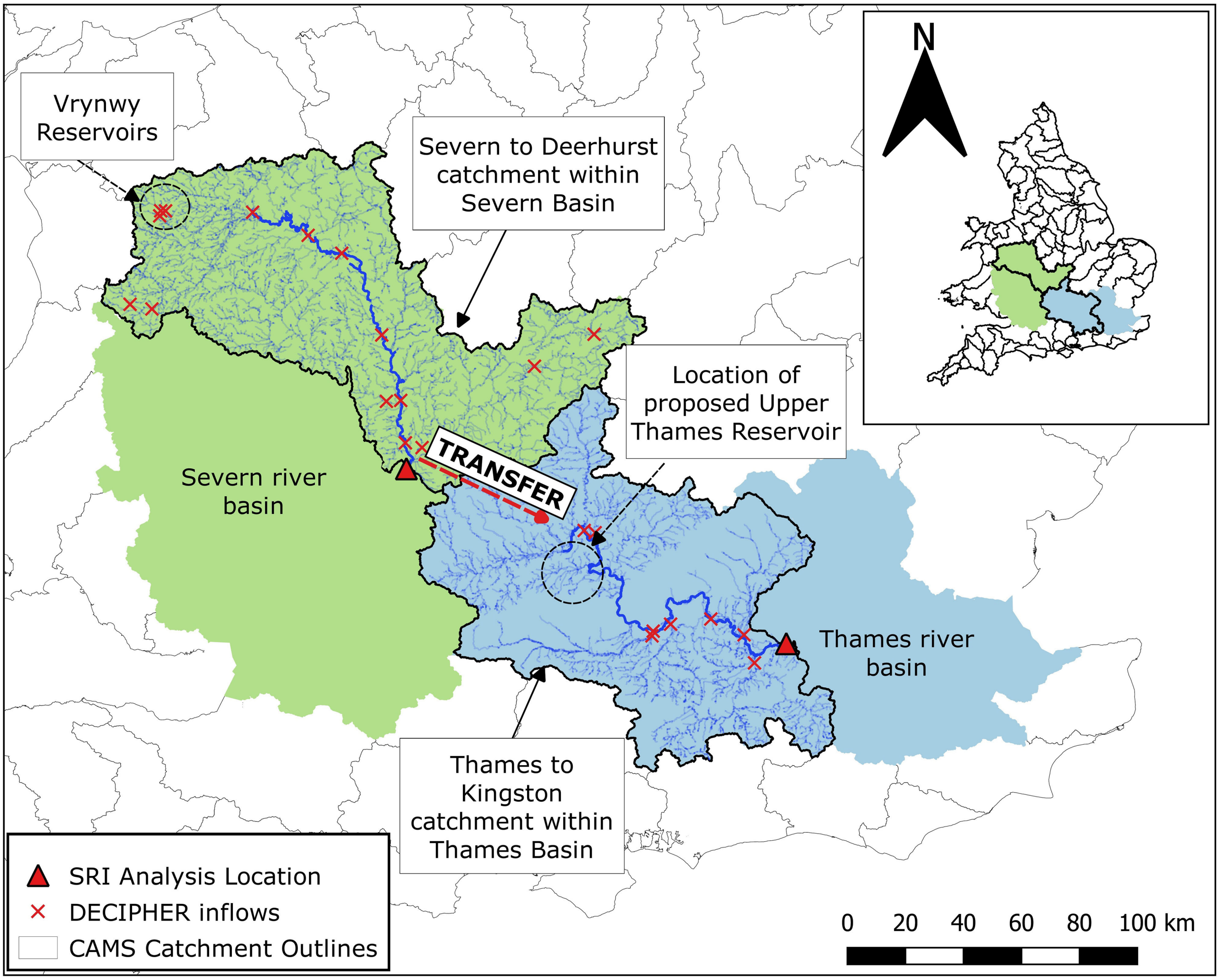


FIGURE 1 | Study area.

2015; Rudd et al., 2017). Streamflow records from the Severn and Thames basins document historic hydrological drought events, with 15 major droughts in the Thames at Kingston and 17 in the Severn at Deerhurst between 1963 and 2015 (Rudd et al., 2018). These droughts varied in duration, severity and intensity, and had wide ranging impacts on the water sector. The 2004–2006 drought, for instance, impacted water supplies to over 13 million water consumers in south east England. Regional spring failures, low river flows, decreased stream connectivity and depleted groundwater levels resulted in increased stress in riverine environments and widespread implementation of drought mitigation measures. In the period between November 2004 and August 2006, total river flow in the Thames Basin fell to 56% of the long term average, while flows in the Severn dipped to only 74% of the long term average (Marsh et al., 2007). With careful management, water transferred from the Severn (or other less stressed areas) may have helped to alleviate environmental and demand pressures in the Thames Basin during this period.

Multiple methods exist to investigate future changes to streamflow and hydrological drought. For example, Hannaford et al. (2011), developed a "drought from drought" forecasting methodology to identify streamflow droughts in Europe based on drought developing in neighboring regions. Other studies have looked into the effects of climate change on groundwater resources in southern England (Jackson et al., 2011), evaluated the use of perturbed physics ensemble of climate models on water resource planning in south west England (Lopez et al., 2009), explored uncertain changes in low flows in the River Thames using statistical downscaling techniques and hydrological modeling (Wilby and Harris, 2006), and conducted multi-model assessments of water resources in the Thames catchment (Manning et al., 2009). A significant study of future changes to hydrology in Great Britain was conducted by Prudhomme et al. (2013), who developed a set of 11 transient daily river flow projections from 1951 to 2098 for 282 river sites using the HadRM3-PPE ensemble and a single hydrological model. Results indicate that spring and summer flows may decrease by −40 to −80% for most of the UK by the 2050's, whilst in autumn river flow may experience up to −80% decreases in the south and east of the country. Changes to mean annual flow were projected to be greatest in the west, with a reduction of up to −40%. However, the baseline simulations showed large deviations from observations in the pre-2000 reference period, due to climate modeling uncertainty and difficulties in validating naturalized flows in highly regulated systems, particularly during periods of low flow (Prudhomme et al., 2013). Moreover, 11 flow series were not a sufficiently large sample to robustly characterize the spatial statistical properties of extreme droughts. The more recent study by Rudd et al. (2019) uses ensembles of twenty-first century emissions driven climate model data to investigate future changes in river flow and soil moisture droughts in catchments across Britain. Results from the threshold based approach indicate increased peak intensity, severity, duration and spatial extent of hydrological droughts in the south east by the end of the century, attributed to overall drying and increased potential evapotranspiration (Rudd et al., 2019).

Recent work has also projected increases in the frequency and intensity of coincident hydrological droughts—the likelihood of drought events occurring simultaneously in neighboring basins (Rahiz and New, 2012)—in the Severn and Thames, with the likelihood of droughts in the Thames affecting conditions in the Severn increasing into the future (Rudd et al., 2018). Correspondingly, the likelihood of non-coincident drought (when the Thames is in drought, but the Severn is not) is projected to decrease. The results emphasize the importance of evaluating future transfer infrastructure relying on water supply from the Severn to the Thames, as periods when the Thames is water stressed are more likely to coincide with periods when the Severn may not be able to spare water via the transfer scheme.

Management of water resources in the Severn and Thames Regions are overseen by the privately owned water companies, Severn Trent Water and Thames Water. Thames Water primarily supplies water from off-line raised reservoirs near population centers that are filled directly from the River Thames and from groundwater sources. Severn Trent's water supply is regulated by upstream on-line storage reservoirs. Operation of the reservoirs and river abstractions are regulated by operating agreements, as described in Section water resource drought analysis. The companies must report periodically to the economic and environmental regulators, OFWAT and the Environment Agency, respectively, submitting investment plans outlining how supply to water customers will be secured into the future. In 2013, Thames Water was classified as being under serious water stress due to climate change and increasing population pressures. In contrast, Severn Trent Water was only moderately stressed (Environment Agency and DEFRA, 2013). For this reason, a strategic water transfer option between the Severn and Thames basins is under review, with evaluations ongoing of its feasibility to provide reliable water supply for Thames Water customers and the wider south east region during periods of high water stress (Thames Water, 2019b).

Data and Models

This section provides an overview of the data and models used in this study. As parts of the data and modeling framework have been previously been applied elsewhere (Guillod et al., 2017, 2018; Coxon et al., 2019; Dobson et al., 2020), Sections historical precipitation to modeled flows provide abbreviated descriptions of the climatological and hydrological modeling framework. Sections water resource modeling, groundwater flows, and water demand and water transfer strategies describe the water system model and infrastructure strategies to be simulated using historical and projected scenarios.

Historical Precipitation

Historical precipitation time series used in this study were obtained from the Center for Ecology and Hydrology (CEH) GEAR 5 km resolution historical monthly areal rainfall dataset for the United Kingdom (1890–2017) (Tanguy et al., 2019). Grid points for analysis were selected if they fell within the Thames to Kingston and Severn to Deerhurst catchment boundaries (**Figure 1**). Total precipitation for each month in the 127-years period was calculated by adding the precipitation at each grid point within the two catchment boundaries. This resulted in two aggregated catchment time series of monthly precipitation.

Modeled Precipitation

A large set of weather sequences from the Weather@Home (W@H) platform are used in this study (Massey et al., 2015; Guillod et al., 2017, 2018), which are generated using a Global Circulation Model (HadAM3P) downscaled with the Met Office Regional Climate Model, HadRM3p, and driven with historic (HasISST) and projected (CMIP5) sea surface temperatures (SST) and sea ice. W@H is a "citizen science" project that benefits from the unused computing power of thousands of participants to generate large ensembles of climate model runs. HadAM3P is suited to the W@H platform, representing atmospheric dynamics in the mid-latitudes well-compared to other GCMs (Mitchell et al., 2017). HadRM3p is also appropriate for the current application, having reproduced accurate distributions of daily mean temperature and precipitation over Europe (Massey et al., 2015). In recent years the Weather@Home modeling platform has been used to study the impact sea surface temperature driven extreme weather events in England (Haustein et al., 2016), heat related mortality in London and Paris (Mitchell et al., 2016), flood damage in southern England (Schaller et al., 2016), and national scale drought severity and intensity (Rudd et al., 2019; Dobson et al., 2020). The Weather@Home climate sequences have also been used successfully in a risk-based planning framework in the Thames Basin, reproducing historical weather observations well (Borgomeo et al., 2018).

The Weather@Home dataset contains precipitation (P) and evapotranspiration (PET) time series at a 25 km resolution, which is then downscaled to 5 km resolution. Precipitation sequences are bias corrected using a linear approach with monthly bias correction factors. The small biases in temperature were not corrected. A complete description of the bias-correction methodology, validation process and resulting data is presented in Guillod et al. (2017, 2018). In summary, the bias correction offers correction for seasonal biases in mean precipitation, but does not affect higher-order moments of the rainfall distribution (Guillod et al., 2018).

This study uses modeled P and PET for the Severn and Thames catchments from the Weather@Home dataset, grouped into three ensembles:

- 100 realizations of the Baseline period (1975–2000), generated using different initial atmospheric conditions, and historic SST and sea ice records from HasISST (Rayner et al., 2003; Titchner and Rayner, 2014);
- 100 realizations of the Near Future period (2020–2049), generated using 50th percentile SST and sea ice projections [CMIP5, (Taylor et al., 2012)] under Representative Concentration Pathway (RCP) 8.5 (Meinshausen et al., 2011);
- 100 realizations of the Far Future period (2070–2099), generated using 50th percentile SST and sea ice projections under RCP8.5.

As with the historical precipitation time series, total precipitation for each catchment is calculated by summing individual precipitation at grid points within the catchment boundaries. The future ensembles are used here to examine the impact of climate change on meteorological, hydrological and water resources drought. Because RCP8.5 represents the upper bound of projected global emissions scenarios, it is appropriate for climate impact assessments focussing on extreme conditions.

Modeled Flows

Rainfall-runoff modeling was performed using the DECIPHeR (Dynamic fluxEs and ConnectIvity for Predictions of HydRology) model, developed by Coxon et al. (2019). DECIPHeR is a hydrological modeling framework developed to simulate and predict flows for catchments across multiple spatial scales with different hydrological characteristics. The hydrological model consists of sub-catchment-based hydrological response units (HRUs) which group hydrologically similar areas according to landscape attributes and spatial variability of climatic inputs. HRUs reduce model run time (see **Appendix 1** in **Supplementary Information**), thus allowing for extensive simulations driven by large ensembles of climate conditions.

The DECIPHeR modeling framework was first used by Coxon et al. (2019) to simulate historic flows at 1,366 catchments across Great Britain, performing acceptably against four metrics of model performance. To calibrate the model, historic daily observed P (Tanguy et al., 2019) and PET (Robinson et al., 2016) were used to run 10,000 model simulations with Monte Carlo sampled parameter sets. Evaluation of the 10,000 simulations showed good model performance across the 1,366 flow locations, with 92% of catchments achieving a Nash-Sutcliffe efficiency score > zero (Coxon et al., 2019).

DECIPHeR has since been used to generate ensembles of historical and future naturalized flows for 338 catchments across England and Wales (Dobson et al., 2020). The flows were generated using historic daily observed P (Tanguy et al., 2019), PET (Robinson et al., 2016), and the 10,000 parameter sets from Coxon et al. (2019), and were evaluated against daily naturalized flows supplied by England's Environment Agency. The best parameter sets for each catchment were identified according to NSE and logNSE scores, and used to simulate daily flows for the 338 catchments under historic and future climate change projections. This study follows the same hydrological modeling framework outlined by Dobson et al. (2020), using the best DECIPHeR parameter set for the Thames and Severn basins to simulate historic and future flows. Daily historic flows were simulated using CEH GEAR daily observed P (Tanguy et al., 2019) and PET (Robinson et al., 2016), whilst daily flows for the Baseline (1975–2000), Near future (2020–2049) and Far Future scenarios were simulated using the Weather@Home projections described in Section modeled precipitation. **Appendix 1** lists the NSE and logNSE of the calibrated historic DECIPHeR flows for the Thames at Teddington (station 39001) and Severn at Saxons Lode (station 54032; Severn at Deerhurst was not included in the model evaluation).

Water Resource Modeling, Groundwater Flows, and Water Demand

The water system model used in this study of the Severn Trent and Thames Water supply systems has been extracted and adapted from the national water resource model, WREW, presented in Dobson et al. (2020). The Severn Trent Water and Thames Water water resource systems are represented by a series of nodes and arcs in the minimum cost capacitated network flow program model, WATHNET-5 (Kuczera, 1992). The arcs represent flow pathways (rivers and pipes) that connect stream, reservoir, groundwater, demand, and waste nodes. In simulation, the model solves a mass balance optimization problem at each time-step, moving water along arcs within the network to minimize demand shortfalls. Each arc is assigned a positive, neutral (zero) or negative cost, which influences the likelihood of flow through an arc. For example, if one water source is more preferable than another it will be assigned a negative cost. Environmental flow arcs are assigned a negative cost to increase the likelihood of a minimum required flow (MRF) being met. Demand shortfall arcs are assigned a very high positive cost, as an incentive for the network flow program to ensure demand is satisfied. In some scenarios a trade-off between demand shortfalls and MRF may emerge. The assumptions made regarding arc cost influence the movement of water throughout the system network. The sensitivity to changes in arc cost assignments are not explored in this study; a notable limitation of the modeling experiment. However, the water system model is a product of collaboration between the University of Oxford and key stakeholders in the UK water industry. Previous work has shown that the model is capable of producing outputs similar to those achieved using water company models (Dobson et al., 2020). It is therefore well-suited to climate impact studies such as the one presented in this paper.

The river flows generated by DECIPHeR are used as stream inflows, represented by the crosses in **Figure 1**. Groundwater inflows are set at the license abstraction limit, defined by the Environment Agency (Environment Agency, 2013). The reservoirs can directly store stream inflows or by pumped abstractions from rivers, depending on the nature of the infrastructure. The demand nodes act as sinks in the network and represent the demand required from municipal, industrial and agricultural water users. Between 1999 and 2014, agriculture used 3.8% of total surface water abstractions in the Thames, and 2.0% in the Severn. In the same period, public water supply accounted for 88.0% of abstractions in the Thames, and 68.0% in the Severn. The remaining water was used by industry or other abstractors (Environment Agency, 2013). Historical demand is estimated using dry year annual average distribution input at water resource zone level and annual demand profiles, and paired with the historic CEH GEAR-DECIPHeR flow scenario. Ten scenarios of future municipal water demand for each water company are estimated from the dry year annual average distribution input at water resource zone level and scaled according to Severn Trent and Thames Water water resource planning tables and demand profiles (Severn Trent, 2019; Thames Water, 2019a). Differences in projected demand scenarios typically result from (i) different rates of population growth and (ii) changes in per capita consumption (Beh et al., 2014). The range of projected demand is presented in **Appendix 2**. Each future demand scenario is coupled with the 100 Baseline, Near Future and Far Future DECIPHeR flow scenarios, to create a library of 3,000 scenarios (total of 85,000 simulation years). WATHNET-5 is used to simulate the water resource system at a daily time-step under different climate and demand scenarios. Simulation output can include demand deficits, end of step reservoir storage and frequency of water restrictions imposed on customers.

Water Transfer Strategies

The main infrastructure option to be evaluated is the proposed raw water transfer from Deerhurst on the River Severn to a location in the Upper Thames catchment. Five transfer capacities are evaluated. The first four tested [300, 500, 700, and 900 mega liters per day (Ml/d)] are limited by the infrastructure capacity to move the water (i.e., the size of the pipe). The 300 and 500 Ml/d transfers are based on the Water Resource Management Plan 2019 (WRMP19) planning options (Thames Water, 2019a), with the larger 500 Ml/d capacity transfer being supported by redeployment of 200 Ml/d of water from the Vyrnwy Reservoir in the Severn headwaters. The 700 and 900 Ml/d transfers are evaluated to assess the impact of larger capacity transfers during future drought scenarios, though these larger transfers are not currently being considered by Thames Water or Severn Trent Water due to environmental challenges. Transfer capacities of this size are uncommon, although not unheard of in water resource planning assessments. For example, following the 2004–2006 drought an investigation was launched into large-scale water transfers in the UK, assessing the feasibility of a multi-pipe 1,100 Ml/d transfer from the northern Pennines (north west England) to London. Findings indicated that the financial cost of large-scale transfers would greatly exceed costs of regional capacity expansion options, but transfers of this scale may be necessary if water companies' existing resource management plans prove inadequate in the face of future water supply and demand pressures (Environment Agency, 2006). For context, 900 Ml equates to (i) ∼0.3% of the combined volume of reservoirs in the Severn water supply system, and 0.41% of the combined reservoirs in Thames Water, and (ii) ∼71% of historical daily demand in Severn Trent and 35% in Thames Water (estimated from simulation of the water system model from 1962 to 2015 using historic CEH GEAR climate sequences).

The final transfer option assumes unlimited capacity, so all flows above the 1,800 Ml/d MRF (Environment Agency, 2014) in the Severn at Deerhurst can be transferred to the Thames Basin. This option is included in the analysis (i) to identify the volumes of water that would be taken for use in the Thames Water system if no infrastructural, financial or environmental constraints existed, and (ii) to explore the impact this would have on hydrology and customer service in the Severn. Importantly, the strategy is purposefully experimental in design and bears no resemblance to real world transfers. The operation is coded to minimize the frequency with which the flows at Deerhurst fall below the MRF, and as a consequence may result in some days when flow fails to meet the MRF.

We also test strategies in which there is a new reservoir situated in the Upper Thames Basin, to explore the value of additional storage in the Thames Water system working in tandem with the transfer scheme. This reservoir (South East Strategic Reservoir) is also being considered by Thames Water as a feasible planning option to manage future climate change and demand side pressures (Thames Water, 2019a). The new reservoir has an initial storage of 75,000 Ml and the operating rules governing inflow into the reservoir and releases from the reservoir are based on rules used for the London reservoirs.

Three transfer operating rules are investigated. The first rule (unconditional) allows Thames Water to use the volume of water equivalent to total capacity of the transfer as frequently as is needed, limited only by water availability in the Severn basin. This rule ignores the consequences of taking water that could otherwise be used by Severn Trent Water and is consistent with Lund and Israel's definition of a permanent transfer, which "involves the acquisition of water rights and a change in ownership of the right" (Lund and Israel, 1995b). The second rule (conditional) only allows transfer of water left over in the Severn at Deerhurst, after all of the water requirements in Severn Trent have been satisfied. This rule is aligned with common riparian water rights, as Severn Trent does not need guarantee water availability for Thames Water, but should ensure that the flow and quality of transferred water remains acceptable (regardless of volume or timing). Rule two is designed to ensure that Severn Trent Water customers are not subject to decreased water supply in order to provide for Thames Water. The third rule (shared risk) follows the same principles of rule one, but also assumes that whenever Thames Water experience a severe water restriction, Severn Trent must impose an equivalent water restriction. This is to encourage full cooperation (i.e., maximum transfer deployment) between the two companies during periods of high drought risk in the Thames. Rule three does not follow traditional riparian rights doctrine and, like the unlimited transfer strategy, is experimentally designed to investigate the impact of this management style on water system performance under drought.

The transfer strategies are outlined in **Table 1**. In the water system model, the transfer arc connecting the Severn and Thames

TABLE 1 | Transfer strategies to simulate under flow and demand scenarios.

Strategy code	Transfer capacity (Ml/d)	Upper Thames reservoir	Operation	Feasible WRMP19 option?
0	0	✗	-	-
300.U	300	✗	Unconditional	Yes
500.U	500	✗	Unconditional	Yes
500.R.U	500	✓	Unconditional	Yes
300.R.U	300	✓	Unconditional	Yes
300.C	300	✗	Conditional	Yes
500.C	500	✗	Conditional	Yes
500.R.C	500	✓	Conditional	Yes
300.R.C	300	✓	Conditional	Yes
300.S	300	✗	Shared Risk	Yes
500.S	500	✗	Shared Risk	Yes
500.R.S	500	✓	Shared Risk	Yes
300.R.S	300	✓	Shared Risk	Yes
700.R.U	700	✓	Unconditional	No
700.R.C	700	✓	Conditional	No
700.R.S	700	✓	Shared Risk	No
700.U	700	✗	Unconditional	No
700.C	700	✗	Conditional	No
700.S	700	✗	Shared Risk	No
900.R.U	900	✓	Unconditional	No
900.R.C	900	✓	Conditional	No
900.R.S	900	✓	Shared Risk	No
900.U	900	✗	Unconditional	No
900.C	900	✗	Conditional	No
900.S	900	✗	Shared Risk	No
Unlim.R.U	Unlimited	✓	Unconditional	No

Feasible WRMP19 Option denotes options which were considered feasible in Thames Water's 2019 Water Resource Management Plan.

water resource systems is assigned a positive cost to ensure that water is only transferred when it is beneficial for the receiving region.

METHODOLOGY

Overview of Workflow

Figure 2 provides an overview of the workflow used in this study. The framework uses a large ensemble of climate scenarios containing a wide array of drought events and multiple demand scenarios. The workflow provides a mechanism to explore drought impacts on transfer reliability, water supply and water use restrictions. The methodology is also designed to investigate how spatial patterns of drought may change throughout the twenty-first century, and how this may impact cooperation between water companies operating in neighboring basins.

Meteorological Drought Analysis

Standardized Precipitation Index (SPI) is used to classify meteorological drought within the two study catchments. The index identifies the relative departures of precipitation from normality for a given location, and has been widely used to identify drought events (Hannaford et al., 2011; Bayissa et al., 2018) and analyse the spatial patterns of drought (Vicente-Serrano, 2006; Fleig et al., 2011). The index is calculated following the sequence outlined by McKee et al. (1993), using a monthly precipitation time series (**Appendix 3**). Calculated SPI values are scale-independent, fluctuating between negative (dry periods) and positive (wet periods) values. This makes SPI ideal for spatial analyses of drought in across multiple locations.

SPI is commonly used as an indicator of drought intensity over a specific time period. Here, intensity is represented by the degree of precipitation deficit (i.e., the value when the index is below zero). The values can be classified to represent different categories of meteorological drought, as shown in **Table 2**. For short time-scales (1–6 months) the index is expected to fluctuate at a high frequency and is suitable for identifying soil moisture deficits and agricultural droughts. SPI fluctuates at a lower frequency for longer time-scales and is more indicative of changes to surface water resources (Edwards and Mckee, 1997). In the context of the framework presented here, we are interested in choosing an index time-scale that reflects the state of water resource supplies in the study area(s). This study therefore uses 12-months observation periods to classify meteorological drought. As Dobson et al. (2020) demonstrate in their spatial analyses of drought and water scarcity, a 12-months observation period is well-suited to identifying meteorological and hydrological droughts that impact

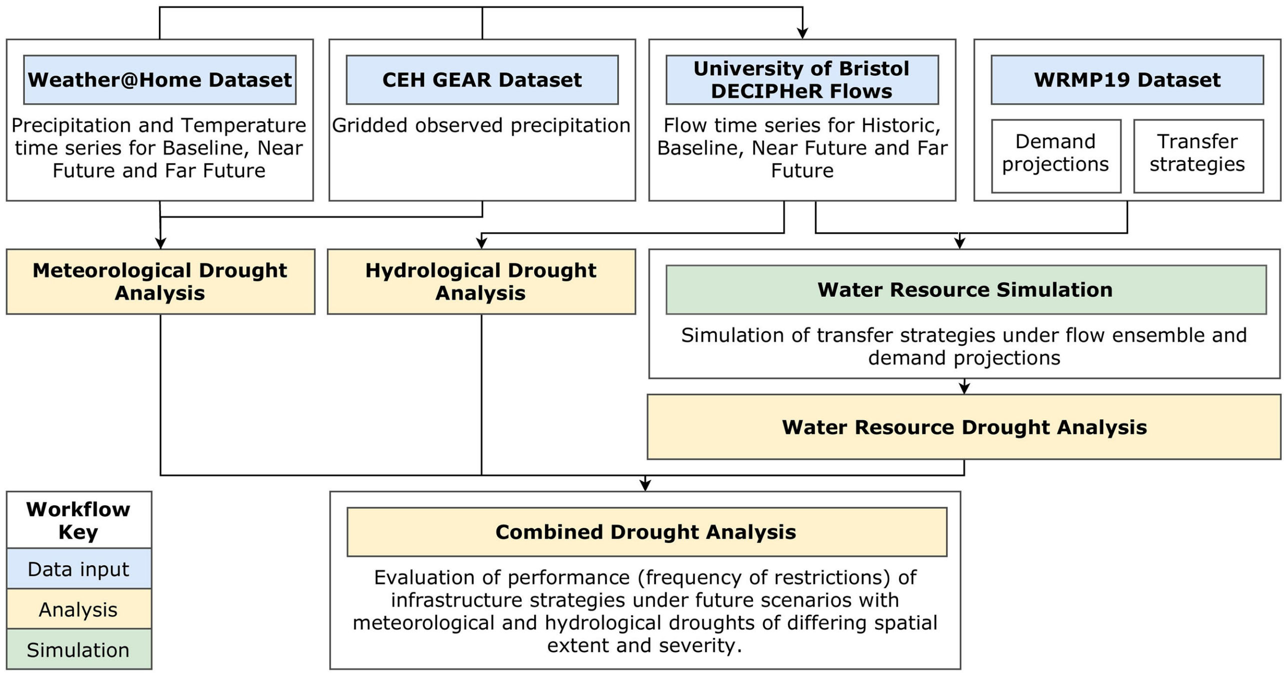


FIGURE 2 | Workflow with data sources, scenarios, and model outputs.

TABLE 2 | Drought categories as defined by SPI value (McKee et al., 1993).

SPI value	Drought category
≤-2	Extreme
−1.99 < 1.5	Severe
−1.49 to −1.00	Moderate
−0.99 to 0	Near normal or mild

water resource supplies in England and Wales (Dobson et al., 2020). In addition to this, 12-months lags are commonly used in drought analyses by water industry practitioners (e.g., Hunt and Wade, 2016). However, the proposed framework lends itself to additional investigation into the relationship between water system state and drought indices of a shorter period. For instance, shorter time-scales may be more relevant for regions without significant water supply storage infrastructure, as short-term rainfall will be more relevant for the planning issues faced by water managers.

To calculate SPI, aggregated monthly precipitation series from the historic CEH GEAR and W@H data sets are first formatted for the two catchments. The GEAR dataset is used to define Gamma parameter estimates for averaging periods in both catchments, which are then used to calculate the cumulative distribution of the precipitation datasets and subsequently standardized precipitation indexes. The resulting dataset contains catchment specific SPI time series for the historic record and the W@H ensemble (total of 301 time series per catchment).

The method outlined by Rahiz and New (2012) is used here to examine the coincidence of major droughts in the Severn and Thames. This approach identifies scenarios within the ensemble containing meteorological droughts occurring simultaneously in both catchments that are equal to or worse than the 5, 10, and 25th percentile drought intensities in the Baseline ensemble. The library of coincident drought events is analyzed to provide an estimate of the probability of coincident drought for the Baseline, Near Future and Far Future ensembles and indicate how the spatial patterns of meteorological drought with different intensities may change into the future.

Hydrological Drought Analysis

Twelve-months Standardized Runoff-discharge Index (SRI) is used to identify hydrological drought events in the historical and future DECIPHeR flow ensembles. The process to calculate SRI is akin to the SPI calculation using a distribution to fit observed or modeled flow data. Research has shown that parameter distributions should well-represent seasonal streamflow regimes and extreme flows (Vicente-Serrano et al., 2012). This is especially important for studies using short-term drought indices (1-, 3-, and 6- months), which are more susceptible to seasonal changes. As this study examines 12-months lag SRI, it is not necessary to vary the distribution intra-annually to take into account seasonality.

In line with the process described in Section meteorological drought analysis, we use a Gamma distribution to calculate SRI. Previous research has used a Gamma distribution to define streamflow in the Feather River Basin in California (Shukla and Wood, 2008), and for multiple catchments across England and

Wales (Dobson et al., 2020). Here, SRI is calculated at a 12-months lag for the Severn at Deerhurst (NRFA station 54110) and the Thames at Kingston (NRFA station 39001), which are the most downstream locations in each basin that can be represented in the DECIPHeR model. To obtain flows for the Severn at Deerhurst we aggregate data from two inflow points upstream of Deerhurst (Severn Bewdley incremental and Avon Incremental); for the Thames at Kingston we use the data from the Teddington Weir inflow point. A one-sample Kolmogorov-Smirnov (KS) test is used to ensure that a Gamma distribution is suitable to define streamflow and precipitation in the two study regions. The KS test evaluates the hypothesis that the calculated historic SRI and SPI time series come from a standard normal distribution (**Appendix 3**).

We use the historic CEH GEAR driven DECIPHeR flows (1962–2015) to define the Gamma parameter estimates used in the SRI calculation. This is because the recorded observed flow at Deerhurst gauging station contains only 17 years of flow (1995–2012) and has two extended periods of missing data in 2007 and 2011 (NERC CEH Wallingford, 2018). The resulting dataset contains catchment specific SRI time series for the historic record and the W@H ensemble (total of 301 time series per catchment).

Water Resource Drought Analysis

When reservoir levels are low, water companies can impose restrictions on water use as part of their drought plans. The frequency of water use restrictions of given levels of severity imposed upon customers is used as a metric of water shortages in the Severn Trent and Thames Water regions (**Table 3**). Level 1 and 2 restrictions are fairly modest and do not represent a significant hardship or economic loss to most water users, but Level 3 restrictions are more severe and Level 4 restrictions are considered to be extreme. Restrictions are imposed based on the current storage of key reservoirs within the water system (**Figure 3**) In Severn Trent Water, restriction level is determined by water levels of the Elan Valley and Derwent Water reservoirs; in Thames Water it is dependent on the combined water levels of the London Storage reservoirs. To avoid imposing unnecessary restrictions to their customers, Severn Trent Water can draw water from other reservoirs in the Severn system (Blithfield, Draycote, Clywedog, Carsington and Ogston, Melbourne, Cropston, and Thornton) before the Elan and Derwent reservoirs are allowed to fall below the thresholds for water restrictions. This is in contrast to the Thames system, which contains no other regulating reservoirs (Thames Water's Oxfordshire reservoir, Farmoor, cannot be used to alleviate water restrictions in London). We use the WATHNET-5 model to calculate the frequency of water restrictions being imposed in the two regions. The simulation results are then used to identify transfer strategies that reduce the probability of restrictions.

Coincident water resource drought is calculated using a similar methodology as hydrological and meteorological coincident drought, identifying periods within the simulation when Severn Trent and Thames Water are exposed to water restrictions in the same month. Simulation will reveal how the occurrence of coincident water resource drought change with different transfer strategies through time.

RESULTS

Meteorological Drought

Table 4 depicts the probability of drought months in the CEH GEAR and W@H ensembles with an SPI value equal to or worse than the 5, 10, and 25th percentiles in the W@H Baseline ensemble for each catchment. Here, values below the 5th percentile represent severe and extreme droughts, below the 10th percentile represent moderate drought (or worse), and below the 25th percentile represent mild drought (or worse). For the Severn to Deerhurst this includes drought months with an intensity equal to or <-1.84,−1.42, and−0.74, respectively, and in the Thames to Kingston months ≤-1.57,−1.18, and−0.56, respectively. The results indicate that the number of months with SPI values worse than the Baseline ensemble will increase into the future for both catchments, more so for the Severn to Deerhurst than the Thames to Kingston. The results also suggest that the W@H Baseline ensemble contains fewer mild, moderate and severe meteorological drought events in the Severn than the CEH GEAR dataset (historic), but more in the Thames catchment.

Table 4 also lists the probability of months in the W@H ensembles with an SPI value less than the W@H Baseline 5, 10, and 25th percentiles in both catchments in the same month. Coincident drought occurrence also increases into the future, with over 1 in 10 months in the Far Future ensemble experiencing a severe drought simultaneously in the Thames and Severn catchments. The frequency of mild droughts also increases into the future, with roughly 40% of all months in the Far Future ensemble experiencing SPI values worse than the historic 25th percentile. This means that 2 in 5 months experienced SPI values <-0.74 in the Severn to Deerhurst catchment and−0.56 in the Thames to Kingston catchment simultaneously. **Figures 4A,C,E** show that the changing spatial dependence of meteorological droughts across both basins is the main driver for increased drought frequency. The area under the curve gives the probability of any given month in each W@H ensemble experiencing a severe (4a), moderate (4c), or mild (4e) meteorological drought in only one or both catchments. The area is divided into three segments: the top segment (light green) represents the probability of any given month in each ensemble experiencing a drought of given severity in the Severn, but not in the Thames catchment; the middle segment (blue) represents the probability of any given month in each ensemble experiencing a drought of given severity in the Thames, but not in the Severn catchment; the bottom segment (orange) shows the probability of a coincident drought of the same severity occurring. The complete set of results from the non-coincidental meteorological drought analysis is presented in **Appendix 4**. The plots show that, for all drought severities, the increase in drought occurrence is caused by a large growth in the probability of coincident droughts. This suggests that meteorological droughts will become more spatially coherent throughout the twenty-first century.

Hydrological Drought

Twelve-months SRI time series were calculated using DECIPHeR flows for the Thames at Kingston and Severn at Deerhurst. The SRI values generated with the CEH GEAR DECIPHeR flow time

TABLE 3 | Example of levels of water use restrictions to customers in Thames Water and Severn Trent Water (Severn Trent, 2019; Thames Water, 2019a).

Severity of restriction	Measures for domestic customers	Expected frequency of occurrence in Thames	Expected frequency of occurrence in Severn
Level 1	Intensive water saving media campaign	1 in 5 years	N/A
Level 2	Partial hosepipe ban and media campaign	1 in 10 years	N/A
Level 3	Temporary use ban and non-essential use ban	1 in 20 years	3 in 100 years
Level 4	Extreme restrictions (standpipes, rota cuts)	1 in 100 years	No planned frequency

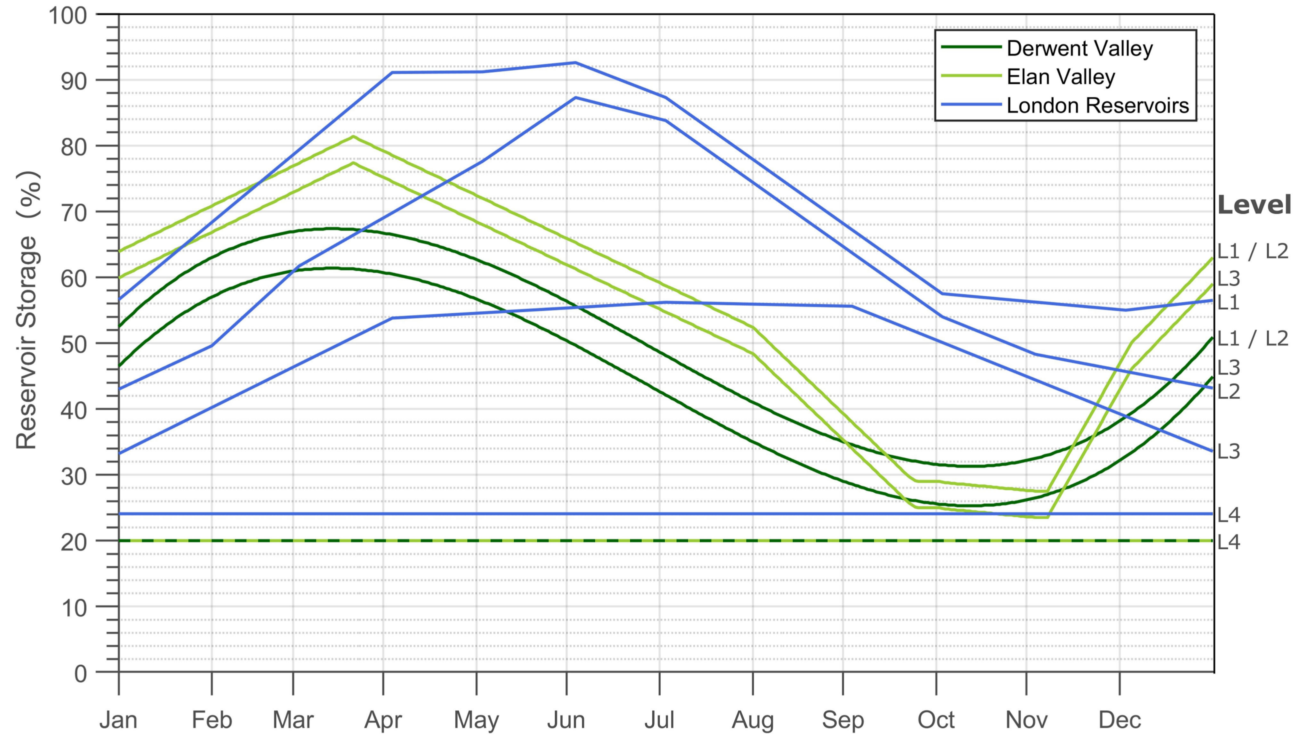


FIGURE 3 | Control diagram for Derwent Valley, Elan Valley, and London Reservoirs showing reservoir levels resulting in water restrictions to public water customers.

series are compared to the W@H ensemble driven DECIPHeR flows. **Table 5** shows the probability of hydrological drought months in the flow ensembles with an intensity equal to or worse than the 5, 10, and 25th percentiles in the Baseline flows. In both catchments 12-months SRI values increase at a similar degree as 12-months SPI, which suggests that projected changes in precipitation and streamflow are closely related. However, unlike SPI, all severities of SRI drought events in the CEH GEAR time series (historic) are less probable than the W@H Baseline, a likely consequence of parameterisation in the hydrological modeling. Future work could explore the sensitivity of hydrological drought severity and frequency to parameter set choice.

The similar values of coincident drought listed in **Table 5** for the historical and Baseline ensemble indicate that the DECIPHeR flows reproduce both independent and cross catchment features of the two regions well. Consistent with the SPI analysis presented in Section meteorological drought, these results suggest an increase in severe coincident hydrological drought throughout the twenty-first century, with coincident drought in the Near Future ensemble occurring more than double the frequency than coincident drought in the Baseline ensemble, and over four times more often in the Far Future. Moreover, mild coincident hydrological drought (25th percentile) occurs nearly once every 3 months in the Near Future ensemble and every 2 in 5 months in the Far Future ensemble. This will likely have a drastic impact on water supply and service to customers.

Figures 4B,D,F support the hypothesis that an increased spatial coherence of hydrological droughts is the main driver for the increase in drought frequency throughout the twenty-first century. The complete set of results from non-coincident hydrological drought analysis is presented in **Appendix 5**. The plots show that for all drought severities the increase in probability of hydrological droughts is caused by a large rise in coincident droughts. The results suggest that the likelihood of droughts occurring in one basin but not the other will remain fairly constant throughout the twenty-first century, whilst

TABLE 4 | Probability of months in historic (CEH GEAR), Baseline, Near Future, and Far Future ensembles with 12-months SPI values <W@H Baseline 5, 10, and 25th percentiles for Thames and Severn study areas, individually and simultaneously.

Percentile	Basin	Historic	Baseline	Near Future	Far Future
Severe (5th)	Severn	0.037	0.050	0.088	0.168
	Thames	0.058	0.050	0.081	0.161
	Severn and Thames Simultaneously	0.027	0.030	0.056	0.114
Moderate (10th)	Severn	0.083	0.100	0.159	0.273
	Thames	0.119	0.100	0.151	0.263
	Severn and Thames Simultaneously	0.061	0.066	0.110	0.200
Mild (25th)	Severn	0.226	0.250	0.343	0.497
	Thames	0.274	0.250	0.322	0.477
	Severn and Thames Simultaneously	0.192	0.184	0.261	0.402

droughts affecting both catchments simultaneously will become more common. Again, this will impact the operation and success of inter-basin transfers reliant on movement of water during high stress periods.

Water Resource Drought

The 26 transfer strategies were simulated in WATHNET-5 at a daily time-step against the library of DECIPHeR flows and demand scenarios. The level of water restrictions in Severn Trent Water and Thames Water is recorded at the end of each time-step and results are aggregated to a monthly time-scale in post-processing.

Figure 5 shows the probability of a month with water restrictions (any level and severe), for both companies and for the different transfer strategies. A complete set of restriction analysis results and visualization of transfer strategy impact can be found in **Appendix 6**. In the absence of any interventions by Thames Water, the probability of water restrictions increases considerably from the Historic and Baseline scenarios to the Near Future and Far Future scenarios, unlike in Severn Trent where the increase in the frequency of restrictions is projected to be less.

The introduction of transfer infrastructure has varying effects on the frequency of restrictions. Strategies operated with the conditional and unconditional rules show little impact to restriction frequency in Severn Trent, which suggests that the loss of water in the Severn water system to Thames Water is not large enough to impact the overall reliability of water supplies. Surprisingly, even the largest capped capacity transfer (900 Ml/d) fails to influence the frequency of water shortages in the Severn water system. This is likely due to the large headwater reservoirs in the Upper Severn catchment, which can release flows to balance demand further downstream. The greatest variation in impact to Severn Trent under the conditional and unconditional rules is observed in the Far Future ensemble, although this is on the magnitude of 0.0001 probability. In contrast, transfer infrastructure significantly benefits the reliability of water supplies in Thames Water, with improvements in all strategies compared to no transfer. The strategies that produce the greatest decreases in probability of restrictions are a product of greater connectivity of supply between the two river basins and increased capacity to store the transferred water in the new Upper Thames reservoir. Strategy 300.C is the least successful strategy for Thames Water, producing similar probabilities of restrictions to Strategy 0. This suggests that the small capacity of water available to Thames Water via the conditional transfer is ineffective during high drought risk periods.

Because the “shared risk” (e.g., 300.S) strategies impose restrictions on Severn Trent when restrictions are required in the Thames, these strategies increase probability of restrictions 4-fold for Severn Trent. The frequency of these restrictions is sensitive to the size of the transfer simply because larger transfers result in less frequent restrictions in the Thames. This “shared risk” strategy does not improve performance in Thames Water as the benefit is governed by the size of the transfer infrastructure and storage reservoir, rather than water availability in the Severn.

Figure 6 illustrates the probability of severe restrictions occurring simultaneously in both water companies. Note that due to the logarithmic scale on the y-axis, probabilities of zero are not plotted. Therefore, strategies in the historic simulation with no severe restrictions are not shown on the plot. Complete results of water resource drought coincidence analysis can be found in **Appendix 7**. As with SPI and SRI, probability of coincident water resource drought increases into the W@H future. Consistent with the results presented in **Figure 5**, the shared risk strategies (e.g., 300.S) result in high probabilities of coincident restrictions compared to conditional (e.g., 300.C) and unconditional (e.g., 300.U) transfers.

For the unconditional and conditional transfers, the probability of severe restriction based coincident drought is proportionally less than the other drought indicators; an artifact of the methodology (fewer severe restrictions being imposed in Severn Trent). Measures of coincidence show less variance between transfer strategies, particularly for the historic and Baseline ensembles. The inclusion of the Upper Thames reservoir decreases the probability of coincident restrictions in all three W@H ensembles, again consistent with **Figure 5**. This suggests that the increased storage in the Thames Water supply system helps to reduce the frequency of restrictions, and therefore reduces the overall likelihood of restrictions occurring coincidently with Severn Trent. The results also suggest that both transfer agreements without additional capacity and reservoir

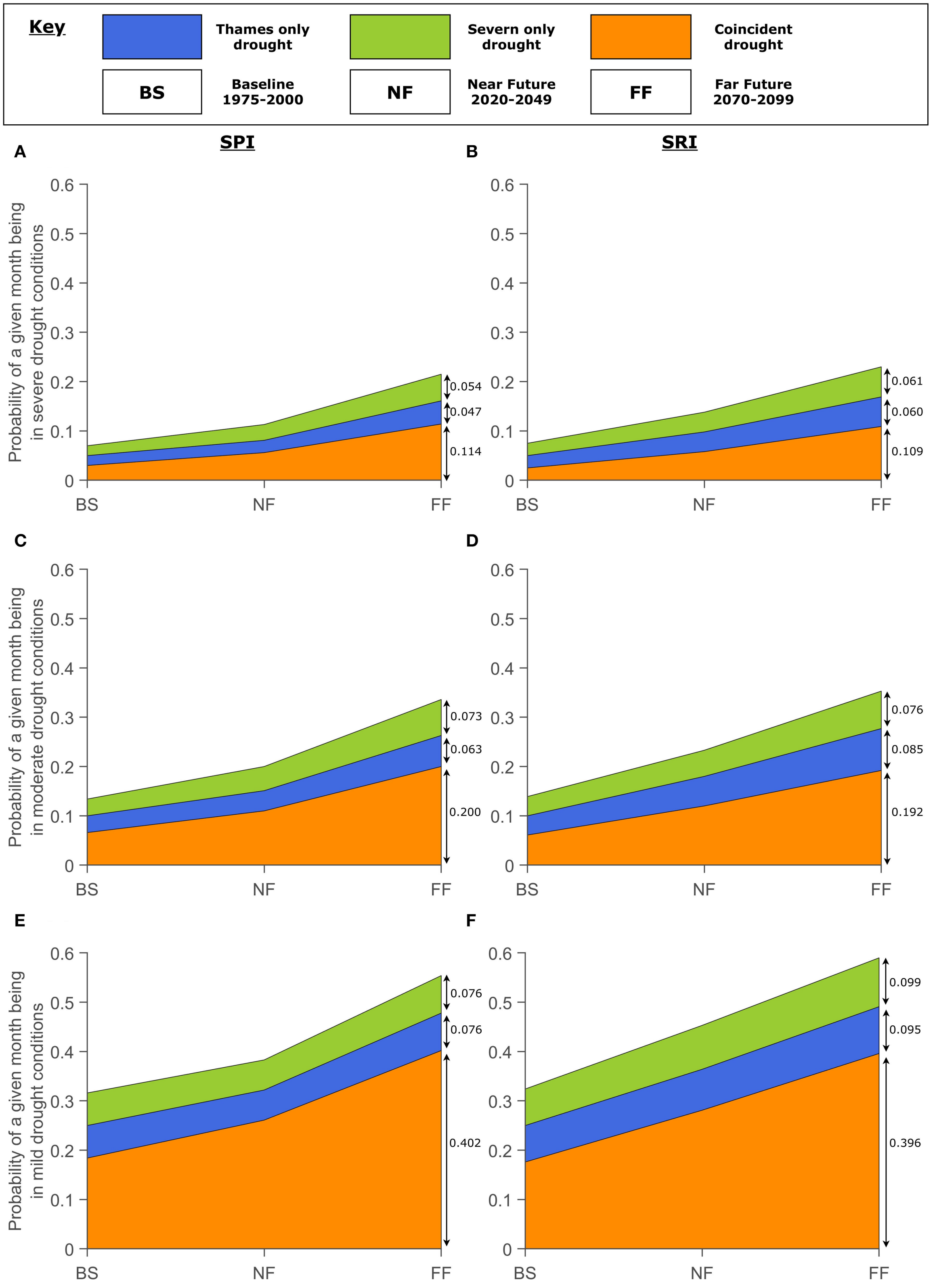


FIGURE 4 | Stacked bar graph showing probability of coincidental and non-coincidental metrological **(A,C,E)** and hydrological **(B,D,F)** drought events of different severities occurring throughout the W@H future.

TABLE 5 | Probability of months in Historic, Baseline, Near Future, and Far Future flow ensembles with 12-months SRI values <W@H Baseline 5, 10, and 25th percentiles for Thames and Severn study areas, individually and simultaneously.

Percentile	Basin	CEH GEAR	Baseline	Near Future	Far Future
Severe (5th)	Severn	0.028	0.050	0.097	0.169
	Thames	0.039	0.050	0.098	0.168
	Severn and Thames Simultaneously	0.011	0.025	0.058	0.109
Moderate (10th)	Severn	0.088	0.100	0.172	0.267
	Thames	0.091	0.100	0.180	0.275
	Severn and Thames Simultaneously	0.047	0.061	0.120	0.192
Mild (25th)	Severn	0.231	0.250	0.370	0.493
	Thames	0.164	0.250	0.364	0.489
	Severn and Thames Simultaneously	0.131	0.176	0.281	0.396

storage provide little additional benefit in reducing coincident water restrictions.

To explore the maximum potential benefit of a transfer to Thames Water, the Unlim.R.U strategy was also simulated against the library of flow and demand ensembles. This strategy simulates an unlimited capacity transfer, which allows the transfer of all flows above the MRF in the Severn at Deerhurst to the Upper Thames catchment, and occasionally flows below the MRF. The exceedance curves and statistics for the volume of water transferred under Unlim.R.U are shown in **Figure 7**. The curves represent volume transfer across the full ensemble; cdfs for individual scenarios are presented in **Appendix 8**. Note volumes equal to zero (days when no water is transferred) are omitted on the graph; a consequence of the logarithmic scale on the y-axis. The plot suggests that the mean volume of water transferred will decrease into the future, a likely consequence of the increased frequency of hydrological droughts, whilst maximum single transfers will increase by the end of the century. These massive transfers at the upper end of the curve occur during high flow periods in the Severn, with 99% of the transfers in the Far Future ensemble equal to or >10,000 Ml/d taking place when flow upstream of the MRF at Deerhurst is higher than 20,000 Ml/d. Indeed, transfers of this size could significantly alter the hydrology and, depending on the timing of the transfer, increase the risk of flooding in the receiving region. This reason, in addition to environmental constraints, makes the unlimited transfer is an infeasible solution for the supply and demand side pressures faced by Thames Water.

Each curve features a distinct plateau between 100 and 200 Ml/d, which is caused by the MRF at Deerhurst. In nearly all scenarios, the MRF is met because environmental flows at Deerhurst are prioritized in the water allocation, so water is allocated to meet the environmental flows before any is transferred. However, in the most extreme low flow scenarios, the MRF is not met. **Figure 7** shows that there is a very low probability of the transfer continuing to transport water to the Upper Thames catchment despite the MRF at Deerhurst not being met, and that the likelihood of this occurring increases with time. This happens only in a limited number of scenarios under exceptional circumstances when a severe drought order permits the violation. Under these scenarios, the network flow optimisation in WATHNET-5 has to balance between the penalty incurred during an extreme demand shortfall in the Thames system and the penalty incurred for violating the environmental flow requirement at Deerhurst. This trade-off reflects the situation that water managers face during droughts when they may be permitted to violate environmental flow requirements but are reluctant to do so. As the simulations show, the probability of this is very low, but is possible in extremely dry, high demand scenarios.

Figure 8 displays the exceedance curves of the flow at Deerhurst after the transfer abstraction point for the Baseline, Near Future and Far Future simulations. The plots illustrate the impact of an unlimited capacity transfer on minimum flows at Deerhurst. For 0.002% of the time in the Baseline, 0.039% in the Near Future and 0.145% in the Far Future ensembles the flow would be equal to or less than the MRF, compared to 0.001, 0.014, and 0.101% under Strategy 0 (respectively). Consistent with **Figure 7** the curves plateau at the MRF, again a consequence of the minimum flow requirement at Deerhurst, which prioritizes the environmental flow below the transfer abstraction point over demand in all but a few scenarios. The curves reiterate the increasing likelihood of the MRF at Deerhurst not being met with time, and that this becomes more likely under the unlimited transfer strategy. Future changes to environmental regulation or river abstraction allowances (Environment Agency, 2019a) could limit the projected impacts on flow below Deerhurst, although this is not explored in the modeling framework used here.

Simulations using the Far Future ensemble indicate that probability of severe restrictions in Thames Water could reduce from 0.157 under Strategy 0 to 0.0151 under Unlim.R.U. This is in contrast to severe restrictions in Severn Trent, which see an increase in likelihood from 0.0102 (Strategy 0) to 0.0149 (Unlim.R.U). This trade-off in risk is due to the unconditional transfer operating rule in Unlim.R.U, which does not prioritize supply to Severn Trent demand centers (nodes in the simulation model) over Thames Water. Whenever possible, the network optimisation in WATHNET-5 aims to equally distribute the demand shortfall experienced by each demand center. In reality this is equivalent to water managers ensuring that customer exposure to water shortages is equally shared among individuals throughout the basin. This equitable risk is achieved under

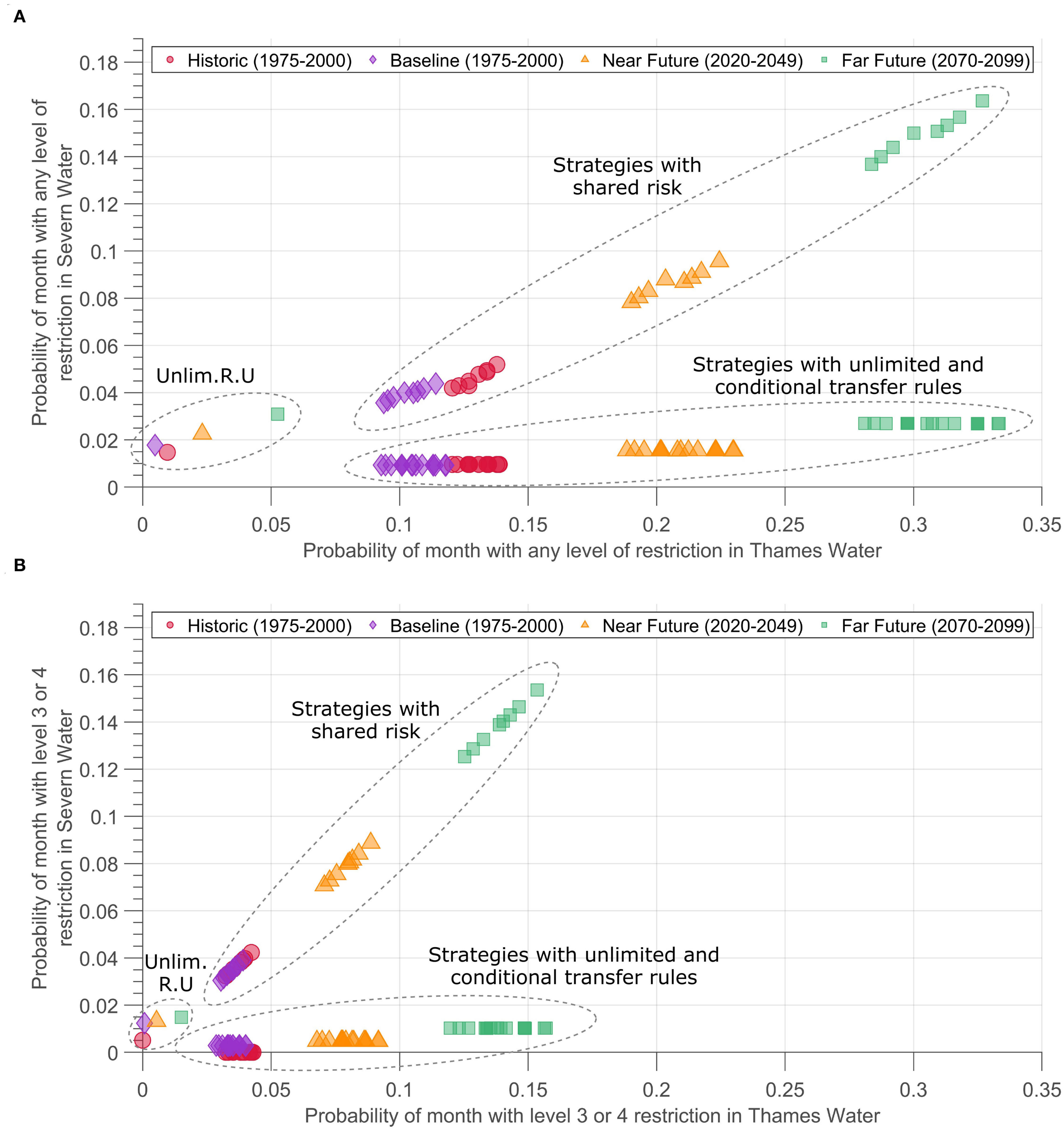


FIGURE 5 | Probability of Thames and Severn experiencing any level of water restriction **(A)** and severe / level 3 and level 4 water restrictions **(B)** in any given month for each infrastructure strategy in Historic (circular markers, red), Baseline (diamond markers, purple), Near Future (triangular markers, orange), and Far Future (square markers, green).

Unlim.R.U, but not in the strategies with smaller transfer volumes that result in little impact on service in the Severn. In addition to this, the probability of severe coincident drought restrictions in the Far Future ensemble under Unlim.R.U are roughly three times less likely than the equivalent measure under Strategy 0 due to the decreased frequency of severe restrictions in the Thames. Indeed, this strategy produces the lowest record of coincident water restrictions across all infrastructure strategies simulated.

These results suggest that transferring upwards of 5,000 Ml/d from the Severn to the Thames would be successful in reducing

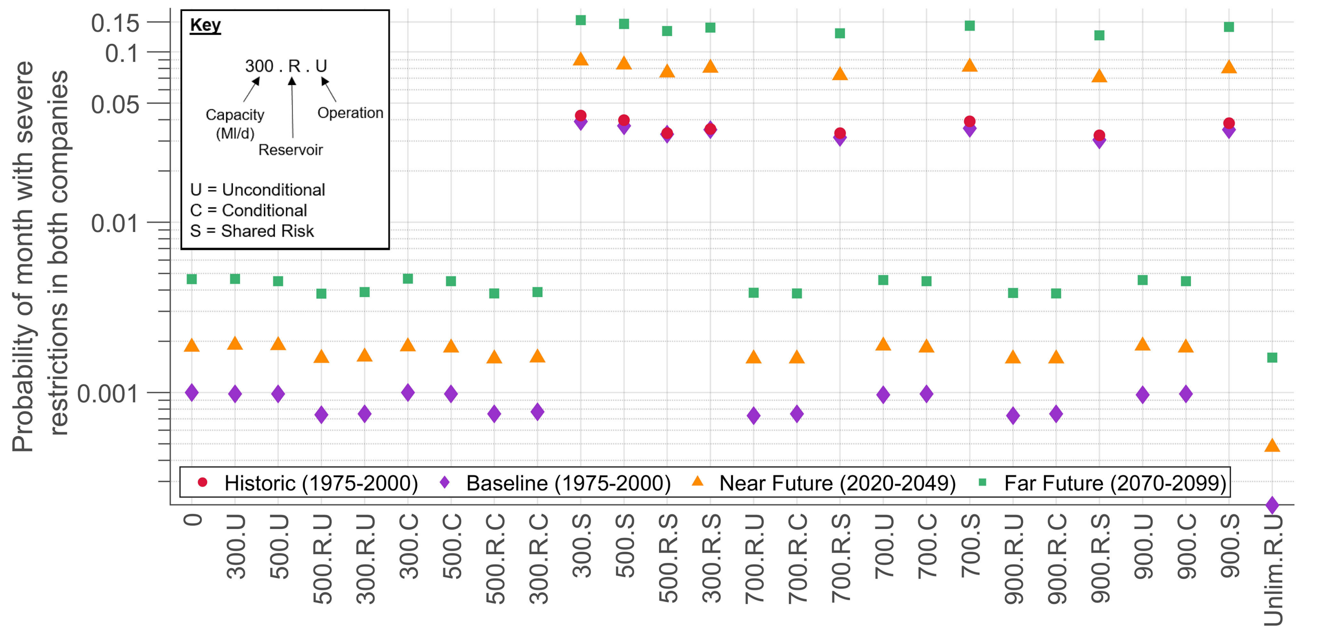
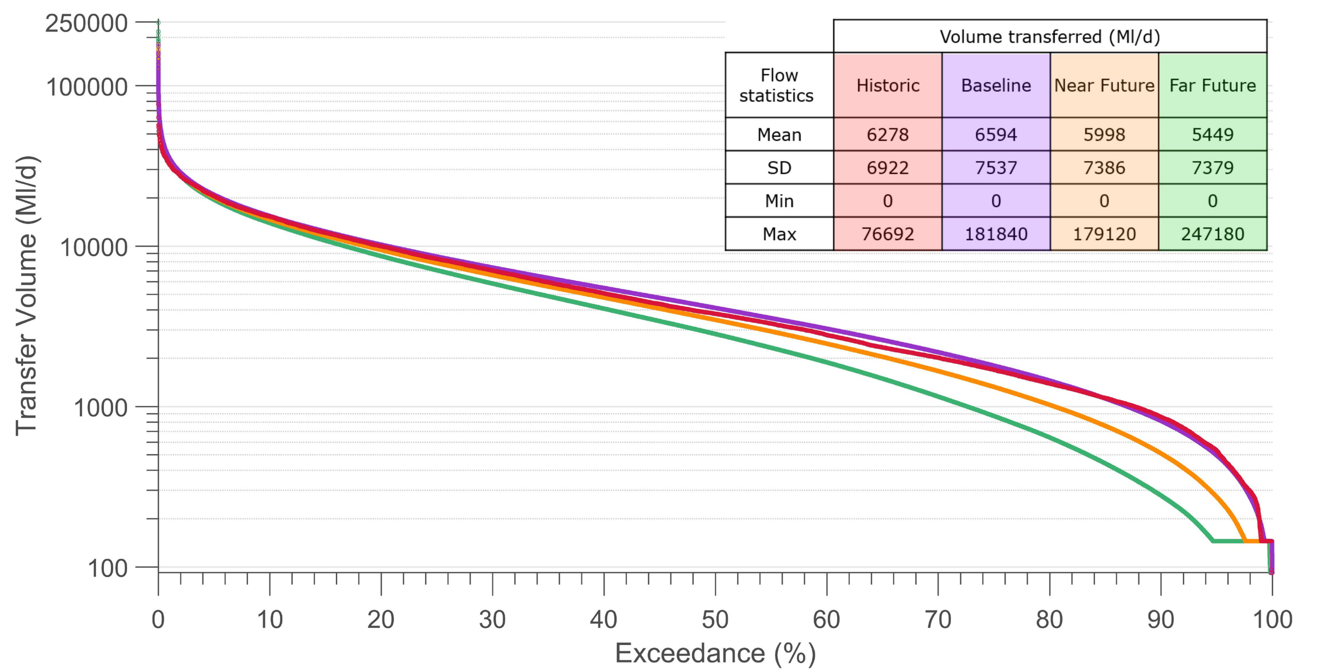


FIGURE 6 | Probability of Thames and Severn water resource regions experiencing a severe water restriction simultaneously in any given month in the Historic (circular markers, red), Baseline (diamond markers, purple), Near Future (triangular markers, orange), and Far Future (square markers, green) ensembles.



Flow statistics	Volume transferred (Ml/d) Historic	Baseline	Near Future	Far Future
Mean	6278	6594	5998	5449
SD	6922	7537	7386	7379
Min	0	0	0	0
Max	76692	181840	179120	247180

FIGURE 7 | Exceedance curves and statistics for volume of transferred water under Unlim.R.U. for each flow ensemble (Historic—red, Baseline—purple, Near Future—orange, Far Future—green).

the likelihood of severe water restrictions occurring in Thames Water by 2100. That being said, transferring upwards of 5,000 Ml/d will cause unacceptable adverse environmental effects in the River Thames and violate environmental flows in the Severn.

The size of the pipeline currently being investigated as part of the feasibility work for the Severn Thames Transfer is <600 Ml/d and is a direct reflection of the environmental effects on the hydroecology in the River Thames from imported water.

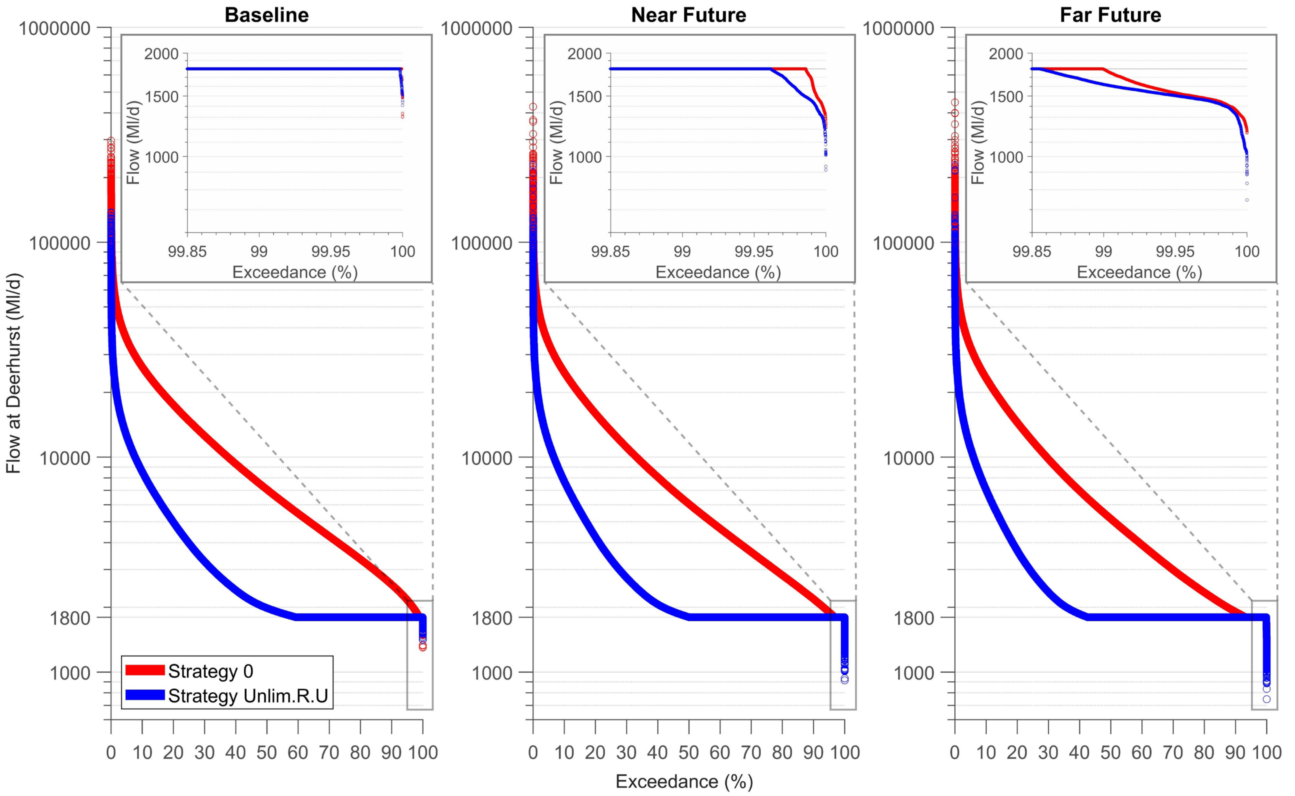


FIGURE 8 | Exceedance curves of flow at Deerhurst below transfer abstraction point for Strategy 0 and Strategy Unlim.R.U when simulated against W@H flow ensembles and demand projections in WATHNET-5. Minimum required flow (1800 Ml/d) at Deerhurst is marked on the maximized plots of the lower end of the exceedance curve.

The larger transfers modeled demonstrate the theoretical benefits of high volume transfers in increasing water supply system resilience to severe meteorological and hydrological droughts, even though they are not appropriate to the real-world Severn-Thames example.

Strategy Performance During Combined Events

The final stage of the drought analysis framework explores the performance of transfer strategies during different types of drought event. "Combined drought" is used to indicate a period when two drought types occur simultaneously. Strategies that prevent water restrictions occurring during a period with a hydrological and/or meteorological drought are preferable over those with little to no improvement in restriction occurrence. **Figure 9** visualizes individual time series of SPI, SRI, projected monthly demand, and severe restriction implementation for the Severn and Thames study areas when simulated against one Far Future scenario under Strategies 0, 900.R.U, 900.R.C, 900.R.S, and Unlim.R.U These strategies are illustrated as they provide the largest benefit to Thames Water's risk of restriction, and have the largest impact to Severn Trent's exposure to restrictions. This future scenario is chosen as it contains the highest frequency of severe meteorological and hydrological droughts in both catchments, the highest frequency of severe coincident drought months, and the greatest projected increase in water demand. Note that **Figure 9** visualizes projected water demand, rather than simulated water demand. This means that decreases in demand as a consequence of water restrictions are not reflected in the time series.

The visualization further validates the importance of testing different infrastructure strategies against severe spatially coherent drought events. Unsurprisingly, the frequency of restrictions imposed in each water company varies depending on strategy. In the Thames, all transfer strategies improve restriction frequency in 2080, 2086, 2089, 2092, and 2096, compared to Strategy 0. Unlim.R.U, 900.R.U and 900.R.S also reduce drought impact on water supply in 2075, 2082, and 2099. 900.R.S proves the most damaging to service in the Severn, with the largest frequency of restrictions in Severn Trent occurring under this strategy. Restriction frequency consistently increases following sequences of years with decreasing SPI and SRI values, as seen between the years of 2085 and 2088. The frequency of restrictions also increases over time, a consequence of greater demand pressures and recurring drought events that gradually lower water levels in the system over a yearly to decadal timescale. Water planners might consider introducing additional supply infrastructure later

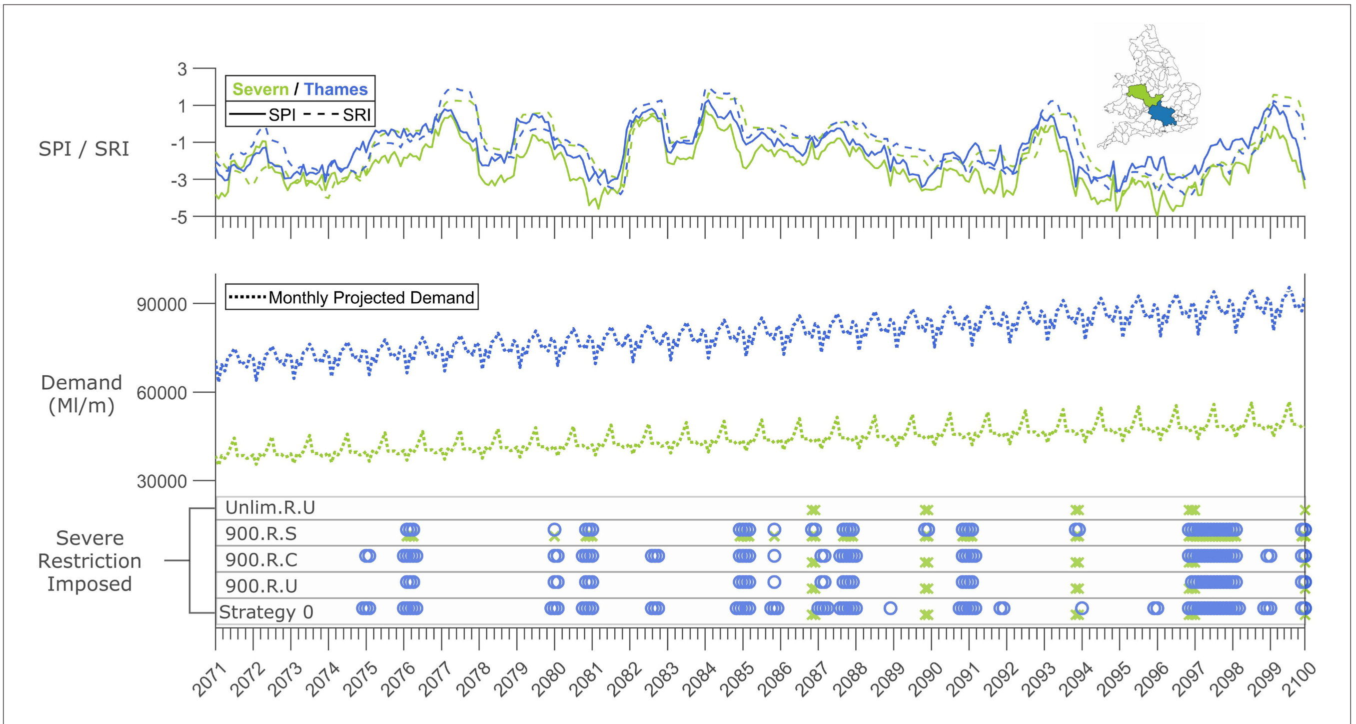


FIGURE 9 | Time series of SPI, SRI, projected water demand, and severe restrictions for the Severn (green) and Thames (blue) study areas when simulated under one Far Future scenario with Strategies 0, 900.R.U, 900.R.C, 900.R.S, and Unlim.R.U. Each marker represents a severe restriction imposed to Severn Trent (×) or Thames Water (○) customers.

in the planning horizon to combat this increase in likelihood of water restrictions.

Complete results from analysis of the probability of combined drought is presented in **Appendix 9**. If a strategy causes a decrease in simultaneous drought occurrence, we infer that strategy increases the resilience of the water supply system to meteorological and/ or hydrological drought. Consistent with the results presented so far, the likelihood of multiple drought types occurring increases into the future for all strategies. This measure is lower in the Severn region, a consequence of the low frequency with which Severn Trent imposes severe restrictions. In the Thames region, water resource drought and hydrological droughts are more likely to coincide than water resource droughts and meteorological droughts, which suggests that hydrological drought events are more closely linked to water restrictions than meteorological droughts. This relationship could be improved by increasing the time-scale of the meteorological drought (here 12-months SPI) to 18- or 24-months, to better correspond with the hydrological response of the catchment.

Transfer strategies including the Upper Thames reservoir have the greatest influence on the probability of combined drought incidence in the Thames area, improving resilience of the water supply system to meteorological and hydrological drought events. Strategy 300.C showed little or no improvement in resilience. Again, strategies designed to "share risk" produce higher levels of combined drought occurrence in the Severn region, due to the increased frequency of restrictions and therefore worsened resilience. Overall, the results suggest that the new transfer only increases drought resilience when it has a volume >300 Ml/d and is supported by additional infrastructure such as the Upper Thames reservoir which provides extra storage for the transferred water, or the Vyrnwy Redeployment which redirects flows in the Severn to replace water lost to the transfer.

DISCUSSION AND CONCLUSIONS

This paper presents a framework for evaluating the resilience of new transfer schemes between neighboring water companies when simulated against an extended historical record and large ensemble of climate change driven future flows, and demand growth projections. The proposed methodology allows water planners to analyse changing characteristics of meteorological and hydrological drought over time and identify adaptation infrastructure that increases the resilience of water supply systems to future drought events.

The approach is applied to a case study in southern England, using a large ensemble of climate change weather sequences, a library of future flows, demand projections, and simulation-based water resource model. Results show that the probability and intensity of all drought types increase into the future, but that the magnitude at which the occurrence of drought increases varies between the two study catchments. The analysis also identifies the probability of coincident drought between the neighboring catchments, revealing how drought dynamics change with time and adaptation. Results indicate that all drought types will become more spatially coherent into the future, with increases in simultaneous severe streamflow and precipitation drought events in both catchments by the mid-twenty-first century. The results are consistent with previous studies of drought in southern England, which suggest that major hydrological droughts are more likely to affect multiple catchments into the future (Rudd et al., 2018) and that meteorological drought intensity and stress will likely increase by the 2050's in south east and south west England (Rahiz and New, 2013). Likewise, in the absence of interventions the probability of imposing water restrictions on customers increases throughout the simulation period as water stress increases (Borgomeo et al., 2014). This is more apparent in Thames Water where, in the absence of any of the adaptation actions that Thames Water are planning, the probability of severe water restrictions in any given month in the Far Future may exceed 0.157 (15.7%). The probability of multiple drought events occurring in the same month could also increase into the future, with 18.1% of all months in the Thames study area in the Far Future ensemble simultaneously experiencing a Level 3 or 4 water restriction, severe meteorological drought and severe hydrological drought (without adaptation).

In line with the suggestions made by Watts et al. (2015), to understand how planning decisions are affected by uncertain changes in the climate and hydrological system, this analysis demonstrates the importance of testing competing versions of infrastructure against climate sequences containing drought events of varying spatial coherence and intensity. The analysis differs from previous studies that rely on historical records to test new infrastructure (Palmer and Characklis, 2009; Kirsch et al., 2013; Zeff et al., 2016), instead comparing the performance of infrastructure simulated under climate change driven scenarios to historical records. Here, the Weather@Home and DECIPHeR ensembles contain more frequent, spatially coherent and intense drought events not present in the historic record, enabling extensive exploration of many possible drought conditions. The ensembles stress test proposed transfer infrastructure between Severn Trent Water and Thames Water, revealing how different management approaches may impact the probability of water restrictions in the transfer source and receiving regions. In general, the most effective strategies include increased storage capacity in the receiving region (Upper Thames reservoir), which provides additional storage for transferred water that can be used in periods of high water stress.

The combined drought analysis explores the probabilities of meteorological and/ or hydrological drought occurring in the same month as water resource drought. The analysis also addresses the role adaptation plays in building resilience to drought. Results indicate that combined drought coincidence decreases in strategies with additional storage capacity, whilst strategies without supporting infrastructure are less successful in building resilience. Unsurprisingly, this suggests that water resource drought resilience to severe climate events improves with greater levels of adaptation. Future strategies should therefore focus on increasing water supply to high risk regions and developing supporting infrastructure to store unused water during periods of low drought risk.

This work also aimed to explore the importance of cooperation between neighboring companies during drought events, evaluating the trade-off between customer service in the transfer supply region with increased resilience to water restrictions in the receiving region. The results suggest that the new transfer will not increase the exposure of Severn Trent customers to water restrictions, unless it is (i) operated under the "shared risk" agreement which imposes water restrictions to Severn Trent customers whenever Thames Water customers are charged with a water restriction, or (ii) if the transfer capacity is unfeasibly large. Regarding point (i), the impact of a shared risk policy on restriction frequency in Severn Trent is exaggerated by the modeling framework used here. In simulation, decisions concerning water transfer and allocation are made at every time-step and are informed by present conditions and regulatory constraints. This is a highly simplified version of decision making in the real world, which also uses trend analysis and weather forecasting to inform future decisions about water system operation. The water resource supply model used here therefore lacks important foresight about changing conditions and the risk of future water shortages. A more dynamic representation of water system operation in simulation experiments would provide a better platform to evaluate the complex decision making required to improve cooperation between water companies during periods of heightened drought risk. Regarding point (ii), the low impact observed in Severn Trent in strategies with unconditional and conditional transfer operation is a consequence of the transfer capacities evaluated here, which are not large enough to disrupt service in Severn Trent. In most instances, the reservoirs in the Severn system (Blithfield, Draycote, Clywedog, Carsington and Ogston, Melbourne, Cropston, and Thornton) can be drawn from before Elan and Derwent reservoirs are allowed to fall below the thresholds for water restrictions (hence the low number of restrictions imposed in Severn Trent). This is in contrast to the Thames system, which contains no upstream regulatory reservoirs for offline water storage.

The authors acknowledge that multiple factors, other than meteorological and hydrological drought, will influence the success of inter-basin transfers. These factors include, but are not limited to: existing water supply infrastructure, such as reservoir storage volume, pipeline connectivity and levels of leakage; unforeseen changes to spatial and temporal patterns of water consumption; land-use change and altered catchment characteristics, and; new demand management schemes. For example, Dobson et al. (2020) reveal that the success of water transfers may be dependent on the proximity of reservoir locations between exporting and importing catchments. Results from their UK-based case study indicate a 40% likelihood of reservoirs in neighboring catchments being in their first percentile of total storage volumes simultaneously, implying that longer distance transfers (>100 km) may prove more resilient to drought conditions. The results presented in this study further highlight the importance of exploring different driving forces of large-scale transfer success.

Whilst there is a growing literature on droughts in the UK, few studies have compared different drought types and their changing characteristics throughout the twenty-first century. It is hoped that the results from this study will encourage decision makers in the water sector to incorporate multi-dimensional drought analysis in future planning tasks, especially in instances where water resources are shared across basin boundaries and may be vulnerable to changing spatial drought patterns.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: The Weather@Home sequences can be downloaded from the Centre for Environmental Data Analysis repository (https://catalogue.ceda.ac.uk/uuid/4eb66be638e04d759939a7af571f18ad). CEH Gridded rainfall estimates can be found in the CEH data repository (https://catalogue.ceh.ac.uk/documents/ee9ab43d-a4fe-4e73-afd5-cd4fc4c82556). The DECIPHeR model code is available at https://github.com/uob-hydrology/DECIPHeR and corresponding flow series at https://doi.org/10.5523/bris.2pkv9oxgfzvts235zrui7xz00g. Monthly water demand profile has been published by Dobson and Mijic (2020) and accessed via https://zenodo.org/record/3764678#.Xs0JNmhKhPY. Demand projections at company level have been published by the Environment Agency (2019b), accessed at https://data.gov.uk/dataset/fb38a40c-ebc1-4e6e-912c-bb47a76f6149/revised-draft-water-resources-management-plan-2019-supply-demand-data-at-company-level-2020-21-to-2044-45#licence-info.

AUTHOR CONTRIBUTIONS

AM conducted the research, analysis, and wrote the paper. JH supervised the research and provided feedback on paper drafts. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Monitoring Droughts From GRACE

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With ongoing climate change, we are staring at possibly longer and more severe droughts in the future. Therefore, monitoring and understanding duration and intensity of droughts, and how are they evolving in space and time is imperative for global socio-economic security. Satellite remote sensing has helped us a lot in this endeavor, but most of the satellite missions observe only near-surface properties of the Earth. A recent geodetic satellite mission, GRACE, measured the water storage change both on and beneath the surface, which makes it unique and valuable for drought research. This novel dataset comes with unique problems and characteristics that we should acknowledge before using it. In this perspective article, I elucidate important characteristics of various available GRACE products that are important for drought research. I also discuss limitations of GRACE mission that one should be aware of, and finally I shed some light on latest developments in GRACE data processing that may open numerous possibilities in near future.

Keywords: drought, grace, water storage change, drought index, remote sensing

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1. INTRODUCTION

Drought is one of the extremes of water availability and one of the biggest threat to sustainable socio-economic development of a region (Nagarajan, 2010; West et al., 2019). In 2019, a quarter of the world's population was reported under severe water stress by water resource institute, and by 2050 this fraction is predicted to double itself (Schlosser et al., 2014). These future predictions are based on models, and they are only as good as our contemporary understanding of the spatiotemporal characteristics of droughts. Therefore, numerous research groups are investigating ongoing and past drought events to obtain novel insights.

Droughts can be classified into four categories that are linked to each other (Mishra and Singh, 2010; Nagarajan, 2010; West et al., 2019). Meteorological drought is driven by a dry weather, usually triggered by less than normal precipitation, high temperature, wind, and sunshine duration. This condition over a prolonged period leads to a drop in soil moisture that cannot support the vegetation, triggering agricultural drought. This usually leads to exploitation of water resources on and beneath the surface of the Earth, which when combined with low runoff and recharge announces the arrival of hydrological drought. Another category is socio-economic drought, defined as the gap between supply and demand of water, which can be a consequence of agricultural or hydrological drought for an agriculture based economy, or due to an unsustainable increase in water demand due to rise in population or changes in lifestyle. Furthermore, onset of drought, its duration, and its impact varies from region to region based on its climate zone, human intervention, socio-economic structure, and impact of climate change and natural variability on the regional water availability (Van Loon et al., 2016). Therefore, monitoring, modeling, and mitigating drought at continental to global scales are few of the biggest challenges in drought research.

Different type of droughts are characterized by different hydrological variables, for example, Meteorological drought is assessed by precipitation, hydrological drought by runoff or reservoir level, and agricultural drought by soil moisture (West et al., 2019). Therefore, to study droughts we require long uninterrupted hydrological observations. Recording and sharing *in-situ* observations require a strong political will and financial commitment, which is missing. A partial solution to this problem has been offered by satellite remote sensing, but it brings several other challenges with it. For example, remote sensing observations and required hydrological variable are not the same, and requires various assumptions to approximate the latter from the former (e.g., altimetry records river height changes which can then be related to runoff) (Tourian et al., 2013). Another issue is the difference in the spatio-temporal scales of remote sensing observations and the hydrological variable of interest. Therefore, how to use remote sensing observations efficiently for drought research is one of the most important challenges being tackled at various fronts (Liu Q. et al., 2020).

Nevertheless, fueled by decades of scientific developments, several satellite based products are being used. For example, soil moisture time series from SMOS, SMAP, and Sentinel 1, precipitation products from TRMM and GPM missions, snow volume from MODIS, and Lansat based NDVI have been used to study droughts (West et al., 2019; Modanesi et al., 2020). These products were able to provide great insights into meteorological and agricultural drought, but struggled with hydrological drought because of their ability to sense surface processes only. Gravity Recovery And Climate Experiment (GRACE), a geodetic satellite mission launched in 2002, was the first remote sensing platform to provide an estimate of ground water storage change as well (Wouters et al., 2014; Frappart and Ramillien, 2018; Tapley et al., 2019). Therefore, GRACE attracted a lot of interest from the hydrology community to map extremes of water availability (Ramillien et al., 2008; Houborg et al., 2012; Long et al., 2013; Vishwakarma et al., 2013; Thomas et al., 2014; Forootan et al., 2019; Kvas et al., 2019; Liu X. et al., 2020). However, complicated geo-physical inversion behind GRACE products, its post-processing, its debated spatial resolution, a short GRACE time-series, and its disagreement with hydrology models, have prevented us from taping the full potential of GRACE mission.

2. AN OVERVIEW OF AVAILABLE GRACE PRODUCTS

GRACE mission consisted of two satellite launched in the same near-polar orbit, one following the other with a distance of 220 km between them, at an altitude of 500 km from the surface of the Earth. By measuring changes in the inter-satellite distance with micrometer precision, we are able to map the gravity field of the Earth, which varies in space due to Earth's interior density distribution and topography, and also varies in time due to mass redistribution (Ramillien et al., 2008; Wouters et al., 2014; Tapley et al., 2019). Water being adequately dense and mobile, constitutes the majority of the time-variable signal in GRACE. The second largest signal comes from the visco-elastic response of the solid Earth to past glacial cycles, known as Glacial Isostatic Adjustment (GIA) (Wouters et al., 2014; Peltier et al., 2015). Various GRACE products are freely available to users. We can categorize them into:

1. Level 2, Spherical Harmonic fields: these are dimensionless spherical harmonic coefficients truncated up to a maximum degree, for example $l_{\max} = 96$. They are made available by science data centers: GFZ, CSR, and JPL (Dahle et al., 2018; Save, 2018). These coefficients, representing full gravity field of the Earth, must be reduced to residual coefficients by subtracting a mean gravity field. To separate hydrology from GIA, a forward model based GIA trends are also subtracted. Then less accurate low degree coefficients (degree 1, $C_{2,0}, C_{3,0}$) are replaced by those estimated from other sources Then using the relations in Wahr et al. (1998), we can obtain global water mass change estimates in terms of Equivalent Water Height (EWH); an imaginary uniform water (density = 1000 kg/m^3) layer of thickness h over a grid cell, which represents the Total Water Storage (TWS) anomaly in that region. It should be pointed out that level 2 GRACE spherical harmonic fields are noisy, hence filtering is essential to extract meaningful information (Swenson and Wahr, 2006; Kusche, 2007; Rangelova et al., 2007). Filtering is known to damage signal amplitude and spatial resolution, therefore, one must apply a correction method to obtain more accurate results (Klees et al., 2007; Vishwakarma et al., 2016, 2017). Since, there are a number of GIA models, filters and corrections method that one can choose from, the final output can vary depending on user's choice.
2. Level 3, gridded EWH fields: these are processed level 2 data with a specific GIA model, filter and correction method. Their spatial resolution and accuracy is dependent on the filter and correction method used (Vishwakarma et al., 2018). They are available from various data centers in a ready to use format that requires minimum effort on the user side, but offers minimum flexibility.
3. Mascons: they are equivalent to level 3 products, but with a different processing strategy. They predict mass changes (in terms of EWH) in concentrated blocks on the surface of the Earth, which would lead to the observed satellite orbit and inter-satellite range rate (Luthcke et al., 2013). The method uses a-prior signal information, physical boundary assumptions (such as continents and oceans), and GRACE variance co-variance information to solve a regularized least squares problem (Luthcke et al., 2013; Watkins et al., 2015; Save et al., 2016). There is no need for an additional filtering and the method claims to tackle signal leakage better than other approaches. These products are available from three centers: JPL, CSR, and GSFC, at a grid sampling of $\leq 1^\circ$. However, it should be made clear that GRACE cannot resolve signals at spatial scales smaller than $\approx 3^\circ$ on the surface of the Earth (Luthcke et al., 2013; Watkins et al., 2015; Devaraju and Sneeuw, 2016; Vishwakarma, 2017; Vishwakarma et al., 2018; Tapley et al., 2019). These high resolution products are interpolated products sampled at $\leq 1^\circ$ grid, and should be aggregated to capture mass change signal accurately. In other words, Mascon products should not be used at single

grid cell scale. If we want to observe mass change at higher resolution, the satellites should be placed in a lower altitude, which will affect the mission's life-time due to atmospheric drag (Wouters et al., 2014).

4. Level 4 time series: there are several institutes that provide GRACE time series for a region/catchment. The philosophy behind providing these products is that GRACE is more accurate and meaningful at catchment scale (Vishwakarma, 2017). Therefore, researchers aggregate GRACE EWH estimates over a minimum spatial area before carrying out hydrological investigations. The accuracy of GRACE products depend on the post-processing method employed, but as a general rule it decreases with the catchment area (Long et al., 2015; Vishwakarma et al., 2018).

The EWH fields from GRACE represents the total hydrological mass change in a region, also referred to as the TWS anomaly that is a sum of change in groundwater, surface water, soil moisture, snow mass, and canopy water. Therefore, estimating change in one component is not simple, and we require model-based estimates or *in-situ* observations of other components (Long et al., 2013; Sun, 2013; Li B. et al., 2019). Since model uncertainties vary in space and time and *in situ* information is scarce, using GRACE for hydrological studies concerning one component of TWS is a challenge (Zaitchik et al., 2008; Sun, 2013; Sneeuw et al., 2014).

3. GRACE BASED DROUGHT INDICES

GRACE is sensitive to a change in TWS that includes groundwater, soil moisture, and surface water, which means it should be able to detect hydrological drought (including groundwater drought) and severe agricultural drought (Ramillien et al., 2008; Thomas et al., 2014; Frappart and Ramillien, 2018; Li B. et al., 2019). This motivated researchers to develop GRACE based drought indicators, such as Total Storage Deficit Index (TSDI), GRACE-drought severity index (DSI), water storage deficit index (WSDI), GRACE-based Hydrological Drought Index (GHDI), and so on. Most of these indices are derived by following the concept behind conventional drought indices (such as PDSI, SPI, SPEI, SMDI) (Zhao et al., 2017; Hosseini-Moghari et al., 2019). For example, Yirdaw et al. (2008) proposed TSDI, written as

$$\mathrm{TSDI} = p\,\mathrm{TSD}_{k-1} + q\,\mathrm{TSD}_k, \text{ where} \tag{1}$$

$$\mathrm{TSD} = \frac{100 \times (\mathrm{TWS}_{i,j} - \overline{\mathrm{TWS}_j})}{\max(\mathrm{TWS_j}) - \min(\mathrm{TWS_j})};\ p = 1 - \frac{m}{m+b}, \text{ and}$$
$$q = \frac{c}{m+b}. \tag{2}$$

Where $\mathrm{TWS_{i,j}}$ is the TWS from GRACE for year i and month j, $\overline{\mathrm{TWS}_j}$ is the mean TWS value for month j. p and q parameters are obtained from cumulative TSD time series. c is the TSDI value obtained from the best-fit line for the period of dryness, m is the slope and b is the intercept of the cumulative TSD time series. Zhao et al. (2017) introduced GRACE-DSI, defined as

$$\mathrm{GDSI} = \frac{\mathrm{TWS_{i,j}} - \overline{\mathrm{TWS}_j}}{\sigma_j}, \tag{3}$$

where σ_j is the standard deviation for month j. GRACE-DSI normalizes the difference between TWS for a time epoch and mean TWS for the corresponding month, with standard deviation of TWS for that month. Similarly there is Water Storage Deficit Index (WSDI) from Sun et al. (2018) :

$$\mathrm{WSDI} = \frac{\mathrm{WSD} - \mu}{\sigma}, \text{ where } \mathrm{WSD} = \mathrm{TWS_{i,j}} - \overline{\mathrm{TWS}_j}. \tag{4}$$

Here μ is the standard deviation of WSD. Another index called total water deficit is written as Leblanc et al. (2009):

$$D(t) = [\mathrm{TWS}(t_0) - \mathrm{TWS}(t)]\ \mathrm{I}, \text{ where}$$
$$\mathrm{I} = \begin{cases} 1 & \text{if } \mathrm{TWS}(t) \le \mathrm{TWS}(t_0) \\ 0 & \text{if } \mathrm{TWS}(t) > \mathrm{TWS}(t_0). \end{cases} \tag{5}$$

Here $\mathrm{TWS}(t)$ is the TWS anomaly at current epoch and $\mathrm{TWS}(t_0)$ is the TWS anomaly observed at time t_0 when a drought threshold was observed. The concept behind these indices relies on the assumption that the short GRACE time series is able to capture the climatology signal represented by $\overline{\mathrm{TWS}_j}$, which is not true. Therefore, efficacy of GRACE based drought indicators has been questioned. Nevertheless, they have been compared with traditional drought indices and over many regions they have shown exciting potential (Zhao et al., 2017). A recent study showed that GRACE based drought indices when computed with detrended GRACE time series can help us capture meteorological and agricultural droughts (Liu X. et al., 2020). The assumption in this study is that the linear trend is completely anthropogenic, which can be a reasonable assumption in some cases, and removing the linear part will help us get rid of the anthropogenic component and target meteorological and agricultural droughts due to climatic variability. However, such analysis should be carried out with caution as decadal climatic variability could appear to be a linear trend in a short time series (Parker et al., 2007), such as from GRACE.

4. CHALLENGES AND MOVING FORWARD

Drought is a complex phenomenon and its signature can be seen in various hydrological variables. Since the water availability varies in space and in time, using different hydrological observations in a robust framework could help us characterize drought. This is the reason, more than 100 drought indices have been proposed till now (Zargar et al., 2011). Each one of them have been shown to characterize/analyze drought with excellent efficacy for a case study, but their global performance is questioned from time to time. GRACE added a unique dimension to our observational capability by monitoring TWS anomaly, which led to several GRACE based drought indices. There are a few things to note, (a) GRACE has a coarse spatial resolution and it is more accurate at catchment scale, which means large scale droughts are more likely to be efficiently studied using GRACE. (b) Mascons and Level 3 GRACE TWS fields are heavily post-processed, and based on the method chosen, the output quality varies. Hence, users should carefully interpret these products. (c) GRACE was launched in 2002 and we do not have data for several months here and there, which means the time series has gaps and is not long enough (less than 20 years) to compute TWS climatology, hence, available GRACE based drought index should be used carefully. (d) The trade-off between temporal resolution and the spatial resolution of GRACE fields is a big obstacle in using GRACE for real-time regional applications.

The above mentioned issues with GRACE products are currently being investigated by researchers, for example, (a) spatial downscaling of GRACE by assimilating it with other hydrological observations to produce higher spatial resolution TWS products (Zaitchik et al., 2008; Miro and Famiglietti, 2018). (b) With the launch of GRACE Follow On mission, we are expecting another decade long GRACE data, and several efforts are going on to reconstruct GRACE TWS for filling the data gaps and reconstructing TWS prior to 2002 (Humphrey and Gudmundsson, 2019; Li W. et al., 2019; Li et al., 2020), and (c) novel daily and weekly GRACE products have been developed and shown to detect short-lived extreme events, such as floods (Kvas et al., 2019). Therefore, ongoing improvements will make GRACE even more effective for drought research. There is no doubt that GRACE based drought indices are an excellent tool to study hydrological and agricultural drought, but comparing them with other traditional drought indices to seek validation is probably not a right approach. Can we expect a perfect match between Palmer Drought Severity Index (PDSI) and Soil Moisture Index (SMI) or between Standardized Precipitation Index (SPI) and standardized runoff index (SRI)? The answer is "no" because these indices deal with different variable that are related to drought differently (Zargar et al., 2011). Hence, GRACE should be used as an independent or a complementary indicator for droughts (Zhao et al., 2017).

Using a longer TWS time series for obtaining TWS climatology should be explored. Existing TWS reconstructions for period before GRACE, such as from Humphrey and Gudmundsson (2019), are not useful as they are able to reconstruct only the inter-annual variability in TWS and the seasonal part is derived from short GRACE time series (Humphrey and Gudmundsson, 2019). GRACE can already tell us about the water mass loss in a period of time (Tapley et al., 2019), we must create a framework that can use this information along with other hydro-meteorological observations and forecasts to predict the probability of drought. This is challenging because both natural variability and human intervention are responsible for drought (Van Loon et al., 2016), and separating their magnitude requires excellent understanding of: (a) relation between climatic variability and regional hydrology, (b) how this relation is affected by change in climate and land use land cover, and (c) anthropogenic response to dry conditions. Using surface observations alone or relying on models will only provide us limited insight. GRACE, although poor in its spatio-temporal resolution, provides us additional information, i.e., TWS including groundwater storage change, affected by both natural variability and human interventions signal. Therefore, carefully integrating GRACE with other hydro-climatic observations and models can greatly benefit drought studies, as was recently shown by Yang et al. (2020). A few projects (such as EGSIEM and GlobalCDA) have been undertaken with this objective, but we need more collaborative efforts between research communities engaged in drought and GRACE to obtain novel insights into prediction of drought, assessing its impact on water resources, calculating recovery time, and predicting its socio-economic cost in a changing climate.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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A Multi-Level Framework for Adaptation to Drought Within Temperate Agriculture

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Droughts affect a range of economically important sectors but their impacts are usually most evident within agriculture. Agricultural impacts are not confined to arid and semi-arid regions, but are increasingly experienced in more temperate and humid regions. A transferable drought management framework is needed to transition from coping to adapting to drought through supporting improved planning and policy decision-making through the supply chain from primary producers to consumers. A combination methodology using a Driver-Pressure-State-Impact-Response (DPSIR) approach, an analysis of weekly agricultural trade publications and semi-structured interviews were used to explore drought impacts and responses, using the 2018 United Kingdom drought as a case study. While most reported responses were on-farm, a diverse range of measures were implemented across institutional scales and through the supply chain, reflecting complex interactions within the food system. However, drought responses were dominated by reactive and crisis-driven actions to cope with, or enhance the recovery from, drought; but which contributed little to increased resilience to future droughts. Our transferable drought management framework shows how improved collaboration and multi-sector engagement across spatial, governance and supply-chain scales to develop human and social capital can enable the transition from coping (short-term and reactive) to adapting (long-term and anticipatory) strategies to increase agricultural resilience to future droughts.

Keywords: adaptation, cropping, impacts, irrigation, coping, livestock, resilience, drought

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INTRODUCTION

Droughts are a serious natural hazard and widely recognized as being one of the dominant causes of global environmental, agricultural and economic damage (Vicente-Serrano et al., 2010). Although droughts affect a range of economically important sectors, their impacts are usually more evident within agriculture (Wilhite, 2007; FAO, 2017), including crop failure and reduced yields, abandoned farmland, increased soil degradation and reduced livestock fertility (and mortality) due to heat stress (Haro-Monteagudo et al., 2017). The impacts of an agricultural drought often also extend well beyond the farm gate, with drought-induced losses in food crop production at the farm level typically spreading along the value chain (e.g., Newton et al., 2011). Such drought impacts are not confined to arid and semi-arid regions (e.g., Azadi et al., 2018; Kuwayama et al., 2019), but increasingly experienced in more temperate and humid regions where droughts were historically not considered a major risk to agricultural sustainability (Bachmair et al., 2015; Rey et al., 2017; Parsons et al., 2019). However, increasing competition for water resources and a changing climate, with reduced rainfall reliability coupled with the increased probability of extreme events, is likely to exacerbate current drought risks (Lu et al., 2019). Thus, there needs to be greater emphasis directed toward building resilience and adaptive capacity to cope with future drought events if potentially serious consequences for rural economies and food security are to be avoided.

In this current and forward-looking context, the development of drought risk management frameworks to support improved policy and planning for adaptation and resilience building appears both relevant and timely (Knox et al., 2020). However, such conceptual frameworks often tend to be geographically focused and highly regional (e.g., Morris et al., 2010; Papadimitriou et al., 2019), only consider specific sub-sectors (e.g., irrigated agriculture - Rey et al., 2017; Hess and Knox, 2013; outdoor livestock–Salmoral et al., 2020a) and focus on farm-level management interventions and responses (Morton and Barton, 2002; Hopkins and Del Prado, 2007; Meempatta et al., 2019), rather than addressing strategic or industry level needs. Recognizing both the multi-functional and multi-dimensional linkages that exist within agriculture and the nuances of drought that are unique to humid or temperate climates are also critically important aspects that warrant attention. Given these gaps in understanding, there is a need for a drought management framework that explicitly considers both the multi-scalar levels of governance and the wider range of actors that are engaged in humid or temperate agricultural systems.

This paper draws on our understanding of the drought impacts and responses of the United Kingdom food system, using the 2018 United Kingdom drought as an examplar, to develop such a transferable framework to contribute to and inform increased drought resilience. The United Kingdom is generally considered a “wet” country with sufficient rainfall to sustain crop production. Most outdoor agriculture is therefore dependent on rain fed production (Defra, 2018), but irrigated production is also regionally important (Rey et al., 2016). However, a number of significant droughts have occurred over the last 40 years with serious agronomic and financial impacts on United Kingdom agriculture. These include 1975–76, 1988–92, 1995–97, 2003, 2004–2006, 2010–2012 (Rey et al., 2017) and 2018. For example, the 2010–2012 drought caused an estimated £400 million in farming losses (Anglian Water and University of Cambridge, 2013) in England. In 2018, much of the United Kingdom (together with a significant wider area in Europe) suffered a combined heatwave and drought. For the United Kingdom as a whole, it was the equal warmest summer since records began in 1884 (and the hottest in England) with June being the driest in England since 1925 (Kendon et al., 2019). This led to a widespread agricultural drought across much of the United Kingdom, a water resources drought in some catchments, and a wide range of impacts and responses across the United Kingdom’s diverse food system (NFU, 2018). Studies suggest that human-induced climate change has increased the likelihood of the 2018 heatwave/drought event (World Weather Attribution 2018; McCarthy et al., 2019), and that future droughts in Europe are projected to become more likely, extensive and prolonged due to climate change (Grillakis, 2019).

The approaches and framework developed here have wider application to other countries and regions where agriculture is an important component of the rural economy and where drought is an emergent risk to food production.

METHODS AND DATA

This paper uses a Driver-Pressure-State-Impact-Response (DPSIR) approach (Lange et al., 2017). Agrometeorological indices (Standardized Precipitation Index (SPI) and Potential Soil Moisture Deficit (PSMD)) were used to characterize the Drivers-Pressures that led to low soil moisture and river flows (State). A synthesis of reported drought Impacts and Responses to the 2018 drought were then combined with semi-structured interviews with key sector informants to elicit insights as to how drought impacts and multi-scale responses were influenced by food supply chain pressures. We then integrated these outputs, with our insights to develop a multi-scalar drought management framework that can inform a transition from reactive drought management to more pro-active approaches to increase agricultural drought resilience.

Agroclimatic Characterization of the 2018 Drought

We used two agrometeorological indicators to characterize the spatial severity and the temporal evolution of the 2018 drought. Firstly, the Standardized Precipitation Index (SPI) (McKee et al., 1993) is a drought severity indicator widely used internationally for drought monitoring (Barker et al., 2016). The SPI normalizes rainfall deficits based on the historic record, meaning the situation at a point in time is expressed relative to the past range of variability for the location in question. To represent the drought effects on the largely rain fed United Kingdom agricultural system, we used the 3-months SPI for July 2018, which provides a comparison of the precipitation in the May–July 2018 period with the precipitation totals from the same 3-month period for all the years included in the historical record. Increasingly negative values indicate a more severe, yet less likely, drought, with an SPI of < -2.0 representing “extremely dry” conditions with an expected probability of exceedence of around 2% (WMO, 2012).

Secondly, we derived the temporal evolution in the potential soil moisture deficit (PSMD) which represents the cumulative interaction between precipitation and reference evapotranspiration (ETo):

$$PSMD_i = PSMD_{i-1} + ETo_i - P_i$$

Where;

$PSMD_i$ = potential soil moisture deficit at the end of day i (mm); ETo_i = reference evapotranspiration on day i (mm) and P_i = rainfall on day i (mm). PSMD on 1st January is set at zero.

The maximum PSMD in a given year ($PSMD_{max}$) provides a useful aridity indicator for comparing individual years and has been extensively used as a drought index for irrigation planning

(Knox et al., 1996) and climate impact assessments in agriculture (e.g., Rodriguez-Diaz et al., 2007; Chung et al., 2011). The $PSMD_{max}$ was calculated for two contrasting weather stations in the south-east (Cambridge–long-term average annual precipitation = 559 mm) and north-west (Blackpool–long-term average annual precipitation = 846 mm) of the country for 1976 and 2018 as well as the long term (1981–2010) average. The drought in 1976 is widely regarded as the most severe and extensive in the United Kingdom in living memory (Marsh et al., 2007; Rodda and Marsh, 2011) and was used as a comparison with 2018.

Synthesis of Drought Impacts From Farming Gray Literature

Farmers Weekly and Farmers Guardian are the two main national weekly farmer-facing agricultural trade magazines published in the United Kingdom. They had an average circulation per issue of >41,000 and >28,000 in 2019, respectively, (ABC, 2020). For each magazine, potential drought-related text in each issue in 2018 was identified by keywords ("drought", "dry", "rainfall", "precipitation", "soil moisture", "scarcity", "stress", or "deficit") and extracted for reading and coding. The coding process led to the inductive identification of impact and response themes and sub-themes within the dataset (Salmoral et al., 2020b), following common practice in grounded theory (Patton, 1990; Bryant, 2014), which were iteratively refined as our understanding of the dataset increased. Classes of impacts and responses, and associated actors, were obtained based on the subject and context surrounding the text.

Semi-Structured Interviews

In terms of sensitivity to drought, the United Kingdom farming system can be broadly separated into enterprises where 1) crops are dependent on rainfall (rain fed), 2) livestock are dependent on rain fed grazing and fodder crops (livestock) and 3) farms where irrigation is used to supplement rainfall on crops (irrigated). Given this diversity and the complexity of supply chains, a series of targeted semi-structured interviews were conducted:

- Arable and horticultural cropping: sixteen interviews with individual key sectoral informants representing arable and horticultural interests, and covering rainfed (mostly combinable crops) and irrigated (potatoes, sugar beet, salads, field vegetables and protected horticulture) crops. The interviewees included growers within the main production areas across England, and informants within commercial and sectoral organizations with national coverage. Face to face interviews typically lasted around 30 min.
- Outdoor livestock: twenty five interviews with individual livestock (beef, sheep and dairying) farmers at two livestock markets in Derbyshire. The length of each interview depended on the farmer's time commitments and willingness, but most lasted between 6 and 10 min.
- Supply chain: nine interviews with key informants through the supply chain, representing major processors, packers and retailers (supermarkets). Due to business practice confidentiality, these interviews explored the businesses' general drought strategies rather than referring to a specific drought event. Each interview lasted between 12 and 30 min, with most around 20 min.

A purposive sampling approach (Robinson, 2014; Bryman, 2016) was used to ensure access to a range of relevant stakeholders so that the perspectives of key informants from the different sectors could be researched. Participants were selected based on their ability to provide useful insights on a particular topic. Hence, the composition of the sample was more important than sample size. The purpose of the interviews was to corroborate and enrich the national analysis, so we considered that the relatively small number of interviews did not significantly affect our findings. Given the different expected drought impacts and responses, each set of interviews used a targeted semi-structured interview template (see **Supplementary Material**), which broadly aimed to understand how they had been affected by drought; the nature of the responses they implemented and what they could have done differently. Each template was framed based on the literature review and trade magazine analysis and refined through pilot interviews with researchers who were knowledgeable on agricultural drought management. Approval of each questionnaire and interview protocol was obtained from Cranfield University's ethics committee (CURES/653/2018 and CURES/8399/3019). Each interviewee was assigned a coded identifier to ensure anonymity.

The interviews were analyzed by synthesizing and classifying the interviewee responses to make better inferences about the impacts and responses reported in the agricultural trade publications. Interview responses were analyzed using a part-deductive/part-inductive approach to thematic coding, in which the themes from the agricultural trade publications were open to the identification of new themes or sub-themes. The paper is not intended as a complete compendium of drought impacts or responses (see Rey et al., 2019), but rather a critique and illustrative summary of the different types of impacts and responses witnessed in 2018 to inform the conceptual development of a drought management framework.

RESULTS

Driver–Pressure–State: The Agrometeorology of 2018

Following an unusually cold and wet April, many parts of central England recorded less than half the average summer rainfall (Kendon et al., 2019) and many places, particularly in eastern and north-west England, broke records for low rainfall and/or high daytime temperatures in the period between May and July. June was particularly dry, with parts of central and southern England recording <5 mm rainfall (Kendon et al., 2019). The combined effect of low rainfall and high temperatures created a "meteorological drought" over much of the country. By the end of July, the 3 months Standardized Precipitation Index (SPI3) was showing "extremely dry" conditions in most of East Anglia, parts of north-west England, south west England, west Wales and the north of Scotland (**Figure 1**). Some heavy downpours in late July ushered in a return to broadly average conditions in August, but in much of England, Northern Ireland and parts of Scotland, September rainfall was again below average.

Figure 2 shows the development of the PSMD at Cambridge and Blackpool during 2018. The dry period in 2018 started later than in 1976 in Cambridge but slightly earlier in Blackpool, however the PSMD increased rapidly between 15 May and 27 July in both locations due to very low rainfall (25 and 52 mm, respectively). Although the maximum PSMD ($PSMD_{max}$) in 2018 was lower at Blackpool (268 mm) than at Cambridge (448 mm) reflecting particularly the higher rates of evaporation in south east England, the annual exceedance probability of the 2018 $PSMD_{max}$ was 2% and 4%, respectively, (Knox and Hess, 2019). The summer of 2018 could therefore be considered an extreme drought in both locations.

By July, exceptionally low river flows were recorded in many catchments (CEH, 2018) although in the south and east, groundwater fed rivers were at normal levels, due to the wet winter and spring. One water company in the north-west of England planned, but did not implement, a "Temporary Use Ban" that limited domestic irrigation (United Utilities, 2018) but agriculture was exempt from formal spray irrigation restrictions. Therefore, the impact of dry weather on water resources in 2018 was not as severe as in the summer of 1976, which followed a very dry 1975 (Marsh et al., 2007).

Impacts

The national extent of dry conditions (**Figure 1**) and the severity (**Figure 2**) meant that drought impacted all three farming systems in 2018, with reported impacts in the trade magazines cutting-across cropping and livestock sectors (**Figure 3** and **Supplementary Table S1**). Most of the reported impacts were negative, particularly poor crop growth and development leading to reduced yields (for both food crops and grassland), and reduced livestock feed availability. Unsurprisingly there was also variability in impacts, with crops on more drought prone sandier soils being more impacted than those on more moisture-retentive clay-rich soils, and rain fed crops were impacted more than those that were irrigated. There was a small number of reported positive impacts, related to increased prices, reduced crop pests/disease pressure and improved soil conditions for farm operations. The increases in United Kingdom prices for some agricultural outputs did not result simply from the drought impacts in the United Kingdom but were also influenced by the concurrent drought in Ireland and continental north-west Europe increasing demand for livestock feed and reducing cereal production, respectively. However, reported impacts on farm income were all negative, indicating that any benefits from increased prices received on agricultural outputs were offset by reduced yields and increased costs, and leading to reported negative impacts on farmer well-being.

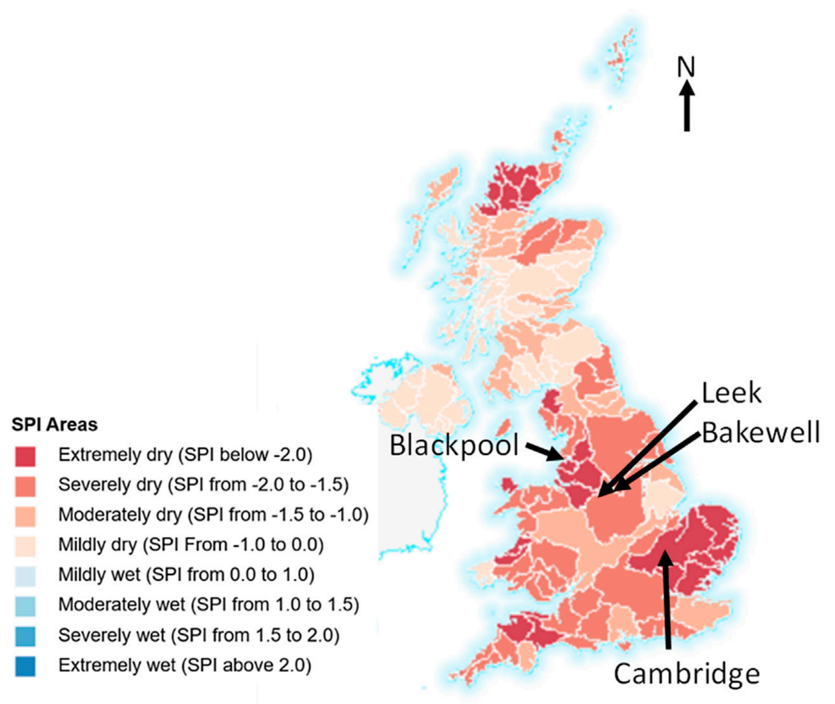

FIGURE 1 | Spatial distribution of the 3-month Standardized Precipitation Index (SPI) for river basins across the United Kingdom for the 3 month period ending in July 2018 (Source: UKCEH Drought Portal). The locations of towns mentioned in the paper are indicated.

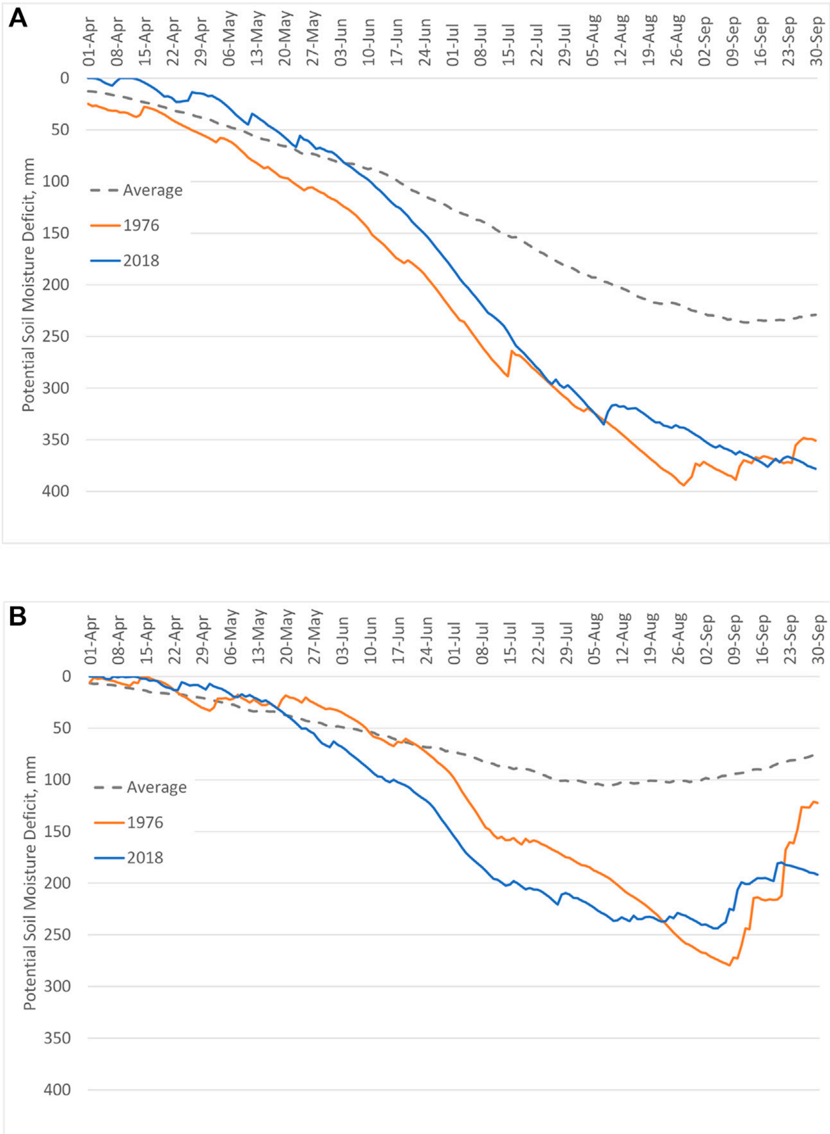

FIGURE 2 | Potential soil moisture deficit profiles for **(A)** Cambridge and **(B)** Blackpool for 1981–2010 average, 2018 and the 1976 extreme drought year. Source: Knox and Hess (2019).

Responses

Given the spatial extent and severity of the 2018 drought, it is unsurprizing that a wide range of responses to the drought were reported in the farming press to minimize yield losses, maintain animal welfare, reduce costs and maintain cashflow. The most commonly reported responses were modifying planting and harvesting practices, feed/bedding management, selling livestock and feed purchases/sales (**Figure 4**), reflecting the significant impact of the drought on outdoor livestock production. Cross-sectoral industry responses to the challenges in the outdoor livestock sector were seen in arable farmers baling straw (rather than incorporating into the soil) to both support the livestock sector and to capitalize on strong growth and prices (**Table 1** and **Supplementary Table S2**).

Growers who had access to irrigation were irrigating at peak capacity for much of the season, resulting in increased labor and energy costs. However, many growers reported that they did not have sufficient irrigation equipment and/or license capacity to meet the sustained agronomic demand over their entire cropped area, due to protracted high temperatures and ET rates. Consequently, growers had to make difficult decisions about prioritizing limited supplies of available irrigation among competing crops, or sacrificing crops entirely. Some were able to expand the capacity of their irrigation system, but there was high demand for equipment all around the country and the rest of Europe.

However, while most reported responses were on-farm, a diverse range of responses were reported from other farming

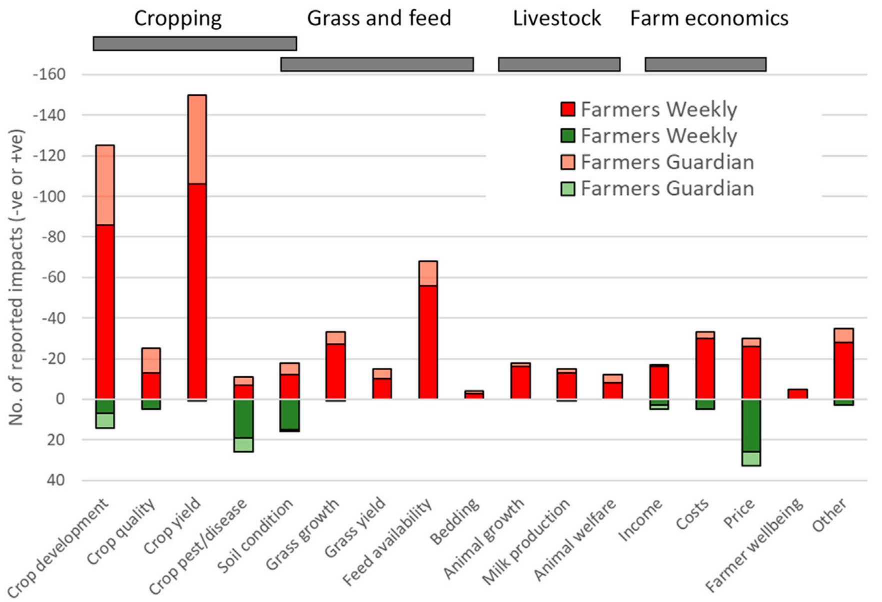

FIGURE 3 | Negative and positive drought impacts reported in Farmers Weekly and Farmers Guardian trade magazines in 2018.

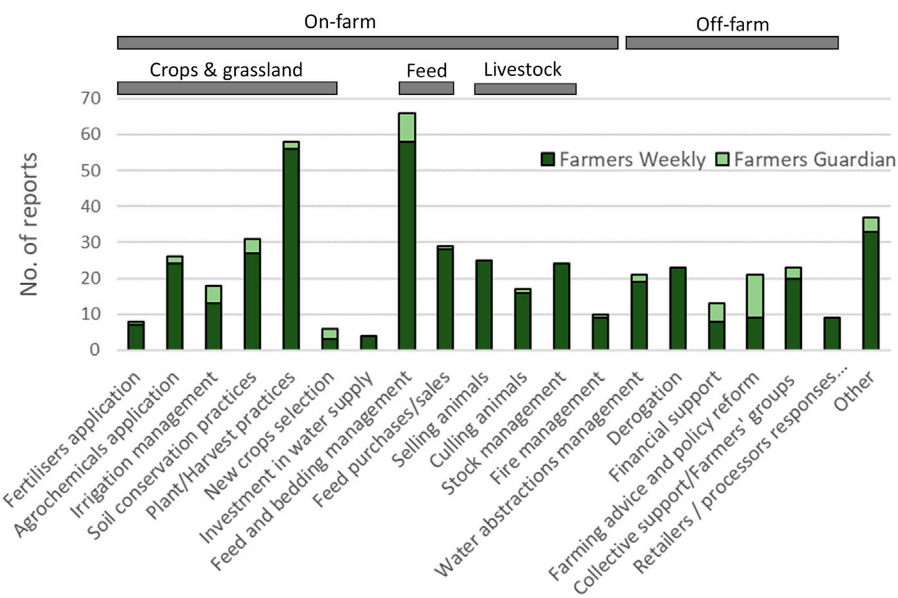

FIGURE 4 | Drought management responses reported in Farmers Weekly and Farmers Guardian trade magazines in 2018.

and non-farming actors (**Figure 4**, **Table 1** and **Supplementary Table S2**). These included actions to:

- Communicate drought management advice: from fellow farmers, the agricultural levy boards, National Farmers Union (NFU), water abstractor groups, independent and retailer agronomists
- Provide collective support: these ranged from the NFU Fodder Bank scheme and the Fodder Aid charity that sought to assist livestock farmers in procuring animal feed; the Royal Agricultural Benevolent Institution (RABI) that provided emergency financial support to struggling farmers; NFU Water Bank to help bringing together farmers who needed water with farmers that had

TABLE 1 | Exemplar reported short-term responses to drought impacts across the United Kingdom farming sector.

Sector	Short-term responses (exemplars)
On-farm (cropping)	"*Growers considering this route should aim to take crops [potatoes] out in the very early morning when they have had a chance to rehydrate overnight*." [FG July]. "*We are doing everything we can to preserve water, including irrigating at night and using boom irrigators rather than rain guns to avoid evaporation*." [FG July]. *"Some fields that weren't planned to be irrigated were brought under irrigation where water was available, but the cost of equipment, pipe, labor, etc. was high."* [I6]
On-farm (livestock)	"*Since there were shortages of feed all over the country I had to mix my silage straw with and feed them to my animals*" [B10]. "*Any animal that was not productive at this time of production was culled*" [L2]. "*We were using some of the winter feed in the summer*" [L11]
Farming community	"*I received advice from a neighboring farmer*" [L6]. "*Support from RABI is tailored to suit individual need and helps with contributions toward domestic bills or providing emergency grants*." [FG July]. *"There was some temporary trading of water among growers. For example, a water transfer scheme provided a 'reserve' of water that some license holders were not using that was made available to others."* [I1]
Suppliers	"*Because we regularly purchase feed from our suppliers even on a normal year, they said "you buy off us 52 weeks of the year, so you'll get yours*"" [L10]
Government agencies	"*We are on the environmental scheme and the only help we received was that we were allowed [by Natural England] to mow early because the grasses were not growing early enough for us to feed our animals*". [L4]. *"The Environment Agency were proactive and gave an extra month of abstraction on winter licences (to end of March)."* [I2]
Retailers/processors	*"British Sugar reduced the factory processing rate by 20% in the first few weeks of the season to allow the crop to stay in the ground longer and put on extra yield."* [I1]. "*We try to work very closely with our growers. . ..We don't really want to take them to court because they haven't achieved their contract, so we are not trying to beat them up over that*" [SC8]. *". . . multiples reduced quality specification but growers felt it was too late."* [I2]. *"we will have to go overseas, to France or wherever to increase the amount of supply we are obtaining from elsewhere."* [SC1]
Government	"*Defra has announced 40 temporary prescription adjustments (TPA) to help drought-hit farmers in stewardship schemes provide extra fodder, bedding or grazing for their stock*" [FW September]. "*the Welsh government announced a £500,000 donation to farming charities to provide short-term support to families in Wales who are least able to meet living costs.*" [FW August]. "*The United Kingdom is under pressure to implement a Brussels decision allowing EU member states to make early direct payments to farmers battling drought conditions*." [FW August]

Note: FW, Farmers Weekly; FG, Farmers Guardian; B, Bakewell market; L, Leek market; SC, Supply chain; and the number refers to the interviewee number.

a surplus; and formal/informal water abstractor groups (which are made up of irrigation abstractors within a given catchment) who facilitated temporary trading of water among irrigators and collectively negotiated with the water regulator (Environment Agency, EA)

- Modify regulations and proscriptions: the EA worked with irrigators to provide flexibility within abstraction management enabling, for example, emergency water trades; while Natural England provided derogations on agri-environment scheme constraints to livestock farmers to increase access to grazing land
- Modify contractual terms: processors, packers and retailers reduced their stringent quality assurance standards for fresh produce to utilize as much of the harvested crop as possible; some supermarket chains relaxed their contractual requirements regarding quantities, delivery schedules and/or quality specifications (e.g., potato size requirements). Retailers started campaigns aimed at attracting customers to buy lower quality or smaller than usual fruit and vegetables (e.g., "Wonky veg")
- Provide financial support: early Common Agricultural Policy (CAP) payments by the Rural Payments Agency to ease cashflow and flexibility from financial institutions were advocated.
- Provide strategic direction: the Department for Environment, Food and Rural Affairs (Defra) held an emergency drought summit with representatives from the EA, Natural England, the Rural Payments Agency, NFU and several farming charities to seek a co-ordinated response to the emerging drought situation. However, much day-to-day direction came from the National Drought Group (formed after the 2010–2012 drought) chaired by the Environment Agency, the regulating agency for Defra.

It is not possible to say whether these measures were 'effective' or not. The average Farm Business Income in 2018/19 (covering the 2018 harvest) reduced for dairy and grazing livestock farms, due largely to higher feed costs (Defra 2019)–for example, the average incomes for grazing livestock farms fell by 39 percent for lowland farms and 42 percent for those in the Less Favored Areas (mostly uplands) demonstrating the large financial impact of the common response to maintain herds through increased supplemental feed. In contrast, the reduced crop yields on cereal and general cropping farms were mitigated by higher prices for some crops, particularly cereals, leading to increased average incomes of 8 and 22 percent, respectively (Defra 2019). However, the total number of United Kingdom farm holdings in June 2019 was 219 thousand (Defra 2020) compared to 217 thousand in 2017 (Defra 2019), suggesting that the adaptation responses had enabled most farms to survive beyond the drought.

Drought responses, both short-term coping (**Table 1** and **Supplementary Table S2**) and longer-term adaptation strategies (**Table 2** and **Supplementary Table S3**), were implemented across institutional scales (farms, farmer groups, farmer organisations, government agencies and policymakers)

TABLE 2 | Exemplar reported longer-term responses to drought impacts across the farming sector.

Sector	Longer-term responses
On-farm (cropping)	*"Many businesses have been compromising on irrigation investment–but not anymore. We hadn't moved on, but now looking long and hard at the resilience of our business planting programmes and water resources needed to meet contracts in a drought year. 2018 was a wakeup call."* [I8]. "*In the short term, building a reservoir is not a quick solution, but we are encouraging farmers to . . . look at longer term resilience options such as a storage reservoirs*." [FG April]. "*. . . he has a strategy of early drilling and high seed rates to prepare for the dry spring and summer which he knows will inevitably come*" [FW September]. "*With this year's drought there's also increasing evidence to show that shelter belts and planting trees in the right place will reduce water loss from the soil, making more available for the crop rather than evaporating*." [FW October]
On-farm (livestock)	"*We didn't sell our animals because we needed the parents with good quality traits to be around during subsequent production cycle*". L6]. "*This has led Mr Gribble to make another difficult decision: to get a part-time job*" [FW, August]. "*In a year of challenging weather conditions which have led widespread grass silage shortages, maximizing the value of alternatives like maize could become increasingly important*." [FG August]. "*I constructed a borehole last year which will serve as alternative source of water in time of drought*" [B9]
Farming community	"*In the short term... we are encouraging farmers to consider water abstraction groups*." [FG April]. "*Lincolnshire farmer and Forage Aid founder Andrew Ward said he hadn't baled straw for many years but was doing so this year, with straw destined for Cumbria and other areas to help livestock farmers*." [FW August]. "*If the farmer group call saying they are going to be short, we know that they will try to fill that by anyone in their group that has a surplus, or other potatoes somewhere else that they can buy for us*" [SC2]
Suppliers	None reported
Government agencies	*"The Environment Agency response was generally too slow to cope with emerging issues, although local staff . . . provided excellent support to growers"* [I9] *"The Environment Agency should allow more flexibility in licensing (e.g., changing abstraction points), earlier. There was a feeling that in 2018 the response was too late".* [I1]
Retailers/processors	"*... we have recently started selling reduced price 'wonky' veg and these have been performing very well, so this indicates a growing customer acceptance of such produce*." [SC5]. "*We have about 10 contracts but they are what we call our growers groups, and within those growers groups there could be 20 growers.*" [SC2]. *"A lot of our farmers have been with us for many years, 2nd or 3rd generation in some cases. We ...work with a farmer in the relationship so we are looking at improving the technical competence of the growers" [SC2]. "water security is definitely one of the attributes we look for in a grower: on farm reservoirs, good irrigation appliances . . . they are key part of growers select" [SC4]. "The big thing each time you have a weather event like that, the whole supply chain learn from that, and those other things like more geographical spread, more CAPEX, better training of the growers" [SC9]*
Government	*". . .need to continue to foster multi sector collaboration and start some local catchment scale interventions".* [I9]. "*Within our grower base we are encouraging farms to be self-sufficient on water, so investment in on-farm reservoirs. Something we need to call for more help from the government in terms of tax break, capital release, easier planning . . .* " [SC4]

Note: FW, Farmers Weekly; FG, Farmers Guardian; B, Bakewell market; L, Leek market; SC, Supply chain and the number refers to the interviewee number.

and through the supply chain (including processers, retailers and consumers), reflecting the complex interactions between Drivers, Pressures, States, Impacts and Response (DPSIR) within the food system (**Figure 5**). Each of the elements in the DPSIR framework in **Figure 5** were also classified according to whether they were related to farming, water resources, climate, markets or policy/regulation aspects. It is evident that the impacts of drought are not solely due to climate pressures within the United Kingdom, while the responses are not solely agricultural.

Consequently, **Figure 5** shows that agricultural drought resilience cannot be considered just at the farm-scale, but has to include spatial, governance and supply-chain scales. Drought can be a large-scale regional phenomenon that can cross national boundaries, magnifying the systemic complexity of impacts and responses. The 2018 drought affected much of central and northern Europe (Buras et al., 2020), causing yield reductions of up to 50% for the main crops (Toreti et al., 2019). This led to concerns regarding the availability and quality of agricultural commodities; competition for limited market availability of key equipment (e.g., new and second-hand irrigation equipment); and unintended consequences of other national drought responses on market demand and prices (e.g., Irish transport subsidies for fodder purchases in the United Kingdom).

DISCUSSION

In their resilience trinity, Weise et al. (2020) identify two decision contexts of relevance to drought management in agriculture–reactive decisions where the loss of the desired functions (e.g., food production) due to a current threat (e.g., drought) is imminent or already happening; and adjustive decision contexts where the desired functions are threatened by future threats (Ault, 2020), but not yet to a critical level. In such a decision context, concerns about losses from future uncertain drought events exist, but initiatives and incentives to adjust current management practices to increase longer-term drought resilience might be neglected (Boltz et al., 2019), slow or even fail because of the lower perceived urgency for actions (Weise et al., 2020).

This potential dichotomy is clearly evident in **Figure 4** in which a wide range of drought responses initiated or advocated by a diversity of actors were identified. The reported drought responses were dominated by actions that focused on short-term actions (**Table 1** and **Supplementary Table S2**) to cope with the drought (e.g., crop management; purchasing additional feed) or short-medium term actions (**Table 2** and **Supplementary Table S3**) that enhanced the recovery from the drought (e.g., maintaining current livestock herd genetics), but which

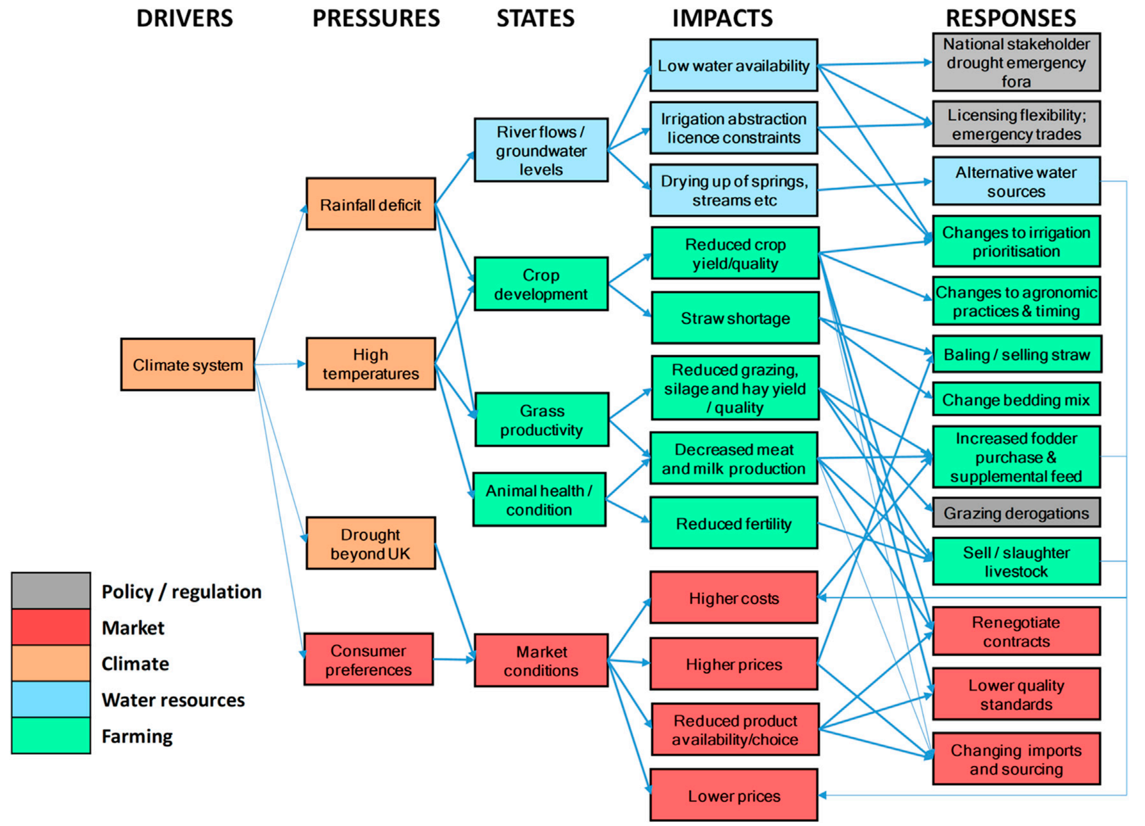

FIGURE 5 | Simplified Driver-Pressure-State-Impact-Responses schematic for agriculture, showing how drought impacts and responses are interconnected to a range of drought pressures both from within and outside the United Kingdom.

contributed to little anticipated increase in resilience to future drought events. This evidence from the United Kingdom corroborates a more widely accepted approach to the management of drought risk that is reactive and crisis-driven (Cruz et al., 2018; Hess et al., 2020), with potentially negative consequences for health and social outcomes (Edwards et al., 2018).

There were fewer reported examples of longer-term adaptive responses within the farming literature and interviews, which broadly separated into four groups of actions: 1) the development or adoption of more drought-tolerant crop cultivars or grasses to reduce drought sensitivity; 2) increased farmer collaboration to increase collective influence; 3) investment in on-farm water supplies to reduce vulnerability to hydrological drought; and 4) risk-sharing through geographically dispersed production and sourcing to reduce drought exposure. This is consistent with earlier evidence of actions to increase drought resilience in irrigated agriculture (Rey et al., 2016; Rey et al., 2019), and outdoor livestock (Rey et al., 2019; Salmoral et al., 2020a). In contrast, Wreford and Adger (2010) suggested that a progressive reduction in the impacts of droughts and heatwaves on national-scale production of three out of five crop commodities and two out of four livestock categories investigated, was indicative of the United Kingdom agricultural sector being relatively well adapted to the current climate. However, this analysis did not account for differences in drought severity and extent, or the spatial coincidence of drought events and production areas.

Adaptive strategies that increased resilience within the farming system, through building diversity (Allison and Hobbs, 2004), redundancy (D'Odorico et al., 2010) or headroom (Cabel and Oelofse, 2012), carry costs. For those strategies seen within the farming literature and interviews, these costs which can represent barriers to change include capital investment costs (eg a farm irrigation reservoir, drinking water infrastructure), operational costs (e.g., soil management; feed mix changes; management overheads), profits foregone (e.g., reduced cropping or grazing areas; reduced livestock numbers) and opportunity costs (Abson et al., 2013) (e.g., reservoir storage that is not used in most years; reduced yields of drought-tolerant cultivars; reserved grazing; increased stored/conserved feed) that must be justified by the penalties avoided in occasional drought years. The willingness or ability to incur these additional costs can be limitted by farm business characteristics, risk attitudes (Knox et al., 2010; Rial-Lovera et al., 2017) and drivers of economic efficiencies. The limiting conditions created by the combination of highly competitive operational environments and the low profitability of some farming systems (particularly upland livestock) results infarm business decision-making often focuses on enhancing the economic efficiency of production,

TABLE 3 | Mapping resilience actions by different stakeholders to increasing the five capitals.

Capital-type	Resilience actions	By whom	Benefits
Natural	Soil organic matter improvement	Farmer	Improved soil structure; higher water holding capacity
	Shelter belts, tree planting	Farmer	Shading for livestock; reduced crop evapotranspiration
	Genetic improvement	Farmers, crop breeders, agri-technology providers	Improved drought tolerance
	Regulatory flexibility	Government, regulators	Increased short-term access to grazing and water
	Geographic spread in purchases	Processors, retailers	Reduced drought risk to supply
Social	Multi-sectoral collaboration	Farmers unions; water abstractor groups; Co-operatives	Increased access to knowledge and support; sharing/trading to meet shortfalls
	Support networks	Charities, farmers	Mental health, support
	Communication and collective negotiation	Farmers, water abstractor groups, regulator	Increased trust
	Developing established business relationships and supply chain collaboration	Farmers, farmer groups, processors, retailers	Increased trust and support
Human	Consumer awareness	Retailers; farmers unions, NGOs	Increased acceptability of 'imperfect' fruit and vegetables
	Farmer training; advice	Agronomists; levy boards; processors and retailers	Improved agricultural practice
	Forecasting and early warning	Scientists, data providers, environmental regulator	Improved decision making
Manufactured	On-farm reservoirs and alternative water supply (e.g., borehole)	Farmer/environmental regulator	Security of supply
	Equipment redundancy	Farmer	Increased capacity during extreme event
	Crop storage facilities	Farmer groups; processors; packers	Smooth supply fluctuation
Financial	Diversification	Farmer	Reduced income volatility
	Insurance	Farmer; financial institution	Reduced financial losses
	Agricultural support payments (PPGs, PES)	Government	Targeted financial support
	Contractual flexibility (quality assurance, prices)	Processors, retailers	Protected farm income; reduced wastage
	Investment support (tax incentives; subsidies)	Government	Increased capital investment

through utilizing any 'spare' resources and minimizing opportunity costs, thereby diminishing system redundancy and eroding resilience (Hess et al., 2020).

With drought events projected to become more frequent and severe due to climate change (Grillakis, 2019), agriculture needs longer-term planning and investment to build resilience that is guided by, and supports, short-term emergency responses, effective adaptation to repeated shocks and appropriate preparation for unexpected extreme events (Harris et al., 2020). However, the wider lack of long-term planning and investment in drought management in agriculture (evident in **Figure 4**, **Table 2** and **Supplementary Table S3**) despite drought being a familiar and relatively frequent stressor, demonstrates that transitioning from short-term reactive coping responses to longer-term and anticipatory responses is a much more entrenched and longer-term challenge for the industry. Adaptations undertaken by different actors will need to work in cohort to increase the resilience of the system as a whole., Retailers (and processors) have a potentially important role to play in enabling change and promoting resilience in the supply chain (MacFayden et al., 2015), by providing farmers and grower groups with agronomic support and longer-term contractual relationships that can provide the confidence for long-term business investments (such as for farm reservoirs).

It is common for resilience theory and sustainability to be considered as complementary approaches (Redman, 2014), although they are independent concepts (Derissen et al., 2011). Nevertheless, while the property of resilience should not be confused with the positive normative connotations of sustainability (Derissen et al., 2011; Kreuger et al., 2020), the five capitals model (Viederman, 1994; Forum for the Future, undated, 2018) forms a framework for sustainability and can support long-term planning for resilience (Harris et al., 2020). **Table 3** characterizes the resilience actions identified within the farming literature and interviews (**Figure 4**, **Tables 1, 2**) according to the capitals they enhance, but recognizes that actors in the food production chain can influence capitals at different governance scales (**Figure 6**).

Natural capital represents the ecosystems/assets from which there is a flow of services and/or products, and is represented by the land, soil and water on which crops, grass and livestock production are dependent. Given the central role of rainfall and water in agriculture (as shown within the DPSIR schematic–**Figure 5**), improving natural capital through improved soil and land management to increase soil water storage and availability is a foundation of drought resilience (Rockstrom, 2003; Vogel et al., 2012; Rial-Lovera et al., 2017). For irrigated agriculture, this also needs to be augmented by an abstraction management regime that is sufficiently dynamic and flexible to create market or regulatory signals that promote an efficient allocation and use of water that balances the needs of the environment with abstractors (Ofwat and Environment Agency, 2015).

Human capital is the representation of people's health, knowledge, skills and motivation, which are all needed for productive work and which are important for resilience

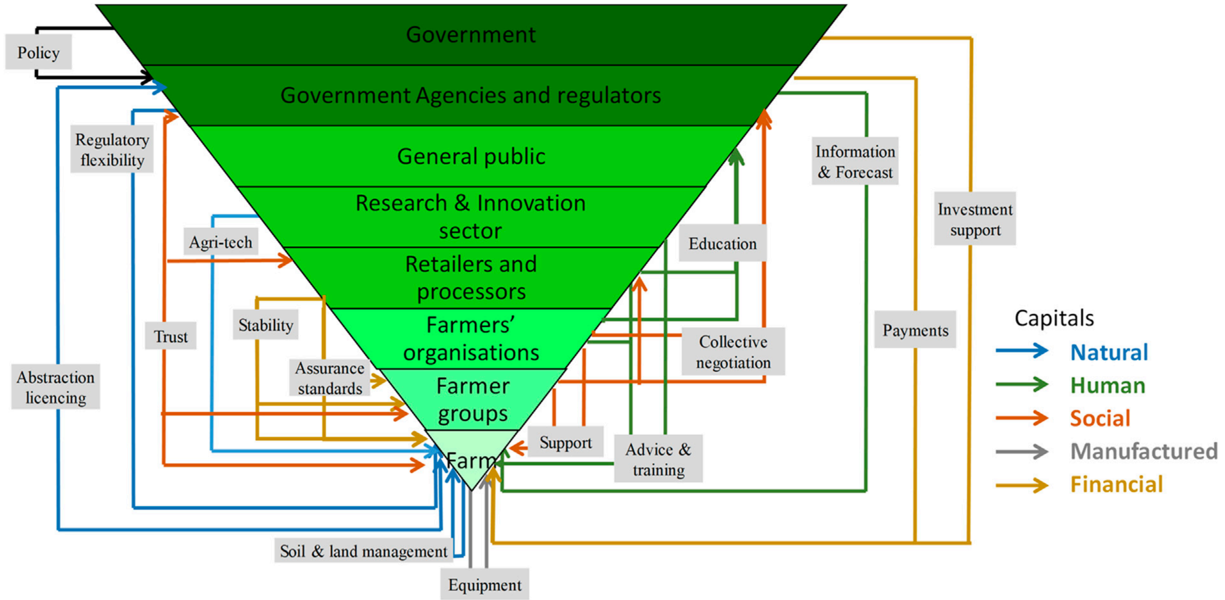

FIGURE 6 | Drought management framework for agriculture, showing the multiple levels of institutions and the relationships between broad actions and capitals.

(Himanen et al., 2016). Being able to appraise and appropriately implement adaptive responses requires improved knowledge and capacity throughout the production system from farmers and agronomists to retailers and consumers (**Figure 6**); and into the system from data and service providers (Hannaford et al., 2019; Haro-Monteagudo et al., 2019; Prudhomme et al., 2019) and agri-technologists (Lowry et al., 2019). While farmers can rely on their own human capital, it can be strongly enhanced by connectedness to shared resources via social capital (Darnhofer, 2014). Social capital is the sum of the institutions and associated networks that help maintain and develop human capital in partnership with others. This includes families, communities, businesses, trade unions, educational establishments, and voluntary organisations. The importance of social capital for enhancing drought resilience is evidenced from the range of actions (**Table 2** and **3**) across governance levels (**Figure 6**) that enhance knowledge development (e.g., provision of agronomic advice), collaboration (e.g., development of water abstractor groups, Leathes et al., 2008), trust, negotiating power (producer groups, water abstractor groups, Whaley and Weatherhead, 2015), risk-sharing (co-operatives, farmer producer groups) and risk balancing (e.g., supplier networks, Hess and Sutcliffe, 2018).

Financial capital (e.g., shares, bonds, cash) enables the other types of capital to be owned and traded. To date, public financial support to agriculture, for example through the European Union's Common Agricultural Policy (CAP), has generally not targeted supporting adaptive changes, with agri-environment payments based on profits-foregone which provides limited incentive for adoption. However a movement toward targeted payment for public goods (Bateman and Balmford, 2018) and payment for ecosystem services (Waylen and Martin-Ortega, 2018) provides the opportunity for a win-win in which enhanced financial support for critical public goods such as carbon sequestration and flood regulation can also help enable agricultural measures that deliver increased drought resilience (Salmoral et al., 2020a). Finally, manufactured (or built) capital is the material goods or fixed assets contributing to the production process, but which are not part of the output, e.g., tools, machines and buildings. Being able to invest in on-farm water storage, irrigation equipment, climate-adapted buildings and storage facilities provides robustness to reduced rainfall, water availability and food production. However, it also requires access to some or all of the other "capitals"; to human capital (for the knowledge to plan, design, and implement), social capital (to facilitate business relationships that provide some degree of financial stability), financial capital (to finance investment), and natural capital (to access, for example, water).

Our drought management pyramid (**Figure 6**) provides an evidence-based and transferable framework to transition from coping (short term) to adapting (long-term) strategies to increase resilience to future droughts by better horizontal (farms, farmer groups, agricultural sub-sectors, agricultural sector) and vertical (supply chain, regulator) integration. This requires increased and improved collaboration and engagement across spatial, governance and supply-chain scales (**Figure 6**) that develop human capital (knowledge) and social capital (trust). Many relevant adaptive actions are initiated reactively at short-notice as drought impacts manifested, as seen in 2018. The challenge for the agricultural industry, supply chain, regulator and government moving forward is to convert this *ad hoc* reactive learning into anticipatory longer-term measures that support drought resilience, food security and rural livelihoods while protecting the environment.

CONCLUSION

Agriculture has always been exposed to climate extremes, whether to agricultural and/or hydrological droughts, and this situation is unlikely to change (Grillakis, 2019). The 2018 drought in the United Kingdom demonstrated how agricultural systems in humid temperate regions are vulnerable to drought, with drought impacts reported across rainfed and irrigated production systems and in livestock, arable and horticultural farming. Despite a number of drought events over the past 40 years, the diverse range of drought responses were mostly focused on short-term actions to cope with, or enhance the recovery from, drought. This arises, in part, because adaptive strategies that increase resilience, through building diversity, redundancy or headroom, carry costs which many businesses are unwilling or unable to carry or which are utilized to enhance economic efficiency given competitive operational environments and low profitability. Transition from coping (short-term and reactive) to adapting (longer-term and anticipatory) strategies to increase agricultural resilience to future droughts requires improved collaboration across spatial, governance and supply-chain scales that develop human capital (knowledge) and social capital (trust). Industry, supply chain, regulators and governments need to work together to use the learning from recent droughts to develop a drought strategy that improves drought resilience, food security and rural livelihoods while protecting the needs of the environment.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: United Kingdom Data Service [https://reshare.ukdataservice.ac.uk/854457/ and https://reshare.ukdataservice.ac.uk/853167/] and Cranfield Online Research Data [https://doi.org/10.17862/cranfield.rd.13259291].

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Cranfield University Research Ethics System. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Conceptualization, IH, TH, and JK; Methodology, IH; Formal Analysis, IH; Investigation, TH and DR; Data Curation, DR and TH; Writing—Original Draft Preparation, IH; Writing—Review and Editing, IH, TH, DR, and JK; Visualization, IH; Project Administration, IH; Funding Acquisition, IH, JK, TH, and DR.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2020.589871/full#supplementary-material.

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Towards 'Creative Participatory Science': Exploring Future Scenarios Through Specialist Drought Science and Community Storytelling

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There is a growing interest in different forms of participatory modeling that bring science and lay knowledge into the same space. This recognizes that, traditionally, the environmental science community has mostly seen stakeholder engagement as a 'follow on' activity to be undertaken once the key scientific research has been completed. By excluding communities from the scientific process, or at best approaching communities in one-way communication, scientists are missing out on the wealth of local community knowledge about the very facets of the environment which they seek to understand. The challenge, however, is in identifying, developing and adopting appropriate platforms for communication and co-creation to allow scientists and local communities to have effective dialogue, efficiently gather, interpret and evaluate lay knowledge, and develop relevant, scientifically robust, but widely comprehensible, results. DRY (Drought Risk and You) was a 4-year project, funded under the RCUK Drought and Water Scarcity Program, with the aim of developing an evidence-based resource to support better decision-making in United Kingdom drought risk management. In DRY, scientific data and multiple narrative approaches have been brought together to facilitate decision-making processes and improve community resilience. Creative experiments were designed by the DRY interdisciplinary team to engage local communities in using specialist science as a stimulus for storytelling at catchment level, but also to give scientists the insight required to develop meaningful scenarios of local change to explore potential drought impacts in a particular river catchment. One challenge of working with storytelling is that it is very often retrospective and linked to past experiences and memories. It can be seen as a backward-looking activity, learning principally from what has happened before. The participatory approaches applied in DRY demonstrated that storytelling can be also used to imagine, interrogate and plan for a future that communities might collectively wish to subscribe or adapt to. In particular, by co-designing and facilitating storyboarding workshops, the DRY team, together with local stakeholders, have been exploring the 'scenario-ing' of possible futures as a way of creating a story and visualizing a picture for the future of the community. By allowing the scientists, community and local stakeholders to develop model drought scenarios iteratively together using storytelling, these scenarios should not only be scientifically accurate, but should also reflect local interests and aspirations, as well as local drought mitigation practices. This process integrates valuable knowledge exchange and the building of mutual capital to support local risk decision-making - scaling up from the level of the individual to the collective.

Keywords: drought, hydrological modeling, storyboarding, scenarios, participation, open science, creative experiments, Community

INTRODUCTION

Drought is a slow onset, diffuse, pervasive, 'hidden' risk that tends not to connect with the public psyche unless through intense heat. It is set to increase within the Anthropocene (Van Loon et al., 2016). As a complex uncertain hazard, drought is socially constructed differently across diverse publics and sectors (Taylor et al., 2009). It also provides well known perceptual and public risk communication challenges among different stakeholder groups (Weitkamp et al., 2020). Past experience of severe drought in the United Kingdom is highly variable, depending on geography, personal activities and local impacts, as drought infrequently develops into full blown 'water supply' or 'socio-economic' drought (see Wilhite 2011 for drought typology). Unlike flooding, at the other end of the hydrological risk spectrum, drought is not easily observed or visualized locally at least in its early stages, and tends to get scant media attention until well into a drought situation. This poses questions about how to engage different publics in resilience thinking about future drought risk, and what the role of visualization in daylighting a hidden risk could be in these engagement processes. The imperative for citizen involvement in local governance, including water risk management, is playing out at a range of scales, linked to diverse agendas (increased recognition of value of local knowledge, climate resilience, austerity etc., McEwen et al. 2020). In tandem, there is increasing concern to develop methods of meaningful participation in environmental decision-making, building on early thinking within Arnstein's 'ladder of participation' (Arnstein, 1969) in how to achieve 'higher rung Arnstein', and relationships between participation, social learning and knowledge for local decision-making (e.g., Callon, 1999; Collins and Ison 2009). This involves exploring the role of the citizen in these processes, how that might be supported, and different understandings of what ecological and hydro-citizenship might look like in an increasingly uncertain future (McEwen et al., 2020). This is evidenced in a growing body of research focused on the tools and methods in participatory modeling with at risk communities mainly related to flooding (e.g., Landström et al., 2011). There is also growing interest in research and practice about anticipatory adaptation (DeSilvey, 2012), and what 'resilience thinking' looks like in practice and, how it might be encouraged (Walker and Salt, 2012; Sellberg et al., 2018).

This interdisciplinary research reflects on ways of interweaving science and narrative approaches for understanding future drought risk within a specific case-study catchment. It analyses its impact on both research and public engagement processes and the different participants. This paper aims to:

- share an emergent creative participatory methodology for bringing science and narrative into the same space as a platform for supporting resilience and thinking about possible adaptive scenarios for uncertain and hidden future risks;
- reflect on the implications for opening up of complex and uncertain science in ways that engage different publics in future thinking;
- critically reflect on the implications for the role of 'storying' in participatory methods not only to encourage creative local resilience thinking, but also to develop locally resonant and meaningful scientific scenarios.

Mirroring the nature of the interdisciplinary and transdisciplinary dialogues that have generated the most innovative insights in the DRY Project, this paper includes multiple voices and proposes different ways of thinking about the process from science and narrative perspectives.

CONTEXT

The shift from uni-directional communication to knowledge exchange and co-generation is a journey of travel involving transitioning (see below/5). Communicating about United Kingdom drought risk, as a hidden risk, is a recognized challenge across stakeholders and sectors (Weitkamp et al., 2020). Most often this risk communication is left to statutory organisations – the water supply companies and environmental regulators – and tends towards one-way or broadcast models. Participatory modeling is classically construed as the bringing together of natural and social sciences (specialist hydrological modeling science and participatory methods). Examples include work on 'environmental knowledge controversies' in flood risk management (Whatmore, 2009). While historically specialist science has been the principal evidence used to support drought risk decision-making, growing recognition exists of the value of local or lay knowledge in local risk management (McEwen et al., 2016), the importance of anticipatory histories (De Silvey, 2012) and anticipatory adaptation and transformation in socio-ecological climate resilience (cf. Shinn, 2018). Recognition also exists of the hybridity of knowledge; for example, Haughton et al. (2015) argue for hybrid knowledge formation and co-production in flood knowledge. In a different take on participatory methods, Holmes and McEwen (2020) explored the role of digital storytelling as creative action in capturing local flood knowledge for resilience and exchanging it from recently flooded communities to those without recent flood experience that faced future flood risk. Elements that traveled included psychological resilience, empowerment and community cohesion during flooding.

Personal storytelling, or sharing of 'small stories', has been explored as a participatory method in other small group settings, for example, in public engagement, deliberation and dialogue to understand public, environmental and governance issues where there may be conflict or argument (e.g., Endres (2012) on competing values in participation). Storytelling can assist individual participants to overcome barriers to deliberation such as limited knowledge as well as having a collective function in building a sense of community (Ryfe, 2006). This approach can allow participants to establish important interactional identities (see Sprain and Hughes, 2015). Black (2008, p. 93) argues that such storytelling can be "a bridge between dialogue and discussion" with stories inviting "dialogic moments because they help group members negotiate the tension of self-other". Forms of expertize in deliberative environmental forums can be differentiated into institutional, local and issue (Sprain and Reinig, 2018). They emphasize the importance of thoughtful deliberative designs and alternative forms of reason-giving that reduce hierarchies, recognize different ways of knowing and support conditions needed for democratic deliberation (see also Sprain et al. (2014) re careful consideration of communication design in deliberative forums).

The Connected Communities Program of research, an initiative by the United Kingdom Arts and Humanities Research Council which began in 2011, supported the participatory turn in research, and, considering different disciplinary traditions in participatory research, expanded the opportunities for academic researchers within the arts and humanities to work with communities in new collaborative ways. This was "characterized by a radical intermingling of disciplinary traditions and by creative methodological experimentation" (Facer and McKay in Banks et al., 2019, p. xii). This strongly recognized communities as repositories of local knowledge, emphasizing them as co-researchers, co-creators, co-producers of knowledge (Facer and Enright, 2016). While participation and consultation have long been a part of research approaches in participatory design, citizen science and participatory action research, for example, the Connected Communities program supported a more fundamental shift in power within the research process.

As stated by Banks et al. (2019, p. xii) 'academic research is increasingly realizing the critical importance of community knowledge in producing robust insights into contemporary change in all fields'. This recognized the value of the different types of knowledge and ways of thinking that emerge from communities' deep connection to their geographical and temporal landscape, and which communities can contribute to processes of interrogation, knowledge production and critical imagination.

The DRY (Drought Risk and You) Project

The four-year, interdisciplinary DRY (Drought Risk and You) project aimed to improve the evidence-base to support better catchment-based drought risk decision-making in the United Kingdom. The team involved drought risk modellers, ecologists and agronomists working with specialists in narrative methods from the arts, humanities and social sciences. The original concept of DRY was to explore different ways to bring together specialist science (in particular, hydrology, ecology, agronomy) alongside stories as an evidence base to support decision-making. This recognized that there is a wide interest in research and practice about how different knowledges come together (Lewis, 2011; Bourbonnais and Michaud, 2018). DRY undertook a series of creative experiments to bring science and narrative approaches into the same space. Its design involved working with diverse stakeholders in seven case-study catchments on gradients (hydrometeorological; urban-rural) across the United Kingdom. The Bevills Leam catchment in the Fens, Eastern England was one such catchment.

The adaptive participatory storytelling approaches that emerged within DRY are outlined in Bryan et al. (2020). This research involved longitudinal co-working with multi-stakeholder, catchment-based, local advisory groups, and multi-stakeholder partners within that process. These local advisory groups met six times during the funded lifespan of the DRY project. The United Kingdom Center for Ecology and Hydrology had a crucial role in facilitating this process within DRY in a number of settings, and, in particular at the catchment level within the Local Advisory Groups (LAG), to share their science early on, and to use that as a stimulus for people to talk about their experiences of drought as part of an arts and humanities rich process for the co-production of knowledge.

The DRY-LAG process was one of true iterative co-development which drew upon local knowledge, data and understanding to improve the drought risk hydrological modeling, to develop and identify locally resonant climate change, land use change and catchment management scenarios, and to explore potential drought risk mitigation measures. At the same time, it also opened up the modeling process, revealing the complex decision making and thought processes behind hydrological model development. It has gone a long way towards addressing the perceived challenges of incorporating citizen science in hydrology (Buytaert et al., 2014).

This paper focuses on one of the creative experiments in that process, drawing on experiences of implementing what we have called a 'scenario-ing' process (which includes participatory scenario building, scenario making, scenario designing) in the Bevills Leam catchment. Qualitative scenario development has been used as a tool in various disciplinary research and practice, sometimes combined with participatory methods that involve stakeholders. However the emergent approach in DRY involved explicit co-working with the arts and humanities in the co-development of its participatory scenario-ing methods involving storytelling, and in particular storyboarding techniques. This specific approach was the result of a co-design process that was implemented through a cross-fertilization of different storytelling approaches as a way to:

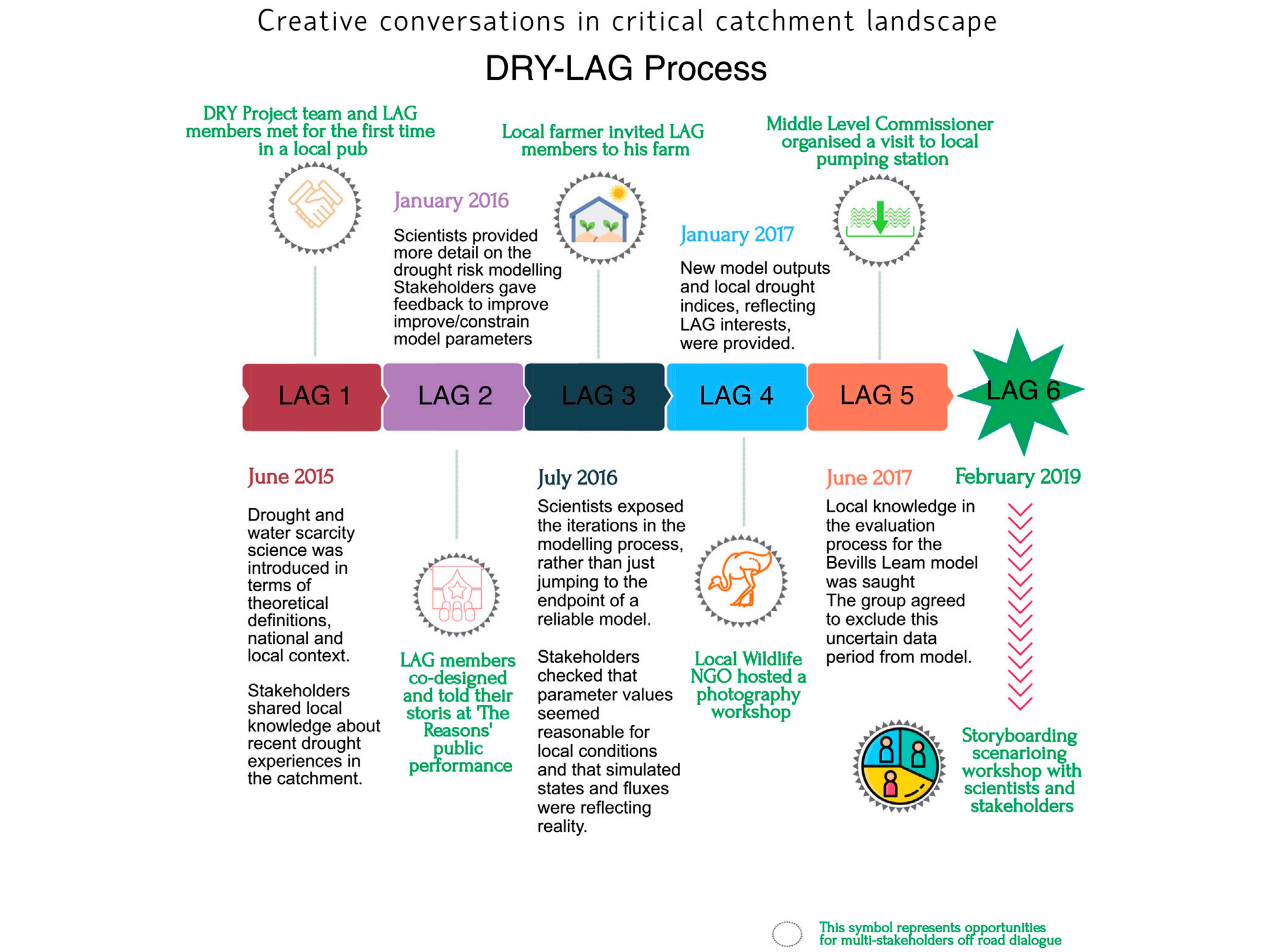

FIGURE 1 | Timeline for stakeholder engagement in the Bevills Leam catchment, indicating past reconstruction and future facing scenario-ing activities.

understand the science behind drought; bring together people from different sectors to discover hidden stories; amplify silent voices and visualize the hidden; dismantle knowledge hierarchies (lay vs. scientific); combine traditional forms of communication with various creative practices (including storyboarding, song-writing, performative and digital storytelling); and rethink open science in an transdisciplinary scenario-ing context.

Bevills Leam as a Case-Study Catchment

The Bevills Leam catchment is a 179 km^2 area of the Cambridgeshire fens in the East Anglia region of the United Kingdom (see Blake and Acreman, 2009; Blake et al., 2012; Blake and Ragab, 2014). The area is predominantly low lying, with large areas at or near sea level. In the 'lowland' area, the soils are generally peat overlying impermeable clay. The hydrology in the area is highly managed following intensive drainage of the peat in the 1800s and earlier to provide land suitable for agriculture. Peat drainage, shrinkage and wastage mean that significant parts of the 'lowland' catchment area are now below sea level. There is a pumped drainage system whereby water levels in the high-level main drains are managed by the Middle Level Commissioners, with water eventually being removed from the catchment at the Bevills Leam Pumping Station at Tebbits Bridge (see **Figure 1**). Other relatively smaller drains are controlled by local Internal Drainage Boards, farmers, the local Wildlife Trust and Natural England. Water level management balances winter flood relief, water storage for irrigation and water levels for boating navigation. There is extensive agriculture in the area with crops including cereals, sugar beet, potatoes, onions and carrots. Much of the horticultural crops are irrigated, traditionally by spray irrigation but with some recent movement towards more water conserving techniques. Irrigation water sources may be direct from the drains, but due to limited summer resources, there have been more recent moves to storage of winter water for subsequent summer use. The catchment is also the location of nationally significant wetland restoration, the 'Great Fen Project' (see *Community Storyboard Scenario-ing Workshop with the Great Fen Project*), which aims to restore up to 37 km^2 of wetland linking the Holme and Woodwalton Fen National Nature

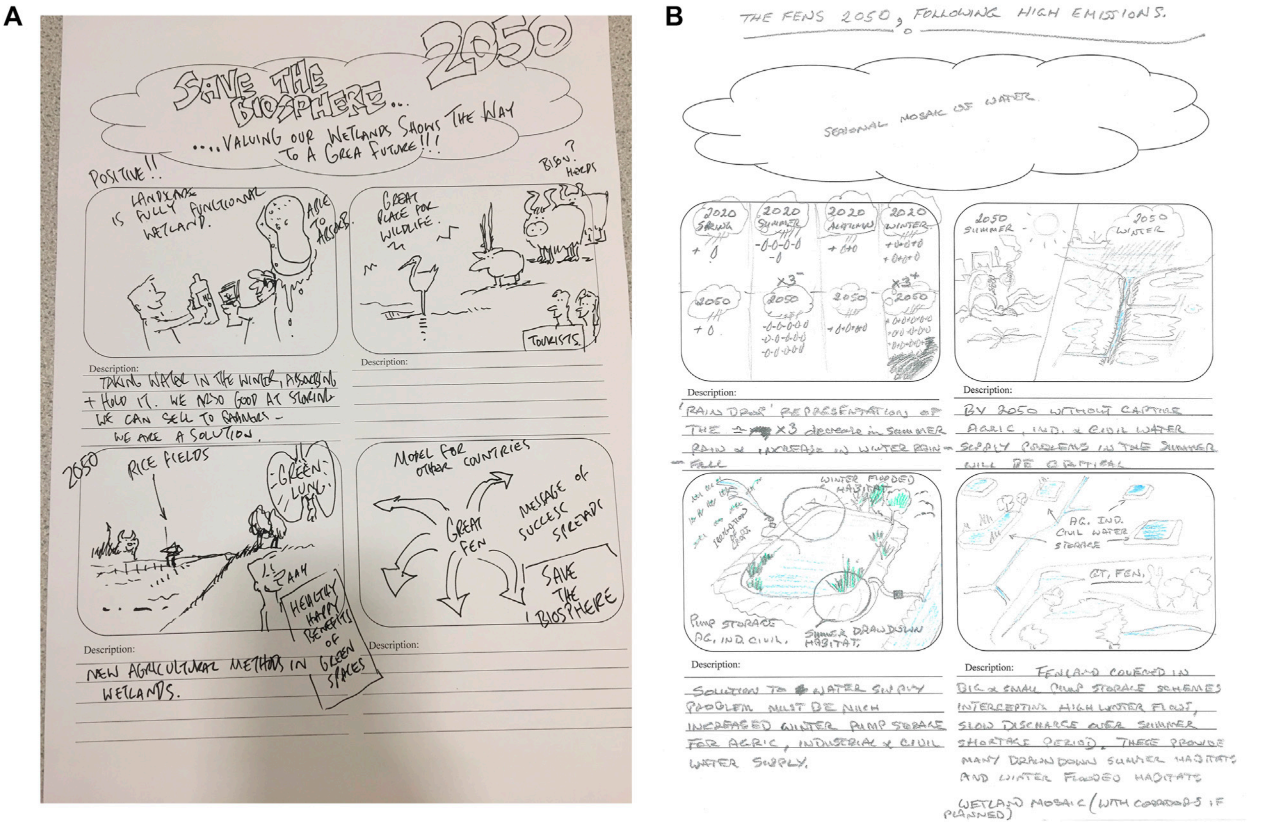

FIGURE 2 | (A,B) A storyboard created during a public engagement event in the Bevills Leam catchment.

Reserves. There are scattered rural villages, hamlets and farms throughout the catchment, with the larger villages of Yaxley and Ramsey to the NW and SW of the catchment respectively. The city of Peterborough is just beyond the NW catchment boundary. The catchment is within one of the driest regions of the United Kingdom, with only 630 mm average annual rainfall (1961–90). Recent drought experience includes: 1965, 1973, 1976, 1990, 1997, 2003 and 2011–12.

METHODS

This section shares the progressive opening up of the science as a precursor to working creatively with the science as a stimulus to the storyboard scenario-ing. It then outlines the initial interdisciplinary scoping of scenario-ing and the emergent methods that followed.

The LAG Process: Communicating Drought Risk and Opening up the Science

An overview of how the interaction between scientists and local stakeholders happened within the Bevills Leam catchment over three years is proposed in chronological order (from the first to fifth Local Advisory Group meetings) to reflect on some crucial steps that could inform future similar research processes. The drought risk science then became a forward-looking activity in the sixth LAG during which scientists and stakeholders explored together the creative use of storyboarding techniques to understand potential impacts of various scenarios on personal lives (**Figure 2**).

During the first LAG meeting, drought and water scarcity science was introduced in terms of theoretical definitions, and national and local context. A key element of this initial interaction with LAG members was to garner local knowledge about recent drought experiences in the catchment. For our scientist, it was essential to present the identified local events as tentatively ascribed on the basis of available high quality, national hydrological datasets, while explicitly highlighting that the reality or experience on the ground might not always match the theory. This provided an opportunity to start working together to compile and refine local drought knowledge. The meeting was also an opening to introduce the Bevills Leam hydrological model (Blake et al., 2012), which had originally been developed to provide an assessment of the feasibility of wetland restoration in the catchment. In the LAG, the scientist outlined how the model might be improved and developed further as part of DRY to investigate drought risks and impacts across sectors and the potential for locally-defined drought indices. This included initial conversations about accessing local (hard?) data which could support the drought risk hydrological modeling. Key to this was having local contacts on the ground - gatekeepers, who knew what data might be available and could help facilitate access.

The second LAG meeting provided further detail on the drought risk modeling, highlighting progress with setting up the model, initial exploratory model simulation runs and recent/potential model developments to improve hydrological process representation. It provided an opportunity to start using local knowledge to attempt to improve/constrain model parameters. It was important to emphasize that scientific models are by definition a simplified representation of reality, seeking to incorporate key processes at a scale relevant for their intended purpose. It was also crucial to highlight that the data used in the modeling also had gaps and uncertainties, and how these could be accounted for. Drawing these two themes together converged to the concept that although hydrological modeling has a sound theoretical basis, its application can be a far messier, fuzzier process with the need for a good degree of pragmatism. Opening up the scientific process in this iterative way therefore attempted to provide reassurance to the LAG members that their local knowledge could also make a valuable contribution to the drought risk modeling.

The third LAG was unusual in that it exposed the iterations in the modeling process (model setup, calibration, development, 'validation'), rather than just jumping to the endpoint of a reliable model. The modeling process is a journey, along which various decisions are made, some of these turn out to improve the model, others might be less successful or even make the model worse. It is not unusual to revisit previous decisions and follow alternative routes to attempt to improve the model. For Bevills Leam, early models were not particularly reliable, and a series of model process developments were needed to provide improvement (following the flexible approach to modeling advocated by Bredehoeft (2010)). It was particularly useful from a drought scientist's perspective, to be able to run the trial model calibrations past the LAG members, to check that parameter values seemed reasonable for local conditions and that simulated states and fluxes were reflecting reality. This has clear parallels with the suggestion to incorporate experimentalist's qualitative 'soft' data about process understanding in model calibration (Seibert and McDonnell, 2002), advancing hydrological model testing to get the right answers for the right reasons (Kirchner, 2006), and innovative approaches to help identify hydrologically realistic catchment models (Wagener, 2003). It could even be seen as a qualitative form of model 'internal validation' (Fawcett et al., 1995). The LAG process facilitated this exchange as by the third LAG, a good open working rapport had built up within the group, so our scientist felt comfortable sharing interim results which were still undergoing improvement.

The fourth LAG meeting focussed on further model development and improved calibration for Bevills Leam. As the Bevills Leam modeling used a tailor-made catchment water balance model (due to the unique hydrological characteristics of this pumped drainage catchment), there was greater flexibility to provide new model outputs and local drought indices, reflecting LAG interests.

The fifth LAG meeting provided a novel opportunity to include local knowledge in the evaluation process for the Bevills Leam model. At this point, our scientist believed that the development of a reliable model was near completion as the final calibration had realistic parameters and reasonable 'goodness of fit' measures. However, although the model could generally replicate the monitored flow data, there was a data period which could not be simulated successfully with the calibration parameter set. Our scientist's inclination was to exclude this period of uncertain data; however, he did not feel able to justify this decision based only on intuition as although the data appeared unreliable, a cause could not be identified. He therefore sought advice from the LAG members, in case there was a local factor at play during this period which may have been responsible for the unusual hydrological response. The group could not identify any local factor, and therefore the group agreed to exclude this uncertain data period from the model. That incorporation of local knowledge provided a more secure justification for this exclusion, rather than just relying on the hydrological modeller's intuition. This could be seen as a novel approach to the issue of excluding periods of hydrological disinformation, as raised by Beven and Westerberg (2011).

Particular benefits of including local knowledge and understanding in the model development process included: i) guidance on how to represent complex hydrological systems in the modeling, e.g. pumped drainage system operation (Bevills Leam: Middle Level Commissioners); ii) confirmation of potentially unreliable data and more secure justification for its exclusion; and iii) ensuring that the model parameters and modeled states/fluxes are reasonable, reducing potential over-reliance on statistical goodness of fit measures. This relies on an open-minded approach from the hydrological modeller, with respect for different forms of knowledge and understanding. It also depends on the LAG members being convinced that qualitative knowledge can be incorporated into the modeling approach. Opening up the modeling process helps greatly in this regard as it exposes the myriad of decisions and iterations needed to develop a reliable model. In this aspect, hydrological modeling can perhaps be seen as part science and part art, incorporating both hard data and process understanding, but also experience, ideas and intuition.

The iterative process of model setup, calibration, improvement and 'validation', can also be seen as essentially a backwards looking activity, using past data and knowledge to create as reliable a model as possible at the present time utilising current scientific and lay understanding. This formed the basis for the forward looking scenario-ing work that followed in the sixth LAG, when the model is 'driven' with data representing different scenarios of possible future climate, land use and water management change.

Interdisciplinary Perspectives on Scenario-Ing

Alongside this emergent process of opening up the science, the DRY team reflected on the possible framing and practice of 'storyboard scenario-ing' drawing on its interdisciplinary expertize. While DRY faced opportunities and challenges in adapting well-established storytelling methods, our processes built in iterative opportunities to reflect collectively on, and confront, what can be understood as 'storytelling', and how this might be applied to bridge scientific and 'lay' knowledge. This involved adopting and re-adapting multiple narrative approaches, with the awareness and willingness to take risks and receive unexpected responses. Our processes aimed to advance knowledge on how drought impacts on different communities and different sectors in nuanced ways and, importantly, to increase their potential agency in adaptation to future drought risk.

The original DRY methodology had 'scenario-ing' as a bridging concept and major element in considering past, present and future drought risk in adaptation. Qualitative scenarios have been used as an approach in other participatory contexts over the last couple of decades, mainly from social science perspectives co-working in socio-environmental systems analysis to support decision making and learning (Elsawah et al., 2020). Such scenarios can be considered as qualitative, ideally integrated storylines (cf. Kok et al., 2006). Reed et al. (2013)'s development of a methodological framework for participatory scenario development cites strengths including the empowerment of stakeholders and the development of robust scenarios that help more effective preparation for future change. Qualitative descriptions of plausible futures have been translated into quantitative modeling (cf. Rao Mallampalli et al., 2016). The European Environment Agency[1] defines the 'story-and-simulation' approach to (environmental) scenario analysis as one that combines different types of information: "narrative describes in story-form how relevant events, key driving forces and step-wize changes unfold in the future. The results from model calculations complement the storyline by presenting numerical estimates of environmental indicators". Critical in framing these methods is the disciplinary understanding of 'narrative' and 'story', and the participatory roles and sequencing within science-narrative processes.

DRY in its transdisciplinary methods involving the socially-engaged arts conceived 'Storytelling scenario-ing', as a possible softer, more fluid way in for community engagement, dialogue and deliberation. Such scenario-ing has potential to release the mind to explore possible futures, and free stakeholders' thinking from the constraints of current water realities, current water governance, current institutional or personal thinking. Nevertheless, this approach presented multiple challenges linked to the different disciplinary and professional understandings of the term 'scenario', and also related to the specific context in which we were delivering our public engagement activities: across catchments and within each catchment. We had to respond creatively to challenges linked to the drought risk focus (challenge: how to engage the public with a hidden risk?), the timeliness of our work (challenge: how to discuss future drought risk in periods with water excess?) and locations (challenge: how to connect with a changing landscape without being actors of change locally?).

[1]https://www.eea.europa.eu/help/glossary/eea-glossary/story-and-simulation-approach

Co-production was a key component of the DRY project and unfolded as an iterative process applied at various stages (for the definition of research problems, delivery of activities, analysis of the results) and various levels (within the research team; with the Local stakeholders involved in the six Advisory Groups; with the general public). At team level, our reflections on the various meanings of key terminology from different disciplinary perspectives enriched the collaborative process at an early stage. 'Scenario' was one of the multi-meaning terms approached, unraveled and explained from each disciplinary perspective represented within our team, not only to bridge these diverse approaches, but also to shape our thinking while extracting and understanding different meanings. In fact, this 'lexical' analysis offered new angles to reflect on how to engage different water users about future drought risk, water scarcity, water shortage, and water efficiency. In a video recorded during an early project team meeting (https://youtu.be/AGPPIHyEcpw; https://dryutility.info/science-and-narrative/), we summarized our multiple understandings of the word 'scenario' from different disciplinary perspectives including hydrology, business, agronomy, ecosystem services, drama, media and communication. From each of those very particular definitions, we extracted key components of what a 'scenario' is as understood in various disciplines, to elaborate new creative tools and engage the general public around issues concerning future droughts in the context of climate change. From a hydrological perspective, scenario was defined as 'a reaction to a hypothetical situation assumed under a *what if* action'. From this approach, we adopted and re-used the notion of 'what if' as a first step to present scientific data to the general public, showing the impact of multiple changes, and to find an accessible common ground to analyze various future projections.

Within business, they talked about scenarios (in its plural) as 'stories that encapsulate possible imagined futures'. From this approach, we understood how important it was to make clear to a wider audience that scenarios are not tools for predictions, but tools to try and surface barriers and enablers that, from a business perspective, might 'aid decision-making and help organisations to be better positioned for the future'. This aspect was particularly useful when we had to design engagement activities for organisations that are working in turbulent and dynamic environments, or environments that are characterized by a large degree of uncertainty. From an agronomics perspective, scenario was defined as 'a plan of specified events to be considered, studied or investigated' and the importance of addressing the unknown while emphasizing the role of knowledge exchange was strongly emphasized. A technically precise description was offered by researchers in ecosystem services where 'scenario' was understood as 'a resolution of a range of drivers of change into principal components, structuring the development of a set of *plausible futures* which collectively illustrate different trajectories within what is known as a *possibility space*'. The notion of a 'possibility space' informed our process in terms of creating new tools to make accessible this exploration of the possible. Talking about 'scenario' from a drama perspective brought into the transdisciplinary dialogue a completely different voice, harking back to the origin of the term 'scenario':

It is, in fact, a word that comes from the Italian 'Commedia dell'Arte', which was an improvised form of theater. Within that original context, the 'scenario' was the piece of paper that was pinned to the back of the scenery to sketch out the structure and key points of the action of the play, around which the actors would improvise. Another distinctive reflection came from a media and communication perspective, from which the importance of understanding who is defining what a scenario is, as well as the meaning of the word itself, was highlighted. Google's search algorithm and ranking system suggest as dominant visual representations of the term 'scenario', images related to planning, pathways, opportunities and decision-making. In addition to the conceptual input offered by the previous definitions gathered within our team, these last two reflections, informed by the arts and social sciences, inspired the form and the structure of the creative tools initially proposed and then co-designed with our Local Advisory Groups, and eventually applied in working with the general public to trigger individual and collective explorations of possible futures. While we used the active term 'scenario-ing' in our team creative experimental processes, in our discussions with Local Advisory Group stakeholders, we agreed 'What if' to be a more accessible way forward for engagement. We spent considerable time creating accessible bite-sized science resources that could act as stimuli for exploring 'What ifs' around possible futures. These included two red/blue tables of summary UKCP09 projections with % change in average temperature and rainfall, along with % change in frost free days and cloud cover for those interested in growing.

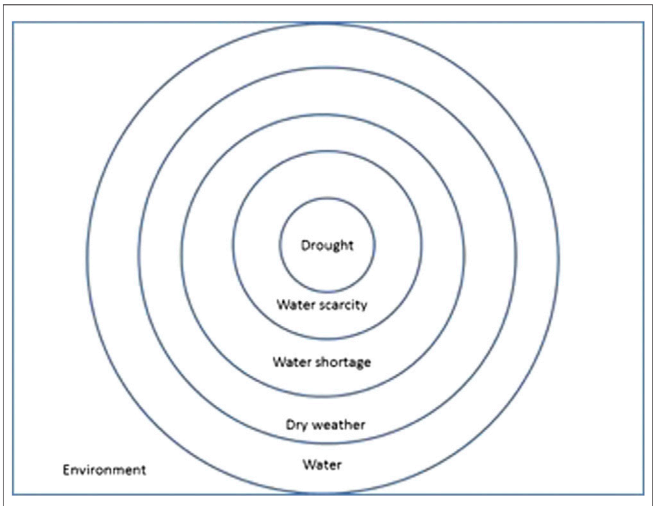

FIGURE 3 | A bull's eye target as a way of defining the spectrum of themes included in the DRY Story Bank.

Our Emergent Process: 'The Reasons' as Initial Future-looking Storytelling Process Within the Bevills Leam Catchment

The co-production process, triggered within the Local Advisory Groups (LAG) in each of the seven catchments selected as case studies in the DRY project, was found to be particularly successful in the Bevills Leam catchment, a rural area in Cambridgeshire described in *Bevills Leam as a Case-Study Catchment*. Stakeholders' engagement in the research at local level offered the DRY academic team the opportunity to co-design context-tailored approaches, and to experiment with a variety of storytelling techniques that could respond to emerging community issues.

Within the Bevills Leam catchment, LAG members also participated in additional public engagement and dialogic activities, such as two public storytelling events, a visit to a local farm, an excursion in the Great Fen nature reserve, a visit to the Bevills Leam pumping station, a photography workshop, and a storyboarding workshop (see **Figure 2**). Through their professional and personal views, the Bevills Leam LAG members inspired our initial future-oriented storytelling process and contributed to conceiving and planning a performance event aimed at capturing community views on local water dilemmas, unlocking their complexity, and questioning possible plans for the future. Two iterations of this performance event, called 'The Reasons', were organized in rural Ramsey and urban Peterborough with the idea of bringing together the local community to share stories about water usage, the flood/drought nexus, and to talk about common views and solutions for the future of the Fens (see video documentation: https://dryutility.info/reasons/). 'The Reasons' was devised by researchers from Loughborough University in collaboration with the local stakeholders as a forum for public storytelling (Bakewell et al., 2018). It was inspired by a traditional forum for conflict resolution that was used until the early 1960s, as an alternative to the official court system, in Gallura, a rural region in Sardinia, Italy.

This original 'judicial' procedure is best described by an oral testimony from November 1963, gathered by the local ethnographer Pietro Sassu (Sassu 2009). What was maintained in the adaptation created in the Fenland was the principal aim of 'la Rasgioni' (to give it its Sardinian name) that consists in preserving community cohesion and reinforcing local relationships by co-designing the resolution to a conflict. The local stakeholders in the Bevills Leam catchment wanted to avoid the word 'conflict' to emphasize the importance of opening up the discussion to the most diverse views on future-looking ways of managing water in the area, preferring to talk about 'water dilemmas'. To expand the range of 'characters' involved in the performances and gain a greater representation of 'voices', in addition to the 10 storytellers (recruited from the various organisations involved in the DRY Local Advisory Group), audience volunteers were appointed to an advisory jury to discuss potential disagreements and propose ideas for the future to the whole community. Another innovation, designed to support community cohesion and future-scanning, was the participation of a singer-songwriter to bring together all the views expressed by the storytellers and the jury, into a community song (see video co-created with local stakeholders: https://dryutility.info/reasons/), performed by all participants after the delivery of the conciliatory, future-looking verdict. As commented by one participant (and also commonly featuring on audience feedback forms), 'The Reasons' represented a new way of engaging people as they had learned 'a great deal about the complexities of water management', which they might not have known otherwise. This was perceived as particularly meaningful because participants (storytellers and audience members) were invited to challenge the various ways of approaching and dealing with those complexities, while reflecting on possible futures. This process attuned the participants to working with storytelling, and made them eager to explore further its potential.

Storyboarding as a Tool for Scenario-Ing

By experimenting with oral storytelling techniques to unlock community knowledge and mull over future water dilemmas on a stage in 'The Reasons', we moved a step closer to the potential use of that piece of paper pinned to the back of the scenery, that a storyteller would call the 'scenario' and here is presented as the 'storyboard' (see **Figures 3A,B**). During the preparatory work for 'The Reasons' and other follow-on discussions with team members and local stakeholders, we identified 'storyboarding' as a possible way to visualize future scenarios that could sit alongside the scientists' toolbox of drought visualization – graphs and maps of drought indices etc. Storyboards are widely used in film production and animation, and they consist of a series of pictorial frames to explore the use of points of view, camera angles, close-up, and to communicate visually the vision for the film or the animation to the wider team (script writers, photographers, filmmakers, directors…). Within this sector, storyboards are generally of a high standard and very detailed. Storyboarding for storytellers is mainly used as a technique to develop a narrative, create a structure and prepare the story for a live performance. Typically, for a storyteller, it would consist of 6–8 frames to describe visually the key moments of action and development of a story. For this specific use, even if the storyboard is visually represented, it does not require a particularly high standard, because it is serving only as a reminder and prompt to the storyteller. Linking back to the theatrical meaning of the word 'scenario', for a storyteller, a storyboard is in fact a scenario, and therefore a visual representation of the structure of a story around which they may improvise in telling their story. Storyboards are also used in other sectors, such as business, communication and marketing, design, for example, to develop ideas, explain concepts, plan actions, create new contents/media, describe user experience, instruct, communicate, imagine in a (chrono)logical sequence of actions (Nardella et al., 2014). Emerging from an understanding of these various approaches, the use of storyboarding was then proposed within the DRY project as a way of reflecting on the structure of a story about a possible future and making decisions around the characters involved in that story, the place, the key moment of actions, and how all the components will fit together. One reason why this approach is particularly effective to explore future scenarios, and to provide a tool to merge scientific and lay knowledge, is because, in order to put together a storyboard, we are required to think very carefully and very deeply how the story is going to unfold. In fact, when we talk about imagining stories about our drought futures, storyboarding has been revealed to be a useful way to build those stories and explore connections to place and people, and their implications for place and people, while understanding the science behind those risk projections. As a participatory workshop activity, it allows the bringing together of scientific information to be shared with the general public, and local knowledge shared by the local participants. It also facilitates conversations among different knowledge domains; and builds together various blocks of knowledge, perceptions, imagination, visual representation, into a complex and multimodal narrative in which different elements, 'voices' and characters can be combined.

It is interesting to note that when storyboarding was used as workshop activity, within the DRY project, the science shared with the audience is often presented in a visual format through graphs, charts and animations, and what happens at the end of this process is that the two elements of the DRY project, the science and the narrative, are both represented visually and discussed starting from the same mode of communication. Yet storyboarding provides opportunities not only to bring together two different types of knowledge into the same form, but also allows different knowledges to support or scaffold each other in developing new knowledge. This happens by enabling participants to identify assumptions within a specific context, to explore the impact of behavioural change in a certain scenario, and to offer personal insights within that scenario. Storyboarding works well as a group activity, as a clearly defined and achievable task that enables creative and reflective thinking, action on knowledge and social learning. It also produces a output that can be easily edited: the audio can be captured during oral sharing of adaptive thinking at the workshop, and the storyboard and audio can then be combined in a video for communication to promote further dialogue (see as example: https://dryutility.info/2019/02/08/the-fens-in-2050-following-high-emissions-seasonal-mosaic-of-water/).

CASE STUDY: STORYBOARD SCENARIO-ING IN THE BEVILLS LEAM CATCHMENT

An iterative 'build-up' process of participatory scientific scenario-ing was critical to the storyboard scenario-ing process.

Scientific Scenario-Ing

The proposed Bevills Leam drought risk future scenario modeling, while mentioned earlier in the project engagements, was formally introduced in the fourth LAG meeting. It was important to attempt to introduce the concept without using excessive technical jargon, with the following definition provided: 'Simulating the potential impacts of changing factors (e.g., climate, land use, water management etc.) on water resources and dependent activities'. Through the use of only example changing factors and the term 'dependent activities', this also attempted to promote the idea that the scenario-ing activity would be an 'open' concept with much scope for co-development, rather than something prescriptive or predetermined by the scientist. It was also very important to emphasize that the scenarios were not a prediction of the future, but merely an illustration of a range of possible changes and potential futures.

Since climate change scenarios, based on the latest United Kingdom climate change impact projections at the time (UKCP09), were likely to be of great interest and potential debate among the LAG members, while simultaneously being less open to technical critique by the group, these were introduced first (in terms of driving data for the model, rather than modeled water resources impacts). To avoid overwhelming the group, only three scenarios were selected for initial introduction, one based on the near future (2020s with 'Medium' greenhouse gas emissions), and then two on the more distant future (2080s) with an optimistic and pessimistic emissions scenario ('Low' and 'High' emissions respectively). The purpose of selecting the near future scenario was to slowly ease the group into the idea of future scenarios by presenting something which was only a slightly modified version of their current experience. The use of more extreme distant scenarios was an attempt to provoke discussion, in terms of the scale and direction of potential impacts and possible step-changed actions for resilience, while invoking a somewhat reassuringly distant time-period to avoid concerns about any perceived inability to influence the extreme scenarios. This happened intentionally during the sixth LAG when stakeholders and scientists participated to a storyboard scenario-ing activity together. It was assumed that there would be a range of familiarity with formal climate change scenarios among the LAG members, therefore, as the concept is relatively abstract, an attempt was made to tie this into local knowledge by sharing a screen grab from the UKCP09 web user interface which overlaid the projection data 25 km grid box on a basic map of the area to illustrate the that projections were indeed tied to the local. An attempt was also made to explain the probabilistic nature of the projections, and how this could be simplified to joint probability 'central estimates' of the most likely changes in average seasonal precipitation and temperature for the Bevills Leam catchment under the various scenarios. While 'central estimates' were found to be simple and effective for communicating the scenarios, this did put the scientist in a position of discomfort as the UKCP09 guidance recommends that these should not be used in isolation and a full range of probabilistic projections should be considered. The presentation ended with a slide outlining a number of potential 'scenario modeling ideas', under the broad headings of climate, land use and water management changes, with some suggested possible areas of exploration identified by the scientist on the basis of previous group discussions and knowledge of the catchment. All suggestions were presented as questions on the slide, to again try and emphasize that the process was open to co-development.

Three initial/trial land use change and water management scenario results were presented at the fifth LAG meeting. These results included example model output in terms of hydrological impact on crop yield, main drain levels and pumped drainage requirements, agricultural and habitat reservoir water levels and on wetland plant community hydro-ecology. Unfortunately, results from the UKCP09 climate change scenarios were not yet available to share due to additional model development required to estimate potential evaporation from the available projections and the need to estimate projected catchment inflows under the different scenarios. As with the initial climate change scenarios presented, the initial land use change scenarios reflected two extreme, end member states: the entire Bevills Leam catchment under either agricultural or restored wetland land use. These extremes were selected, not because they might be likely in reality, but because they would hopefully provoke useful discussion within the group which could be used to agree on more plausible potential scenarios, and also as a mechanism to investigate if the model outputs were sensitive to this change. In effect, this was a deliberate strawdog to be pulled apart, with the aim of encouraging a group, with potentially conflicting views, to come up with and agree upon more plausible alternative scenarios, which they would then have more interest in as they were part of the scenario development process. This appeared to work as the LAG participants developed several good ideas for locally relevant land use change scenarios. The third scenario involved more flexible water abstraction during the winter for storage in reservoirs and subsequent use for summer irrigation. This scenario had been developed from the previous LAG meeting discussion, and was shown to have multiple benefits in terms of increased drought resilience and reduced requirements for pumped drainage in winter. In an iterative process, it is essential to provide feedback along the way, in effect showing the results and benefits of previous co-development. This acknowledges the value of previous contributions and provides stimulus for future input.

The finalized results from the climate change, land use change and catchment management scenarios were shared at the sixth and final LAG meeting. There were nine scenarios, with four apiece for 'agriculture' and 'Great Fen wetland restoration' interests followed by a final merged continuing agriculture and Great Fen wetland restoration scenario under climate change (with 9 combinations of time period and emissions scenario). Based on local interests gathered through the LAG process, the agricultural scenarios included increased peat wastage, potential for reduced irrigation and potential for more drought tolerant crops. The Great Fen wetland restoration scenarios included more flexible water abstraction for winter storage, varying sizes of potential reservoirs for habitat restoration and the potential impact in a reduction in the water diverted into the catchment from the River Nene (due to increased abstraction for public water supply). These scenarios were really tied into the local, in terms of local crops, local wetland plant communities, local soils and local water management. It would not have been possible to develop such locally resonant scenarios without the LAG scenario-ing process. While sharing the results of the scenario modeling, it was important to acknowledge the LAG members who had contributed to the particular results being presented as the work was not solely the work of the scientist, but the co-produced work of the involved group as a whole.

Community Storyboard Scenario-ing Workshop with the Great Fen project

In addition to their involvement in the LAG process, some local stakeholders, working with the research team, co-designed public engagement activities to expand the exploration of future scenarios with the general public, as it

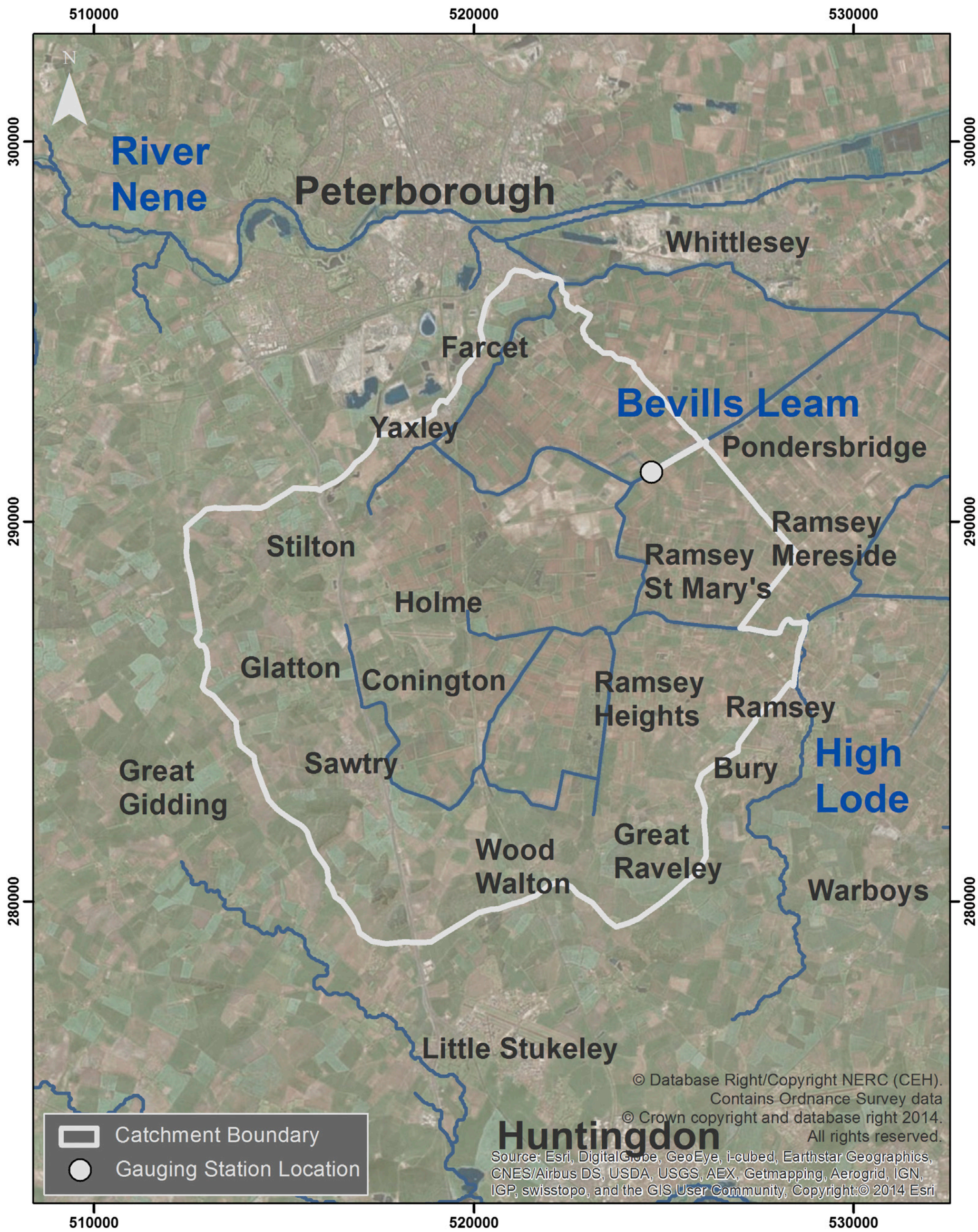

FIGURE 4 | Bevills Leam catchment map.

happened during the community storyboard scenario-ing workshop organized with the Great Fen project (**Figure 2**). The Great Fen project is an ambitious restoration initiative led by Environment Agency, Huntingdonshire District Council, Middle Level Commissioners, Natural England, The Wildlife Trust for Bedfordshire, Cambridgeshire and Northamptonshire, with the vision of restoring 14 square miles of land to wild fen and creating in 50 years-time a vast nature recovery network between Peterborough and Huntingdon, in Cambridgeshire. Since 2001, they have been undertaking local consultations and, more recently, they have been also contributing to research projects, such as DRY, to expand their public engagement activities and understand people's perceptions around their long-term plans. As part of DRY project, the Great Fen project was actively involved in the Local Advisory Group for the Bevills Leam catchment, and hosted local meetings and storytelling community workshops.

In February 2018, during a storyboarding workshop, facilitated in collaboration with the cartoonist John Elson, at the Wildlife Trust Countryside Centre, in Ramsey Heights, local community members were invited to imagine future water stories about climate change impacts in the Fenland in the next 30/60 years. Scientific scenario-ing was briefly introduced by examining potential future impacts of climate change at a local level, including accessible summaries of climate change projections for seasonal changes in temperature and rainfall compared to the 1961–1990 baseline period. Participants were then invited to use this scientific framework to set the context for their story by selecting one of the three potential greenhouse gas emissions scenarios ('low', 'medium' and 'high'), and to project that scenario into one of two given time-frames, the 2050s and the 2080s (see **Figure 4** for cartoon note-taking from the science-narrative scenario-ing workshop). Before starting the practical and creative part of the workshop, participants reflected collectively on how to frame their ideas in a narrative form, and how to visually represent the story arc on a simplified storyboarding template in four blocks that they were expected to complete in an hour. Looking at previous examples of using a similar template to develop stories on water use and showing what was created during a previous LAG meeting was an effective way of explaining the creative process. The majority of them worked individually drawing and writing text on their own storyboard; some worked in pairs, with one being the storyteller and the other one the story-listener and creator of the storyboard. Two participants were supported by the cartoonist John Elson to visually translate their thoughts into drawings. After everyone had completed the storyboard, all the stories were shared with the group, and further discussions were facilitated to scope variables that will change in the Bevills Leam catchment over time in the near and far future, and also to explore the scale of that change.

When community members reflected on both land use and demographic scenarios, urbanization and population growth in the areas around Peterborough, Huntingdon and Cambridge were mentioned. This was often linked to the growing disconnection of the new population with the local heritage and landscape, and more broadly a general disconnection between the city and the countryside. Other stories revealed different hierarchies of needs among various sectors, and also different ways of perceiving impacts of the Great Fen project on land use. Talking about population growth linked to the wetland restoration project, a local farmer expressed his apprehension about increasing food demand:

> "I look at really good farmland around here, which is going to be flooded and taken out of production. I'm all for not just myself being self-sufficient, but the whole country being self-sufficient and were going to end up importing a lot of food".

Extreme weather events were often considered in stories that included water use scenarios (see as example: the story "The Fens in 2050": https://dryutility.info/2019/02/08/the-fens-in-2050-following-high-emissions-seasonal-mosaic-of-water/), especially to talk about the role of agriculture within the restoration project, and also to reflect on how vital reservoirs are for farmers' drought resilience and how farmers could contribute to undertake flood mitigation measures, with potential implications on land use. While listening to other stories, those types of concerns were mitigated by the general understanding that new measures are required for better local water management. One community member highlighted:

> "The Great Fen should hopefully sort out water storage and hold some of that back, then release it back in the summer. We need something in the future because of the way the patterns have changed".

For the ones who imagined a positive future scenario linked to a wider access to green and open spaces, such as the Great Fen area, the positive impact of the natural environment on communities' health and wellbeing was a recurrent theme (See, as example, the story "The Great Fen is a diamond: https://dryutility.info/2019/02/08/the-great-fen-is-a-diamond-exploring-the-conflict-between-people-and-wildlife/). One of the participants pictured the area as a 'green lung' that in the future will mitigate the increasing air pollution.

Comparing stories is a way of uncovering conflicts and dilemmas, and of discovering unexpected common ground in the dialogue between lay and specialist narratives due to the authenticity of personal stories and the natural 'mess' (Wilson, 2014) of the world that storytelling both exposes and helps us navigate. Furthermore, exploring future scenarios with different sectors of society through science-informed storyboarding activities revealed a critical tension around the interaction between opinions and facts, which requires a deeper reflection on the perceptions, beliefs and value-systems that drive people's behaviours. This also highlights the urgency of connecting scientific and local knowledge, and of approaching stories as a way of beginning a conversation that allows facts to be better engaged with. In addition to analyzing the stories produced during the workshop in a way that could inform our research process and enhance our understanding of the variety of local needs, we have also reflected with the stakeholders on the co-production process itself, and in particular on our creative experiments to bridge scientific and community knowledge, and explore future scenarios.

One of the measures of success of this type of intervention was for us their replicability in various contexts and beyond the duration of our project. In this regard, the feedback received from LAG members offered a very positive insight, as said by a participant from a local Angling Trust:

> 'From my prospective the most useful output from the DRY project was the underlying experience from the citizen trial and evidence. I have used the material and experience many times and even most recently as pressures continue on water needs'.

DISCUSSION AND CONCLUSIONS

In returning to our three aims, we found that exploring future scenarios across disciplines and knowledge systems generated multiple transitions in ways of thinking as part of what was revealed to be a transformative process for multiple actors. These

FIGURE 5 | Cartoon note-taking from the science-narrative scenario-ing workshop.

diverse actors comprised the researchers of different disciplines involved in DRY, the local stakeholders in the catchment as individuals, and the local community.

Inter- and Trans-Disciplinary Reflections on Our Processes

Various positive impacts were gained through feedback and observation during the participatory storyboard scenario-ing workshops designed and delivered as part of DRY. The process supported co-design and co-creation, enabling specialists and 'lay' people (that can be expert in their realm) to work together. It made communication and deliberation (during and after the creative process) more accessible and engaging, and translated scientific principles into locally meaningful information. Critical reflection was encouraged throughout the process on the impact of individuals' behaviours on community preparedness and resilience. The storyboard scenario-ing promoted creative thinking and open sharing about different possible futures and anticipatory adaptation.

Yet the two main obstacles identified as potential disadvantages of storyboarding scenario-ing revealed opportunities for further improvements of the process. For instance, a cartoonist was invited to be part of the workshops and help resolve the potential barrier of drawing, working closely with those participants who appeared to be reluctant for various reasons to do so. His contribution to the creative process also emphasized the importance of dialogue and active listening in storytelling, and highlighted some crucial issues within the knowledge sharing processes, in particular related to jargon, specialist language and scientific capital. Furthermore, the use of storyboarding as tool for creating stories about an imaginative future sometimes generated contributions that are far off the 'what is a drought story?'. To respond to this lack of focus or obliqueness of some of the stories reflecting on future scenarios, during story screening sessions and participatory tagging activities organized with local stakeholders, we have proposed the use of a bull's eye target (see **Figure 5**) as a way of defining the spectrum of themes included in the DRY Story Bank (https://dryutility.info/story-bank/) and their 'distance' from the central theme of drought risk.

Reflections on Transitions

Scenario-ing was approached as a 'bridging concept' in our creative experimentation with science and narrative, as something to which everyone could relate, but throughout this journey, it manifested as something more than a process to link different entities. In fact, throughout our participatory processes that started with an exploration of language and meanings, scenario-ing was found to be better represented as a coalescing concept. Here different components were integrated into one new holistic concept, working beyond any simplistic notion of 'bridging', looking outwards in multiple directions, to draw in meaningful experiences and practices, and shifts in understanding, some transformative.

We are not pretending here that it was a neat and linear process. We recognize that some of the actors, who found it questioning of their pre-existing ways of working and practices, preferred to withdraw rather than trying to adapt to some of the challenges implied in this collective journey. Those who were open to dialogue within hybrid knowledge systems that value both science and lived experience, have participated in a set of transitions that produced an innovative model of transdisciplinary and inter-professional work.

[Transition 1] Insights to Inform Scenario-Ing as Concept and Practice

The scenario-ing work in the Bevills Leam catchment provided an opportunity to experiment creatively in how to communicate complex results and invite dialogic moments in a group with very varying levels of scientific and technical expertize, and different narrative capital. As well as providing sets of technical tables and plots with detailed results for each broad scenario class, the scientist, working in opening up his science, also attempted to distil the key information down into higher level text summaries, and finally into a bullet point summary of 'take home messages' presented in accessible qualitative terms. Starting with these summaries provided a route into the results without overwhelming the LAG members with all the scientific details. It was then possible to explore and discuss selected scenarios, based on the specific interests of those LAG members present at the final meeting. The iterative longitudinal nature of the LAG process also presented challenges, particularly in the temptation for the scientist to keep improving the hydrological model as much as possible, given the extended timeframe for model development and calibration. It was also challenging at times to reconcile local practice and theory. For example, in the Bevills Leam catchment, much irrigation practice is based on experiential knowledge, with little regard made to published irrigation guidelines. This required model development to include more realistic, but unquantified, practices. It was also important to manage expectations and remain impartial. Some potential drought indices suggested based on local interests were not possible given the scope of the hydrological model, and it was important to select a balanced range of scenarios for modeling.

[Transition 2] Developing Researcher Skills at Transdisciplinary Scenario-Ing Interface

Communication and creativity are constantly interwoven within the catchment-based DRY-LAG process, and this implied scientific upskilling on working with narrative approaches. Storyboard scenario-ing progressively unfolded its own strong arts elements and required the co-design of different participatory tools and a longer two-way engagement process. At the start of that process, our scientist introduced the drought risk science using a formal presentation with multiple slides with graphs that although as scientific convention might expect, may in hindsight have been too technical for some of the LAG members. Scientific communication at the LAG meetings evolved into more informal presentations with less formal graphs, often with digressions, anecdotes, vignettes and discussion, in effect bringing story into the science. For one of the early meetings, the scientist spent some time providing a hands on demonstration of the Bevills Leam water balance model, both to demystify the science and to demonstrate how changes in model inputs affected the model behaviour. This both opened up the hydrological modeling process and emphasized the high degree of flexibility in the model which would facilitate the incorporation of local knowledge, understanding and land use and catchment water management scenarios. At the final LAG meeting, the scientist and the stakeholders, as a group, had the opportunity to participate in a storyboard scenario-ing activity: participants were creatively stimulated to investigate scenarios of particular interest in a more conversational style and use their imagination to explore possible adaptive scenarios for uncertain and hidden future risks. The scientist definitely changed from being somewhat apprehensive with an unknown audience at the first LAG to very comfortable with a trusted group of co-developers at the final LAG, and this was reflected in their communication skills within an art-based process. As a proof of that 'transition', when the scientist presented his storyboard during the sixth LAG, it is worthwhile sharing a comment form a participant:

> 'You're wasted at CEH. You should think for a change in your career'.

Nevertheless, there was a tangible difference between the scenario-ing in longitudinal engagement with LAG members, and that in the one-off community workshop. Stakeholders' participation within the LAG process allowed deeper connection with the science in a longer-term perspective, and also more familiarity with the storytelling approach. One-off workshops presented the challenge of making several aspects of our processes accessible to the general public in a short time. This involved exposure both to new cultures, and the interweave of science and storytelling, with the ambition to create a safe environment for knowledge sharing and for co-developing a practice.

[Transition 3] Challenging Storytelling: From Personal Memories to Future Community Narratives

The scenario-ing process represented a learning experience for local stakeholders as well as for academics from the arts and humanities and beyond: stories float around within the science; they exist within the world of science in a way that it was not expected when this coproduction process started. The original assumption that imagined the science world as being very closed and very protective through its use of specialist knowledge language, very difficult to penetrate and being very suspicious of people, was completely dismantled by this co-production of knowledge. That is not to say that the original assumption was incorrect, but that our scientist was interested and willing to experiment with a more flexible and open scientific approach without succumbing to peer pressure from more traditional colleagues. This may well have been aided by his prior exposure to the humanities as an undergraduate and an interest in the arts, leading to a receptive view of multi-disciplinary working. Science therefore opened its doors to other disciplines and knowledge systems, and offered storytelling a new platform to challenge the practice itself and experiment with two main transitions: from past to future, and from individual to community storytelling.

While creating their stories to explore future scenarios, LAG members and local stakeholders shifted from personal memories to community-oriented stories much more often than while recalling memories from their past lived experiences. One participant concisely pinpointed something that completely changed our perspective:

> 'I remember my life as individual because I know more details and I can explore those memories more deeply from a personal perspective; but I project myself in the future as a community member or on behalf of someone else, my children, someone younger than me, because it's easier to imagine the unknown as a shared and collective experience'.

Switching from memories to future projections throughout the creative process appeared to be perceived as a sort of transition from self-interest to participation (Liguori 2019).

The connection between imagination and community building is articulated by Irene Baker thus: 'Listening to a story is not a passive act. It engages imagination and abstraction. It creates a community' (Dorer, 2018, pp. xxviii, 20). Her main focus is on the educational value of storytelling. Nevertheless, she is mainly referring to the social function of story-sharing that is revealed to be even more evident when future stories are created.

[Transition 4] Valuing Hybrid Knowledge: Towards Inclusive Knowledge Networks

Transition in how the different knowledges were valued in the process occurred when scientists shared the decision-making around the progression of the science with the stakeholders, in particular about data, quality and its gaps (what to collect and how).

To counterbalance the challenge of presenting scientific data when it is over-simplified to make information accessible, new settings for scenario-ing engagements were developed. This was particularly relevant to the specificity of the landscape in the Fenland in which the local community wants to be informed about how the system is managed to understand the flood/drought nexus, and be more proactive in thinking about its future management and also in terms of socio-ecological resilience. This was in spite of the potential tensions between ecological thinking and adaptive strategies from one side, and engineering thinking to control the system on the other side; and additional potential tensions with farming vs. ecology. The latter in fact did not materialize during our research project, perhaps as those farmers participating were self-selecting, and therefore more open to different views and perhaps all too well aware of long-term issues of peat wastage and consequences for agricultural productivity.

In the Bevills Leam catchment, additional field visits, communal eating and collective dialogue within the landscape as part of the LAG meetings (hosted each time in a different venue by one of the organisations involved in the process) were found to be an excellent way of both exploring the various catchment interests and their future interaction (e.g. farming, wetland restoration and drainage) in more detail and also building a strong LAG group. The LAG members were in effect opening up their work, their lived experience, in the catchment, showcasing achievements and highlighting issues, and in doing so providing a far deeper insight and understanding for the wider group, including the scientists.

CONCLUSION: TOWARDS 'CREATIVE PARTICIPATORY SCIENCE'?

Storyboarding scenario-ing was revealed to be a new way of creative participatory working in transdisciplinary research, innovatively involved socially-engaged arts practices in creative participatory science. This distinctive longitudinal process was found particularly effective as a co-produced open research method that could be adapted and re-applied in various contexts or fora that aim to promote dialogue, knowledge co-generation, and deliberative democracy. This is despite its uniqueness in terms of levels of creativity and human capital and the specificities of locale.

One of the main learning outcomes for the researchers was generated by multiple 'lay-ness', derived by the fact that each of the actors involved in our research process (academics from different disciplines, multi-sectorial stakeholders from a catchment, and community members from different groups of the society) has challenged the self-evidence and truth of each other's practice, knowledge, beliefs and value systems, questioning the validity of what was done. By doing so, each of the actors involved in this 'journey' had to adapt their own language and forms of expression (oral, visual) to make both the process and the outcome meaningful to everyone. This co-creative journey was always nourished by the awareness that risks were involved in the process and serendipity could generate innovative approaches and insights. Within this process, a strong arts element catalyzed participants' creativity and produced methodological innovation as an iterative experience: by interweaving different skills and languages (including drawing and song-writing), new participatory tools and arts practice were co-designed and applied. Some of them have also already demonstrated their transferability and success in other research and community engagement contexts. In particular, the storyboard scenario-ing has been adapted and re-applied as a workshop practice for museum audience engagement by educators at the Smithsonian Institution in the United States, and as a tool for youth participation as part of the East Education Summer School at Here East in Queen Elizabeth Olympic Park in London; 'The Reasons' event, including community song-writing, was re-framed and performed in a Nairobi slum, in Kenya, as part of an initiative led by UN Live – The Museum for the United Nations on UN Sustainable Development Goals. The efficacy of these different participatory tools on public engagement and co-production of knowledge, and their very effective replicability, would suggest that a more diffuse and meaningful use of creative methods (also co-facilitated by professional artists) would be desirable to achieve a greater impact of research around environmental issues and to pursue a more active and deep community engagement on societal challenges.

In hybrid-knowledge research environments as within DRY, it is important to emphasize the role of individuals, in terms of dispositions and skill-sets, to facilitate discussions for the co-production of knowledge. It is not just the method that counts; it is also how it plays out iteratively within an evolving co-productive 'community of practice'. There is in fact an important human element to be considered: in this specific case study, social dynamics also worked well because there was a significant investment in terms of time and energy to create local connections, personal and collective relationships, and build mutual trust across all participants including the research team. It is obvious to observe that where those connections are generated and nourished over time in a research process, the legacy of community-based research and learning will last longer.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://dryutility.info/.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Approvals (Human Participants) Sub-Committee, Loughborough University, United Kingdom. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

All authors contributed to conception, design and evolution of the DRY study. JB performed the drought risk hydrological modelling and associated scenario-ing. The participatory research process involved all authors. AL, LM, and JB wrote the first draft of the manuscript, with MW providing first edit. All authors contributed to manuscript revision, read, and approved the submitted version.

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Drought and Water Scarcity Management Policy in England and Wales—Current Failings and the Potential of Civic Innovation

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Drought management in England and Wales takes place in a narrow, confined governance space. Assessed against current literature on drought management, England and Wales show little innovativeness and little actual willingness to change. We ask how drought and water scarcity management is currently done, who is involved (or not) and, foremost, what are the current problems and deficiencies with current English and Welsh drought and water scarcity management that require attention. We are also interested in the question of what can be done to improve drought and water scarcity management in England and Wales. This research therefore explores how we can create a continuous relationship between the different actors contributing different levels of knowledge and we plead to widen the drought governance space in order to face the current and future water governance challenges. First, we present an empirically based critique of current drought and water scarcity management in England and Wales, highlighting the contrast between available drought and water scarcity management options and what is currently applied in England and Wales. Second, we present and introduce Environmental Competency Groups, a methodology aiming to bring local residents' experience-based knowledge of water management in relation to particular catchments to bear on the generation of scientific knowledge. It has been successfully trialed in relation to both droughts and flooding in England and Wales. We argue that this is a successful way to bring together people with different perspectives and knowledge in order to overcome the deficiencies of current drought and water scarcity management in England and Wales.

Keywords: drought, water scarcity, civic innovation, policy, United Kingdom

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1 INTRODUCTION

Droughts are a recurring feature of the United Kingdom climate (Marsh et al., 2007) and besides the recent dry spell in the summer 2018 and its comparison with the benchmark drought of 1976 (Hannaford, 2018), the United Kingdom experienced droughts between 2010–2012, 2004–2006, 2003, 1995–1996 (Marsh et al., 2007; MetOffice, 2012; MetOffice, 2013; MetOffice, 2016). The United Kingdom Climate Change Risk Assessment 2017 attributes a "medium magnitude now" but a "high magnitude in future" for the "risk of water shortages in the public water supply, and for agriculture, energy generation and industry, with impacts on freshwater ecology" (Committee on Climate Change Risk Assessment, 2016). The overall assessment is that more action is needed in this area. The principal drivers are climatic changes, populations growth and changing demand patterns (Grecksch, 2019). The chief executive of England's Environment Agency, James Bevan, emphasized these points in 2019, by saying that unless action is taken to change things, England will not have enough water to supply its needs (Bevan, 2019).

The purpose of this article is to present an empirically based critique of current drought and water scarcity management policy in England and Wales and also to propose a way to re-invigorate the drought and water scarcity management discourse in England and Wales. We are guided by questions of how drought and water scarcity management is currently done, who is involved (or not) and, foremost, what are the current problems and deficiencies with current English and Welsh drought and water scarcity management that require attention. We are also interested in the question of what can be done to improve drought and water scarcity management in England and Wales. By addressing these questions in relation to several empirical materials, we will make a contribution to the debate on drought and water scarcity management policies and we will discuss how civic innovation could improve current and future drought and water scarcity management in both nations.

We will argue and demonstrate that current drought and water scarcity management policy in England and Wales is to a large extent reactive rather than proactive and that it lacks the inclusion of vital stakeholders and their knowledge. This is especially true for the inclusion of local knowledge and the communication with the public about drought and water scarcity. We will introduce and discuss the Environmental Competency Groups (ECG) methodology as a public engagement technique that could elicit civic innovation to improve drought and water scarcity management policy in England and Wales. Engagement with local communities has become common in other areas of water management in England and Wales over the last decade. A prominent example is the Catchment Based Approach, established in 2013 with the intent to involve a broad range of local stakeholders, including local communities, in river management (Collins et al., 2020).

For the purpose of this article we define and emphasize that drought is not just a natural event of limited duration (cf. Lloyd-Hughes, 2013 for a discussion about drought definitions), but also a socially constructed event as it can result from social factors such as agriculture, housing and transport policies (Lange and Cook, 2015). Although England and Wales' agriculture is mostly rain-fed, demand for "perfect" produce can lead to additional irrigation thereby putting stress on water resources (Rey et al., 2016). Equally, new housing development projects in urban and peri-urban areas, especially in the already water-stressed south-east of England could exacerbate existing water supply issues especially during drought periods (Committee on Climate Change, 2019). Droughts can also have an effect on the navigation of rivers and canals, hence, transport policies that involve the transport of goods by ships should take into account that river navigation might be interrupted during drought periods (Environment Agency, 2017). Van Loon et al. (2016) explicitly factor in human processes in drought definitions, an issue that so far has been neglected, according to the authors. Water scarcity is defined as the result of long-term unsustainable use of water resources, which water managers can influence (Van Loon and Van Lanen, 2013). It is thus human induced and subject to the socio-political and economic context (Walker, 2014). Hence, issues like population growth and increasing water demand further exacerbate the problem. Water scarcity and drought are both conditions in which water availability is less than the collective demand for water from humans and the environment. Drought, however, is an acute phase of water scarcity linked to hydro-meteorological conditions while water scarcity is not necessarily linked to hydro-meteorological conditions (Cook, 2017).

This research picks up on the point that drought and water scarcity are also social phenomena and argues that they must, hence, be treated as such, i.e., the drought and water scarcity governance should include a wide range of social actors before, during and after a drought. Enlarging the governance space for drought, we will argue, could lead to an increased production of knowledge and innovation to address drought and water scarcity. Second, a proactive and broad societal discussion about drought and water scarcity needs to take place across all levels. This is especially the case for the local level where drought action should be empowered. Local knowledge is available yet hardly used, at the moment. This, we will argue, also relates to the issue of communication. Incorporating local knowledge into drought and water scarcity management in England and Wales could not only lead to a better evidence base, a more pro-active and localized communication about drought and water scarcity could improve the communication between water companies and their customers, helping them to get the message about water saving in relation to drought and water scarcity through.

In the following we first briefly overview the challenges facing water governance and outline the literature on adaptive water governance. Next we draw on empirical material generated within the interdisciplinary MaRIUS project[1], to argue that the United Kingdom water sector focusses on restricting water use in times of drought, but works less with preventing drought. This limitation closes the door to integration of more stakeholders in drought and water scarcity governance. This part is underpinned by a desk study on drought and water scarcity options, a study of how environmental science knowledges are used in drought planning and a scenario planning exercise with English and Welsh drought and water scarcity stakeholders. After this we introduce the notion of civic innovation and discuss it in relation to local community participation in United Kingdom water management. The Environmental Competency Groups (ECGs) methodology is introduced as an example of how local communities can participate in drought and water scarcity management in a way that promotes civic innovation. The ECGs methodology brings local residents' experience-based knowledge of water management to bear on the generation of scientific knowledge and has been successfully trialed in relation to

[1]The multi- and interdisciplinary MaRIUS (Managing the Risks, Impacts and Uncertainties of Drought and Water Scarcity) project aimed to produce a risk-based, future oriented approach to drought management, a task that involved natural scientists, engineers, legal and policy experts, and social scientists. www.mariusdroughtproject.org

both droughts and flooding in England and Wales. We present ECGs as an empirically based possible way to overcome the lack of involvement of local actors and their knowledge in English and Welsh drought and water scarcity management.

In the discussion we identify a knowledge deficit showing that knowledge does not cross different levels of decision-making. Local environmental matters are inadequately addressed in terms of knowledge about physical processes and information does not travel across levels of decision-making in order to facilitate the work done by for example local stewardship groups. We note that water companies largely fail to understand the knowledge and innovation these local groups can contribute.

2 DROUGHT AND WATER SCARCITY—THE NEED FOR ADAPTIVE WATER GOVERNANCE

Sustainable water governance is a key challenge of the 21st century and it is foremost a crisis of governance (Gupta and Pahl-Wostl, 2013). Sustainable is defined as development that meets the cultural, social, political and economic needs of the present generation without compromising the ability of future generations to meet their own needs (United Nations General Assembly, 1987).Water governance is defined as "the practices of coordination and decision making between different actors around contested water distributions" (Zwarteveen et al., 2017). Rapid urbanization, population growth and climatic changes put enormous pressure on the earth's freshwater resources and its governance. Floods and droughts will be more frequent and there will be impacts on streamflow and water quality (Grecksch, 2019). Three main issues follow from this (see Grecksch, 2019 for a detailed discussion): First, water governance, and this includes the governance of drought and water scarcity, needs to be flexible and deal with uncertainty. Uncertainty arises because we do not know if the projected effects of climate change will happen and to what extent. Flexibility means that drought and water scarcity policies need to be flexible enough to be changed in the future based on the latest scientific knowledge. Second, adaptive water governance requires tailor-made approaches. In other words, policies need to be adapted to each river basin taking into account local or regional characteristics and contexts. And third, adaptive water governance requires public participation, and the involvement of local stakeholders. This, however, is also often one of the main challenges and is further exacerbated by silo mentality and little or no collaboration between neighboring policy fields (Grecksch, 2013). Yet, a better involvement and participation of civil society groups, water users and their knowledge is a key success factor for future adaptive water governance (Grecksch, 2019).

The successful management of drought and water scarcity requires the availability of a broad array of management options before, in drought and after drought. According to Sayers et al. (2017), who developed eight golden rules of strategic drought risk management, one rule is to "implement a portfolio of measures to transition toward a drought resilient society." (ibid., 247) Robins et al. (2017) would like to see the creation of a more water-literate society that will better enable water managers to shift from reactive, crisis-driven approaches to long-term, agenda-driven plans in line with agreed strategies. Speight (2015) says about the United Kingdom water sector: "The water industry is notoriously slow to implement change, often embracing tradition and tried-and-true methods for achieving their goals." In her comparison between the US and the United Kingdom water sector, Speight concludes that, "based on the availability of capital, the United Kingdom water companies should be better positioned to implement innovation than publicly funded US utilities. Yet the United Kingdom companies need a regulatory driver to justify innovation expenditures within their short payback periods. Ofwat is uniquely positioned to increase spending on innovation and infrastructure replacement, both of which will soon be needed to meet the challenges of increased water demand, high public expectations about service and water quality, and energy efficiency" (Speight, 2015).

The breadth of empirical material presented in the following highlights issues within current English and Welsh drought and water scarcity management and underlines our proposition that drought and water scarcity management is the management of people and a matter of communication, before, in and after a drought. By presenting these rich empirical materials we first of all want to lay open the current knowledge practices in drought and water scarcity management in England and Wales. We will demonstrate the need for a broader set of management options to be included in drought and water scarcity policy. This is especially important with regard to cross-sectoral collaboration and more engagement with society including the harnessing and use of local (expert) knowledge.

3 Current Drought and Water Scarcity Management Options in England and Wales

This section presents empirical material from social science research on drought and water scarcity management in England and Wales. The first is a desk study, which analyzed all English & Welsh water companies' Water Resources Management Plans (WRMPs) and contrasts them with academic literature and documents or project reports on drought and water scarcity management options. The second is a scenario planning exercise with actors from the regulatory authorities, water companies and other researchers. The third example discusses what types of environmental science knowledge and regulatory tools influence drought planning in England and Wales, thereby highlighting key themes such as local knowledge or rather the lack thereof. The purpose of presenting this material is to outline current drought and water scarcity management in England and Wales, especially its deficiencies. Chapter 4 then discuss a tool to overcome them.

Currently, drought planning in England and Wales is event focused. Water companies are obliged to provide drought plans. These statutory documents are operational plans, i.e., they focus on the practicalities of an actual drought event, working with drought trigger curves, thresholds determining specific timely action by decision-makers, and detailed plans of steps taken when in a drought (Defra and Environment Agency, 2015). In this regard, they are disconnected from Water Resources Management Plans (WRMP), another statutory requirement for water companies (HM

Government, 1991 Section 37A-37D). WRMPs are strategic plans and lay out how a water company secures deployable output, or in other words, that enough water is available for its customers. This includes a wide, yet limited range of management options that emphasizes supply side options over demand side options, which would necessitate a larger involvement of actual water users as we will see further below.

The management of drought and water scarcity in England and Wales includes the following actors: the Department of Environment, Food & Rural Affairs (Defra), the Environment Agency (EA), Natural Resources Wales (NRW), Natural England, the Water Services Regulation Authority (Ofwat), private water companies, the Drinking Water Inspectorate (DWI), the Consumer Council for Water (CCW) and consultancies.

Defra sets the overall water and sewerage policy framework for the United Kingdom and is responsible for example for developing policy and legislation. The EA is the principal adviser to the government on environmental matters. As a key regulator, the EA protects and improves the environment of England. With regard to drought and water scarcity, the EA holds a strategic role being involved in long term planning processes as well as short term through its role in making specific drought management option happen during a drought, such as granting drought orders to water companies or applying to Defra for drought permits (Cook, 2017). NRW is the environmental regulator for Wales and ensures sustainably maintained, enhanced and used natural resources. Natural Resources Wales covers a wider spectrum of roles and responsibilities, with regard to drought and water scarcity this includes advising the Welsh Government, managing natural resources and gathering evidence through research and monitoring (Natural Resources Wales, 2020). The government's advisor on the natural environment, Natural England, provides practical, science-based advice, on England's natural wealth. Natural England is for example involved in commenting on water companies Water Resources Management Plans and Drought Plans (see below in this section). Natural England also advises on the potential impacts of water abstractions from protected sites and habitats. Ofwat is the economic regulator and promotes for example competition and ensures that water companies can finance their functions. Ofwat is necessary since all English and Welsh water companies are private companies and occupy a natural monopoly. Ofwat carries out a so-called price review every five years limiting the prices water companies can charge their domestic and non-domestic customers.

The DWI regulates drinking water quality and is also involved in Ofwat's price review process. It is the technical auditor of water companies and for example assesses water company sampling programs or incidents potentially affecting drinking water quality (Drinking Water Inspectorate, 2020). The CCW represents English and Welsh customer interests in the sector for example resolving complaints between customers and water companies. Consultants are important actors in English and Welsh drought and water scarcity management since some smaller water supplier do not have in-house capacity to carry out all necessary tasks and hence rely on consultancies to do research and reports.

All actors operate within a legal framework that is variously shaped by legislation and guidance such as the European Union Water Framework Directive (EU-WFD) (European Union, 2000), the Water Act (HM Government, 2014), the Water Industry Act (HM Government, 1991), the European Union Habitats Directive (European Union, 1992) and the EA's Drought Planning Guideline (Defra and Environment Agency, 2015; Environment Agency, 2017). The mentioned European Union directives applied for the time we covered in our research. Brexit, i.e., the United Kingdom leaving the European Union, will bring changes to United Kingdom water governance, however, how these changes could look like or their implications cannot not be assessed yet. In addition, further actors such as the National Farmers Union, the Rivers Trust—an umbrella organization for 60 local river trusts protecting and improving river environments, local councils and the United Kingdom Irrigation Association have a stake in drought and water scarcity management.

As part of the MaRIUS project, current drought and water scarcity management options were reviewed and contrasted to available options identified through a literature and document review on drought and water scarcity management options, in order to get a picture of where English and Welsh drought and water scarcity management currently stands. The literature and document review was non-systematic. Literature and documents were searched using Web of Science, Scopus and World Wide Web search engines. All literature, documents and research project websites were searched to identify drought and water scarcity management options. Articles and documents were selected on the basis of dealing with drought and water scarcity management options and a snowball search using cross-references but also the authors' previous experience in the field. This included management options and strategy for water efficiency, how to balance supply and demand, leakage reduction and preventions as well as for example metering. Examples of search terms include "drought management," "water scarcity management," "drought planning". 50 academic journal articles, documents and reports published between 2000 and 2017 were analyzed and four major European research projects on drought and water scarcity and their results were also included. The literature, documents and WRMPs (see next paragraph) were analyzed using qualitative content analysis (Mayring, 2008; Bryman, 2012). The analysis of the data produced an understanding of drought and water scarcity management options and it included the identification of key themes and patterns that emerged inductively from reading the literature, documents and WRMPs (Saldaña, 2016). Themes are recurring ideas, issues or statements expressed in the data, however, often not directly. Hence, identifying themes can .help to uncover further dimensions and facets of in this case drought and water scarcity management. The following paragraphs present a concise description and analysis of this study, a full and detailed account can be found in Grecksch (2018a, 2021).[2]

[2]The results presented here are a concise description and analysis of the material. Grecksch (2018a) provides a full account including the complete data set with all analyzed WRMPs and a detailed account of all drought and water scarcity management options categories. Grecksch (2021) embeds the study and its materials in a wider United Kingdom drought and water scarcity governance context that includes, among others, a discussion on the role of knowledge and power relationships.

This desk study included an analysis of all current English and Welsh water companies' WRMPs[3] for the period 2014–2019. WRMPs are strategic documents and were therefore favored in the analysis over Drought Plans (DP), another statutory requirement as mentioned above. WRMPs are broader in terms of the issues water resources management they address, they are outward looking and hence more relevant and interesting to answer the question of which drought and water scarcity management options are currently applied. They are an important, credible and valuable source for analysis. DPs are operational plans describing actions necessary to deal with various drought situations. They set out how a water company will continue to meet its duties to supply water during drought periods. However, all water company DPs are based on Defra's and the Environment Agency's Drought Plan Guideline (Defra and Environment Agency, 2015), which was part of the analysis. In this sense, DPs were identified as one of the many management options.

In relation to this, it is worth mentioning two themes that emerged from the research. First, the unclear relationship between water company drought planning and Environment Agency voluntary drought plans, which revealed a misfit of scales as the Environment Agency's areas do not match the water resources zones water companies work with (Grecksch and Lange, 2018). The second theme relates to the flexibility of drought planning. This refers to how much water companies are restricted in how they deal with droughts and water scarcity. Looking at it from a different perspective, from the regulator's point of view this theme relates to power relationships within the drought governance space. Lange and Cook (2015) develop the notion of a drought governance space with reference to the regulatory space metaphor, which is a conceptual lens that aids small-scale empirical analysis of both public and private actors, their roles, and aims, within a specific regulatory regime. They use "governance space" to emphasize two distinct features of United Kingdom drought and water scarcity management. First, the importance of networks and second, the steering across different political levels (Lange and Cook, 2015). Drought plans are shaped by the Drought Planning Guideline (Environment Agency, 2015), a non-binding soft law. Some water companies found it too restrictive, a potential barrier to alternative and more flexible drought management options (Grecksch and Lange, 2018). However, it also brings water companies and regulators closer together, because many water companies chose to collaborate closely with the Environment Agency developing their drought plans. Water companies in England and Wales are important because they "occupy a central, powerful position in the governance space" (Lange and Cook, 2015). Since 1989 all water companies in England and Wales are privately owned. Welsh Water, which supplies water to most parts of Wales, is a company that has no shareholders and is run for the benefit of its customers and hence the only exception to the privately-owned model.

The purpose of both, the literature review as well as the analysis of the WRMPs was to highlight the contrast between available drought and water scarcity management options, as identified by the review, and currently employed options in England and Wales. The results from the literature and document review of the WRMPs reveal a broad array of drought and water scarcity management options (Grecksch, 2018a; 2021). There is a tendency in the academic literature toward proactive measures that focus on cross-sectoral collaboration such as catchment management, integrating water scarcity into planning processes or the collaboration of water suppliers with actors from neighboring policy fields such as flooding policies, agriculture or spatial planning (Wilhite, 2002; Hanak et al., 2011; Kampragou et al., 2011; Farmer, 2012). Other drought and water scarcity management options pay attention to certain abstractor groups such as farmers and include measures such as agricultural insurance, or income support (Nelson et al., 2008). Another set of options puts emphasis on the value of water, for instance the promotion of water stewardship or the creation of water saving cultures (Farmer, 2012). **Figure 1** illustrates the results from the literature review and WRMPs and presents the non-exhaustive list of options in a novel typology of drought and water scarcity management options that differs from the supply and demand dichotomy we usually find in water resources management. This typology helps to identify where the emphasis in current drought and water scarcity management lies and it helps to point out weak points, i.e., areas that could and should potentially be given more attention in the future. It also helps to easily contrast these options with currently applied drought and water scarcity management options in England and Wales (cf. Grecksch, 2018a; Grecksch, 2021 for a discussion of the typology).

Figure 2 provides this overview and all encircled options are either currently applied or their implementation is planned in the future. The illustration shows that English and Welsh water suppliers are using only a fraction of the options available and identified by the literature and document review. **Figure 2** also highlights a tendency toward using options provided by the current regulatory framework and supply side options before drought actually happens. Thus, it can be concluded that currently employed drought and water scarcity management options in England and Wales rely significantly on restricting water use in times of drought and are therefore, with the exception of elements of drought plans and WRMPs, potentially too focused on thinking about water scarcity in the context of actual drought events. Given the large number of drought and water scarcity management options identified in the literature review that focus on proactive measures such as the ones represented in the "Valuing water/ attitudes" box or "Land use planning" box, English and Welsh water companies are missing out on current trends in drought and water scarcity

[3]Water Resources Management Plans (Dee Valley Water, 2013; Peel Water Networks, 2013; Affinity Water, 2014; Anglian Water, 2014; SSE Water, 2014a; Bristol Water, 2014; SSE Water, 2014b; Cambridge Water, 2014; Cholderton and District Water, 2014; Essex and Suffolk Water, 2014; Northumbrian Water, 2014; Portsmouth Water, 2014; SES Water, 2014; Severn Trent, 2014; South East Water, 2014; South Staffs Water, 2014; South West Water, 2014; Southern Water, 2014; Thames Water, 2014; Veolia Water Projects, 2014; Welsh Water, 2014; Wessex Water, 2014; Yorkshire Water, 2014; Sembcorp Bournemouth Water, 2015; United Utilities, 2015)

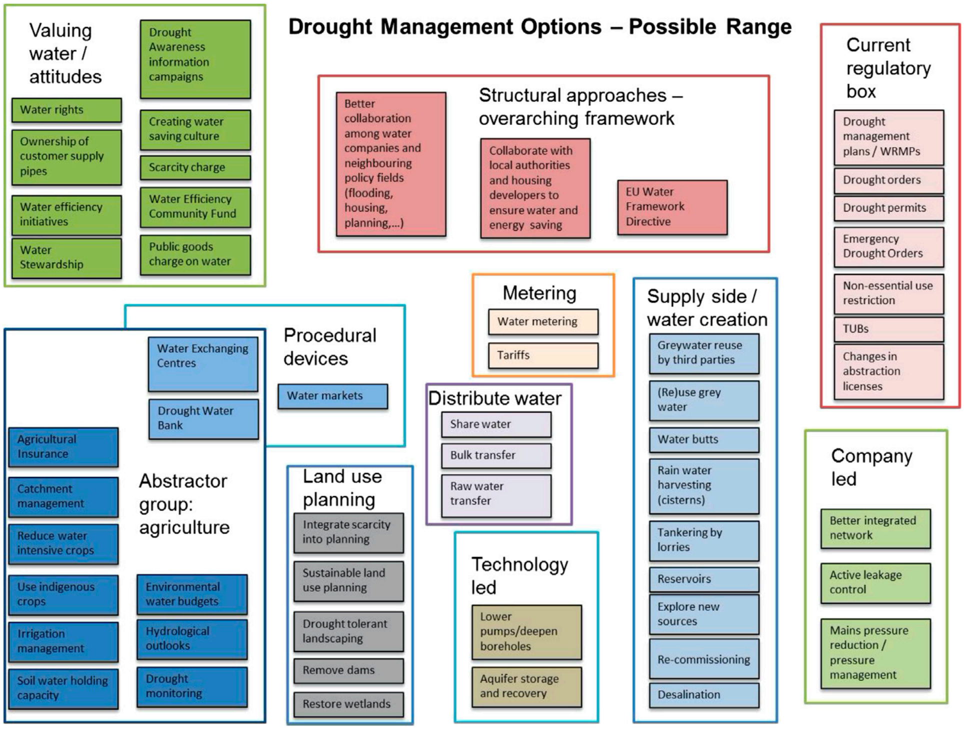

FIGURE 1 | Overview drought and water scarcity management options based on the literature and document review (adapted from Grecksch (2021))

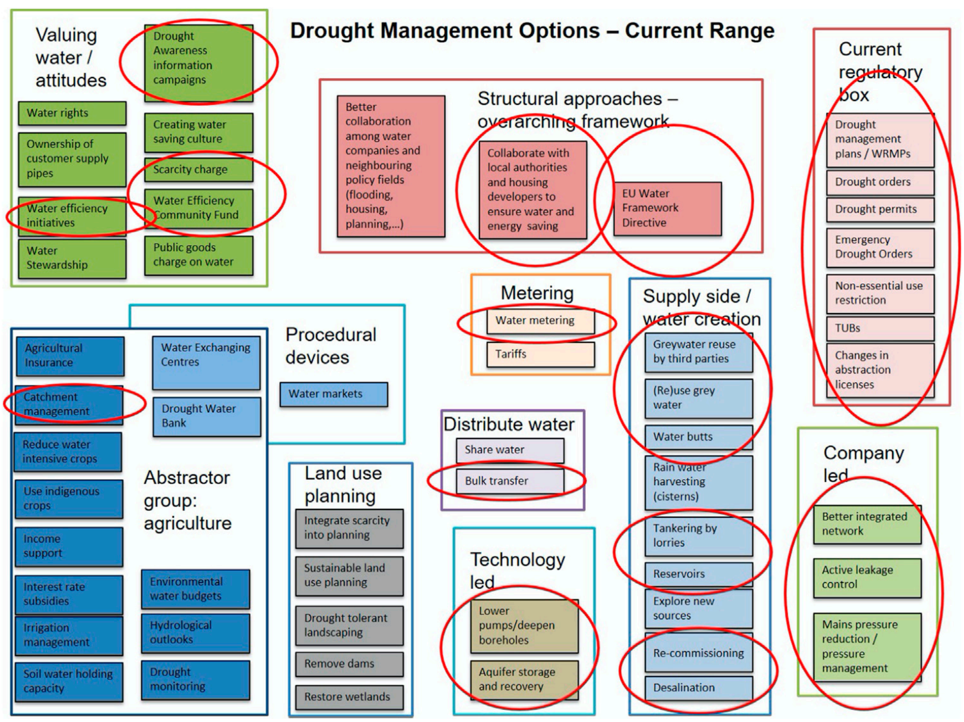

FIGURE 2 | Overview current range of drought and water scarcity management options (circled) [adapted from Grecksch (2021)] management that could potentially be beneficial and shift the emphasis away from measures that are too focused on thinking about water scarcity in the context of actual drought events.

Hence, broadening the array of drought and water scarcity management options is paramount to tackle the future water resources challenges. However, some water companies are also engaging in innovative management options. For example, the "water efficiency community fund," which provides the installation of water saving devices in public buildings such as schools (Wessex Water, 2014). Or, the concept of the "scarcity charge" (Southern Water, 2014) that would introduce a higher price to be paid for water which is abstracted from areas where there is less water available. Portsmouth Water (2014) and Cambridge Water (2014) highlight the benefits of gray water (re)use. Efforts to collaborate with other sectors such as the housing or energy sector in order to contribute to overall water and energy savings are also noteworthy (Essex and Suffolk Water, 2014). The majority of United Kingdom water companies collaborate among each other through bulk water agreements. So far, only three examples of water company collaboration go beyond this: The Water Resources in the South East Group (WRSE), Water Resources East Group in Anglia and Water Resources North (WReN). This includes the development of regional water resources strategies, frequent talks addressing sub-themes of water supply management such as supply or water efficiency measures, coordinated press and public statements and collaborative research among other things. Both organisations foster collaboration between water companies, regulators and other stakeholders in the respective regions, but they lack a wider stakeholder inclusion that could bring fresh perspectives into the groups. Thereby they are neglecting recent trends in water research such as the nexus approach (Gupta et al., 2013; Green et al., 2017) or catchment based management (Robinson and Dornan, 2017). The same holds true for collaborations with other policy sectors. Flooding, agriculture, forestry and housing are just a few of the many policy fields that are highly interconnected with the water sector and could be given more attention by water companies. Although water companies do not have any legal powers in these areas, integrating actors from these policy fields could increase awareness for problems or coordinated approaches to address these problems. Personal communications with representatives from water companies about the results of this research indicate that future drought and water scarcity management options should reflect current trends in water resources management such as more collaboration among water companies, regulators and stakeholders better[4].

A second exercise, exploratory scenario planning, was undertaken to discuss drought and water scarcity management options with key stakeholders from the English and Welsh water sector—including water companies, consultancies, regulatory bodies, the energy sector and researchers engaged in drought related research (Grecksch, 2018b). An exploratory scenario workshop offers the opportunity for unconstrained blue-sky thinking and is helpful if one is interested in exploring alternative developments of, in this case drought and water scarcity management. The result of the workshop were four scenarios, developed by the workshop participants that can be helpful in policy formulation and water resources management planning. During the penultimate step in the workshop, the key drivers that influence future drought and water scarcity management are selected. Among the top five key drivers are "society's expectations/water use culture" and the "willingness to share water" (ibid.). These two drivers indicate that actors within the drought governance space would like to see more engagement with society and also more collaboration among water companies but also with other sectors. This is in line with the results of the literature review on drought and water scarcity management options (see above), and would bring drought and water scarcity management in England and Wales more in line with international experience.

A third piece of research within the context of drought and water scarcity management options was a study of 50 semi-structured expert interviews with stakeholders from the drought governance space with regard to what types of environmental science knowledge and regulatory tools influence drought planning in England and Wales (Grecksch and Lange, 2018). Among the key themes identified in this research was the desire, expressed by water companies and regulators, to include more local (expert) knowledge into drought planning (Grecksch and Lange, 2018). Based on the responses we received, local knowledge is knowledge generated and provided by local people, e.g., inhabitants of a catchment and usually derived from observations and motivated by personal interest. Local expert knowledge is knowledge generated and provided by semi-professional and professional bodies, such as local environmental non-governmental organisations or angling clubs. Local expert knowledge also includes knowledge generated by experts who in their capacity as professionals working either for a regulatory body or water company have accumulated extensive *local* knowledge, e.g., about a catchment or a certain stretch of a river. (cf. Grecksch and Lange, 2018) Including local knowledge in the application of regulatory tools for preventing and managing drought and water scarcity can empower stakeholders and strengthen the legitimacy of regulatory decisions. However, currently it is hardly used but a number of interviewees emphasized its benefits once included into water resources management (ibid.). For instance, in relation to recent controversy over a particular abstraction site, the emerging relevance of local (expert) knowledge was discussed in the following terms: "Besides formal knowledge generated and gathered at a national or regional scale by the current key actors in the drought governance space, local knowledge—generated and provided by semi-professional or professional bodies such as local environmental non-governmental organisations or local experts in their capacity as professionals working for example for a regulatory body—can be a valuable addition to the existing

[4]These communications took place during drought and water scarcity related conferences or workshops in the United Kingdom between 2016 and 2019. The author (KG) was approached several times after a presentation, where he highlighted the lack of for example the inclusion of local knowledge in drought and water scarcity management.

stock of environmental science knowledge" (ibid., 12). The next section will further develop the idea and usefulness of local expert knowledge.

4 LOCAL KNOWLEDGE AND CIVIC INNOVATION FOR A BROADER RANGE OF DROUGHT MANAGEMENT OPTIONS

The shortcomings of United Kingdom drought and water scarcity management discussed in previous sections could, to a certain extent, be addressed by widening the scope of knowledge and concerns contributing to the range of options available. One way of doing this would be to engage with local communities, to align with experienced impacts of drought and water scarcity. In this section we consider how in-depth engagement with local communities could contribute to make drought and water scarcity management in the United Kingdom more pro-active.

Public participation is becoming increasingly common in the governance and management of environmental challenges, including water management (cf. van Buuren et al., 2019). Recent papers by Collins et al. (2020) and Fritsch (2019) document the organizational changes made to accommodate broader stakeholder and public engagement with water management in England and Wales and discuss challenges and limitations encountered. The development of more participatory water management and governance has involved social science research in different disciplines offering insights on how to engage with local publics and stakeholder organizations for the benefit of environmental science and governance (cf. Kindon et al., 2007; Chilvers and Kearnes, 2015). Originating within this area the Environmental Competency Groups (ECG) approach applied in the MaRIUS project sits at the intersection of science and technology studies (STS) and human geography (Whatmore, 2009).

STS and human geography share an analysis identifying three key rationales motivating institutional actors to invite laypeople to take part in environmental management—normative, instrumental and substantive (Stirling, 2007; Wesselink et al., 2011). A normative rationale insists on the right of publics to participate in matters that affect them, the instrumental rationale emphasizes the effective implementation of decisions and the substantive rationale holds that public participation can improve the quality of decisions. We suggest that a substantive rationale would be the driver for institutional actors in the drought governance space to invite public participation in drought and water scarcity management.

To clarify what a participatory approach, such as ECG, can contribute to drought and water scarcity management the notion of civic innovation is useful. Contrasting with public participation in deliberative decision making, civic innovation pertains to activities drawing on local knowledge to generate novelty that can impact on the ways institutional actors work (Sirianni, 2017). Civic innovation can range from new procedures to new technical artifacts. More commonly used in the context of urban re-generation than environmental risk management the notion resonates with the ECG methodology that aims for scientists and laypeople to co-produce[5] knowledge and communicate it to the local community and relevant decision makers.

The ECG methodology was developed for situations of public controversy over the nature of a problem and/or the best way to address it. As the approach creates a space in which those most directly affected can interrogate expert knowledge and bring their experiences to bear on how the problem is framed and what different courses of action are available, it is also applicable in situations were no disagreement is articulated. In non-conflict contexts the ECG approach enables collective production of new knowledge that incorporates both scientific and local, experience-based, perspectives.

ECG is one among several co-production methods used in environmental research and it also shares some important features with participatory methods used in environmental management. The origin in working with public controversy and the underpinning critical social science analysis resonate with the Collaborative Learning (CL) approach originating in US natural resource management (Walker and Daniels, 2019). Using the terminology of ECG, both approaches insist on the right of citizens to disagree with institutional environmental management decisions and policies. This distinguishes them from public engagement activities primarily aiming to educate participants or being done to fulfill legal requirements. Another similarity is the ambition to keep the problem at hand open which contrasts starkly with consultation of citizens on ready-made solutions. Both approaches promote a view of publics as knowledgeable and with a right to take part in environmental science and governance that affect them. ECG and CL also emphasize the benefits of using things, e.g., maps and photographs, in the participatory activities. However, with regard to objectives and who to invite to participate they differ.

Whereas CL aims to manage complex conflicts to arrive at decisions informed by all parties involved, the purpose of ECG is to co-produce new science-based knowledge. Treating lay participants as research partners, not as representatives for "the public" expected to provide "values" ECGs focus on generating new knowledge and well-founded ideas for interventions, not to make decisions (Whatmore and Landström, 2011). The focus on knowledge in ECGs provides a rationale for participant recruitment that selects for local residents with personal experience of an environmental problem and an interest in finding out more about it. It is advantageous for a group if experiences and concerns differ and if there is a balance of men and women from different backgrounds, but achieving "representativeness" is not primary. Thus, it is very important to remember that if the knowledge innovations presented by an ECG are taken up by environmental management actors, they are not to be viewed as being exhaustive of local civil society concerns.

Having been successfully trialed in a project on local flood risk management (Landström et al., 2011; Lane et al., 2011) the

[5]In this context "co-production" is used with reference to Callon (1999) identification of three models for public engagement with science, the other two are "education" and "dialogue."

MaRIUS project offered an opportunity to apply the ECG method to drought and water scarcity. Aiming to co-produce new knowledge this ECG, focusing on the River Kennet west of London, comprised local residents in the Marlborough area and natural and social scientists from Oxford and Bristol Universities[6]. The local residents had varying relationships with the river, some were riparian homeowners, some were members of a local environmental charity and others were members of other groups or just interested individuals. Over a one-year period, from September 2015 to July 2016, the group drew on the knowledge and experience of the members to investigate local matters of concern with regard to water management challenges facing the River Kennet. The group used multiple approaches, including analysis and discussion of water policy documents, sharing and discussing photographs as well as other personal artifacts related to past drought events. Scientific computer models were deployed to assess water quality issues and supply and demand dynamics under a range of future development scenarios[7].

The starting point for the Kennet ECG was local hydro-social knowledge, constituted in direct experience. The local participants' concerns were based in experience, local history and knowledge of local environmental decision making. One important matter of concern was groundwater abstraction. Although being alleviated by the replacement of the chalk aquifer as a key water source with a new pipeline from Farmoor reservoir to Swindon, the risk of deterioration posed by groundwater abstraction to this very sensitive environment remains. Because the impact of abstraction is very difficult to establish, the group developed this local matter of concern into questions that could be addressed with the expertize and tools available. Rather than trying to prove a negative impact of abstraction the focus shifted to measures that could be incorporated in local planning to prevent negative impacts on the river by future local and regional development. It had become clear to the group that regardless of the pipeline future development would increase water demand in ways that could intensify the vulnerability of the Kennet in times of drought. The collective re-formulation of the matter of concern into questions that the group could examine was key to the co-production of knowledge, the research questions that emerged were distinct from both local matters of concern and scientific discourse.

The distinctiveness of research questions formulated in transdisciplinary collaborations, integrating scientific and experience-based knowledge, has been acknowledged in environmental and sustainability science (cf. Fam et al., 2016). In addition to being a participatory method as mentioned above ECG can also be understood as one of many transdisciplinary approaches that center on creating locally relevant science-based environmental knowledge (Landström, 2017). The Kennet ECG produced transdisciplinary knowledge that connected local understanding of the river with scientific analyses of climate change; water supply and demand; and land use in the past, the present and possible futures[8]. Topics considered in the group included analysis of the effects of local trials with cover crops to reduce polluting runoff to the river from agricultural land and the potential of wetland restoration to retain water in the river ecosystem and in addition reduce polluting runoff.

Critical of a perceived neglect of river and water concerns in local planning the River Kennet ECG made contact with local authorities expressing the ambition to use the knowledge produced to inform the Area Neighborhood Plan (ANP), a local level planning tool, with regulatory force, that was being developed at the time. This was done by some of the local residents who took the opportunity to get involved with the engagement process initiated by the local council to ensure the democratic legitimacy of the ANP.

Engaging with local matters of concern in the Kennet ECG brought to light some important tensions resulting from lack of connections between policies and actors. For example, local ECG participants had experiences of marginalization when trying to engage with drought management. Some of the local group members engaging with water issues through the Rivers Trust ARK (Action for the River Kennet), had found that their matters of concern ended up in the gaps between separate governance domains. One such gap occurred because drought and flooding were treated as completely separate issues in science and policy, but for local communities they are connected. Knowing that when a drought breaks flooding often occurs local ECG members wanted to address the two as endpoints on a continuum and understand how the risks posed to water quality (and thus, river ecosystems) at both extremes could potentially be mitigated by the same physical interventions, such as wetland restoration. However, scientific models used to assess risks and impacts represented either drought or floods and policies for risk mitigation also addressed one or the other. Management options were thus circumscribed to focus on either, not both. The consequence of the separation of drought and flooding—taken for granted by scientists and water management experts—for the local community had not been visible to the scientists in the ECG. The Kennet ECG expanded the drought management lens, beyond a myopic, compartmentalized view toward a broader more holistic, integrated systems orientation. In follow up conversations, some of the scientists participating in the ECG remarked on how their initial understanding of drought management had evolved in new directions when engaging with the knowledge and concerns of the local group members (Landström, 2017).

The River Kennet ECG exemplifies the potential of local participation to bring attention to drought management options that were not currently in the range identified in

[6]The Kennet ECG was undertaken within the multi-disciplinary MaRIUS (Managing the Risks, Impacts and Uncertainties of Drought and Water Scarcity) project. See note 1.

[7]The six bi-monthly meetings were audio and video recorded and photographs were taken. The audio recordings were professionally transcribed and uploaded to the group's Dropbox, to which all group members had access. The Dropbox served as a repository for materials that group members wanted to share with each other. There were also a Google group with an email list through which all group members could email each other and an archive of all messages sent was available.

[8]See Kennet ECG (2017) for a full account of the work and findings of the group.

Figure 2. Land use planning and agriculture options were both brought to the forefront in the ECG. The former a perceived neglected issue in relation to drought and water scarcity management, the latter as a local experiment with different cover crops that the group could analyze the impacts of by using scientific computer modeling. In the context of United Kingdom drought and water scarcity management this amounts to civic innovation, in this case of new science-based transdisciplinary knowledge that broadened the scope. The ECG arranged as a part of the MaRIUS project thus indicates that introducing more active engagement of governance actors with knowledgeable local communities could have the potential to, at least, make United Kingdom drought and water scarcity management aware of options not previously recognized.

5 DISCUSSION—WHAT NEXT FOR ENGLISH AND WELSH DROUGHT AND WATER SCARCITY MANAGEMENT?

The following subsections summarize and discuss the key findings based on the above. We present four key findings: widening the drought governance space, the need for local drought action, knowledge, and communication.

Widening the Drought Governance Space

The drought governance space is highly professionalized, i.e., the main actors are state regulatory bodies, water companies and consultancies. Other non-state actors are only included in the drought governance space on an ad hoc basis or issue specific, often during or after drought event (Grecksch and Stefán, 2018). This confined governance space limits, we argue, innovativeness and it also shapes power relationships among the key actors (Grecksch and Lange, 2018; Grecksch, 2021). We therefore argue for a permanent widening of the drought governance space. This would not only let English and Welsh water governance catch up with current trends in the water governance literature and practice as demonstrated, but it would also enlarge the knowledge base for drought and water scarcity management policy. Water companies have clearly indicated that they wish to include more local (expert) knowledge in their decisions. This also means that proactive initiatives like the WRSE, WReN and the Water Resources East Anglia group need to widen their stakeholder base. Water companies do have so called Customer Challenge Groups (CCG), who formally are independent, yet they are company led and focus on business planning. CCGs have been established for the price review process to provide challenge to water companies' business plans and consist of local groups of customer representatives and other stakeholders; their remit is narrow though.

Scale Matters: Local Drought Action

The regional differences in water supply in England and Wales are huge. For example, while the southeast relies largely on groundwater, the northwest relies upon surface water abstraction. This has also implications for the governance of drought and water scarcity. As mentioned before, droughts are local in space. Hence, having a variety of options available that can be adapted to a locality and its conditions is important. **Figures 1**,**2** and the introduced typology of options could be helpful here, as for example a water company or an initiative like WRSE, WReN or Water Resources East Anglia could make an assessment based on their local needs with regard to options. The crucial point however is to be aware of the diversity of options, which current drought and water scarcity management in England and Wales currently is not as shown. A good example is the recent dry spell in the United Kingdom in the summer 2018. While it was hot and dry all over the country, it was the northwest of England that was threatened by a Temporary Use Ban, which, however, was called off a few days before its intended implementation date (BBC News, 2018b; BBC News, 2018c). A hosepipe ban was, however, introduced in Northern Ireland (BBC News, 2018a). This calls for localized action with regard to drought and water scarcity management. In other words, scale matters and should be the focus of attention.

The Kennet ECG introduced a local perspective on drought and water scarcity management. At the local geographical scale people experienced powerlessness in relation to science and policy with limited practical relevance. While treating different hydroclimatic risks and hazards as distinct phenomena makes sense in policy terms and in scientific research these processes often affect the same geographical location and thereby the same local communities. Trying to improve local resilience through local physical catchment management interventions environmental stewardship groups, such as ARK, have to negotiate numerous, often contradictory, policy and regulatory frameworks. They can also be told that the potential and effectiveness of local physical interventions, such as wetland construction, aiming to ameliorate both drought and flooding have no scientific basis and are not subject to investigation.

Expanding the Knowledge-Base for Drought Management

Regardless of the correctness of the perceptions emerging in the Kennet ECG they show that knowledge does not cross different scaling practices. Local matters of concern are not being adequately addressed in terms of knowledge about the physical processes and the relationships between local interventions and catchment dynamics. Nor does information travel across decision-making levels to facilitate the work done by local stewardship groups to increase local resilience.

In relation to drought and water scarcity management and in the context of privatized water supply in England and Wales, local residents are cast as "customers" or "consumers." This definition disassembles local communities into individuals existing only in relation to the water supply, in between the tap and the drain. Such a positioning constrains the possibilities of communication and action in a way that breeds disaffection. The restricted agency of the "customer" is challenged by the existence of local environmental stewardship groups, in which residents join together to improve their local water environment because they care. While policy makers and water utilities know about these groups and try to use then to implement decisions they largely fail to understand them as resources. The potential of such groups to contribute to knowledge and innovation is largely ignored as it requires a shift in perspective away from the view of society as an aggregate of customers.

Communication and Collaboration

The Kennet ECG was a transdisciplinary research project, that focused on co-producing knowledge that integrated scientific and experience-based perspectives. Communicating the outcomes of this project was done, on the one hand, by the university researchers in the form of research reports and publications, on the other hand, by the local participants in established forums for local democratic engagement. To systematically use a participatory methodology, such as ECG, in drought and water scarcity management would require new communication pathways, as well as new skills in transdisciplinary engagement among the experts in the drought governance institutions (cf. VanDyke and King, 2020). Efforts to introduce participatory ways of communicating and collaborating with local stakeholders have been documented and analyzed in environmental management (e.g., Westberg et al., 2010) and environmental policy (e.g., Challies et al., 2017). The research shows that local engagement requires skills that most technical and scientific experts do not have. Hence, demands for more participation need to be accompanied by offers of communication and collaboration skills development to professionals.

More localized address of challenges could also lead to better communication between water companies and its customers before, during and after droughts. Water companies perceive that they have difficulties with "getting the message through," i.e., to encourage customers to save more water[9]. One example of a drought management instrument option that sends out a strong message to save water are Temporary Use Bans (TUBs). Yet, while the message is strong, the actual water savings are low (Grecksch and Lange, 2018). In contrast, water saving measures introduced in non-drought periods promoted by local groups and networks of people trusting each other has the potential to reduce water use permanently, mitigating water scarcity, thus reducing the need for restrictions, such as TUBs in less severe droughts. Communication of drought and water scarcity as challenges that can be mitigated by pro-active measures is key to changing demand.

6 CONCLUSION

The purpose of this article was to present an empirically based critique of current drought and water scarcity management policy in England and Wales and also to propose a way to re-invigorate the drought and water scarcity management discourse in England and Wales. We were guided by questions of how drought and water scarcity management is currently done, who is involved (or not) and, foremost, what are the problem and deficiencies with current English and Welsh drought and water scarcity management that require attention. We were also interested in the question of what can be done to improve drought and water scarcity management in England and Wales. We addressed these questions in relation to several empirical materials and the preceding paragraphs summarized our main points. We were able to demonstrate the positive role civic innovation can play in harnessing local knowledge and how it could improve management, in this case drought and water scarcity management. Our findings are useful in the English and Welsh context as drought and water scarcity management has not adopted many of the options and policies that have been successfully adopted in other jurisdictions. Yet, especially the introduction and discussion of the ECG methodology also contributes to the overall discussion on the role of civic innovation and how to improve drought and water scarcity management policies beyond the English and Welsh context.

In a recent perspective on transitions to freshwater sustainability, Gleick (2018) notes that "sometimes, individuals or groups with an interest in maintaining the status quo hold far more authority or power than those with an interest in implementing new approaches." This is certainly true for England and Wales as we have shown and for example the recent United Kingdom government 25 Year Environment Plan (HM Government, 2018) focusses too much on water industry goals such as leakage reduction and does not mention a stronger focus for instance on (re)connecting people with the environment as it does in relation to other environmental issues (ibid. 23). However, the empirical material presented here also showed that shifts in thinking, especially with regard to cross-sectoral collaboration are visible and the example of the ECG highlights the merits of civic innovation, in this case an approach that takes local concerns and knowledge into account. Moreover, Anglian Water, one of the larger of the more than two dozen private water suppliers in England and Wales became the first United Kingdom water company to change its articles of association to embed public interest in the organization's constitution, thereby underlining their new, more socially and environmentally oriented focus (Anglian Water, 2019; WWT, 2019). Our key findings—widening the governance space, scale matters: local drought action, knowledge and communication and collaboration—could lead to a drought and water scarcity management in England and Wales that focusses on the management of people and their perceptions, knowledge and water behavior before, in and after drought.

AUTHOR CONTRIBUTIONS

KG and CL conception, design and writing. KG: critique of current drought and water scarcity management; **Sections 1**, **2**, **3**, **5**, **6**. CL: Environmental Competency Groups; **Sections 1**, **2**, **4**, **5**, **6**.

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[9]Personal communications by the author with representatives from water companies confirmed this.

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frontiers in Communication

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How Does Personalization in News Stories Influence Intentions to Help With Drought? Assessing the Influence of State Empathy and Its Antecedents

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Personalized stories are a powerful tool for communicating about science, particularly when a scientific topic is complex or unfamiliar. One example of such a topic is drought, something many regions of the world face regularly. Like other environmental challenges, drought recovery efforts benefit from a mobilized collective response through prosocial action, including volunteering and donations. The objective of this study was to examine how storytelling about drought influences emotional responses and empathic processes that in turn contribute to prosocial action. Using data collected from an online survey ($N = 249$) with undergraduate students, the current study tests the hypothesis that, relative to non-personalized stories, personalized news stories about drought will increase audiences' cognitive and emotional responses, including perceived suffering, narrative engagement, and state empathy. In addition, this study examines how emotional responses to personalized news stories influence readers' intentions to donate to farmers suffering from drought. Results reveal that personalized news stories are more likely than non-personalized stories to increase readers' state empathy and perceptions of others' suffering. Perceived suffering was directly related to the affective and cognitive dimensions of state empathy. Narrative engagement (i.e., transportation) was also directly related to the affective and cognitive dimensions of state empathy and indirectly associated with intentions to donate to assist those suffering from drought. Affective state empathy was directly associated with donation intentions, suggesting that an emotional response to media portrayals of suffering may promote prosocial intentions. We discuss the potential implications for using personalized news stories about drought and other natural disasters to motivate prosocial action.

Keywords: trait empathy, altruism, prosocial behavior, emotions, identification, affective news

INTRODUCTION

News media are a key source of public information about natural hazards and natural disasters such as drought (Wilson, 2000; Houston et al., 2012). Droughts, defined as prolonged periods with rainfall below normal recorded levels[1], are associated with reduced water supply, poor water quality, diminished crop yields, elevated food and energy prices, wildfires, impaired riparian habitats, and deteriorated rangeland (Mishra and Singh, 2010; Church et al., 2020). Droughts are ubiquitous, occurring in most countries and climatic zones (Wilhite et al., 2014). The cumulated cost of drought in the United States make it, in economic terms, the costliest recurring natural disaster (Cook et al., 2007). The negative social, environmental, and economic effects of drought are "further aggravated by growing demand for water" and earth's increasing mean surface temperature due to climate change (Mishra and Singh, 2010, p. 205). The public looks to news outlets for information about natural hazards, including what areas are affected, the consequences of the hazard, and community response efforts.

Until recently, environmental news has generally adhered to the doctrine of "just-the-facts" reporting, often de-emphasizing the role of emotions. Yet a growing number of scholars have criticized this approach to reporting, suggesting that emotional storytelling is a critical tool to engage audiences and encourage public action around social and environmental crises (Papacharissi and de Fatima Oliveira, 2012; Swim and Bloodhart, 2015; Beckett and Deuze, 2016; Maier et al., 2017) and large-scale distant disasters (Solman and Henderson, 2019). Reporting about natural disasters often features people in crisis or emotional images of people suffering (Solman and Henderson, 2019). Indeed, the emotional focus of news media's coverage of disasters has been described as an important tool for arousing compassionate responses from readers, which in turn may mobilize public engagement, volunteering, and other forms of prosocial action (Joye, 2015).

Emotional storytelling is characterized by the frequent use of dramatic and personalized narratives (Wahl-Jorgensen, 2013). As a form of strategic narrative, personalized narratives focus on individual experiences, rather than collective or group experiences (Zhou and Niederdeppe, 2017). Extensive scholarship in health communication has documented the persuasive effect of personalized news stories and their potential limitations (Green, 2006; Kreuter et al., 2007; Kim et al., 2012; Zhou and Niederdeppe, 2017). While mass media coverage of science and biological topics regularly includes personalized stories (Dahlstrom, 2014), little is currently known about the implications of including personalized storytelling in news coverage of natural hazards such as drought and water scarcity. The potential for more frequent and severe natural hazards associated with climate change highlights the importance of understanding how personalized stories engage readers and may contribute to public action during environmental crises.

[1]Definitions of drought vary widely. An overview of the definitions is beyond the scope of this paper, but see Mishra and Singh (2010) for a detailed review.

Wahl-Jorgensen (2013) suggests that personalized storytelling can trigger an emotional reaction in readers that is "an indispensable prerequisite of political action (Boltanski, 1999)" (p. 132). Thus, when the goal of communication is to motivate action, personalized storytelling may be key (Maier et al., 2017). Yet to date, the links between exposure to personalized news stories about natural hazards, the arousal of empathy, and action to support hazard recovery or mitigation efforts are far from clear. The present study explores audiences' responses to both personalized and non-personalized news stories about drought conditions in the Western U.S. Using an online experiment ($N = 249$), this study tests the hypotheses that personalization will increase audiences' perceptions of others' suffering, narrative engagement (i.e., transportation into the story), state empathy, and ultimately, intentions to donate money to those affected by drought. Additionally, this study seeks to identify the specific pathways contributing to the arousal of the cognitive, affective, and associative dimensions of empathy, and intentions to support farmers affected by drought.

THEORETICAL BACKGROUND

Narratives and Personalization

Narratives are generally defined as a story about an event or a chain of events that occur over some time period to an individual or group of characters (Dahlstrom, 2014). Narratives can entertain or be strategically employed to promote social or individual action (Zhou and Niederdeppe, 2017). Broadly, compared to informational formats, narratives evoke a greater emotional response, including empathic concern (Shen et al., 2014), and help audiences identify with specific characters or contexts (Murphy et al., 2013; Dahlstrom, 2014).

Situated within the domain of strategic narratives, personalized stories are characterized by a focus on individual experiences, feelings, and perspectives (Zhou and Niederdeppe, 2017). Personalization has received a great deal of attention in the field of communication, particularly in the context of persuasive health communication. Prior work in this area has suggested that personalized news focused on characters' perspectives and feelings can promote behavior change. For example, stories focused on individuals' experiences produced significantly greater positive emotions, empathic attitudes, intentions, and behaviors toward stigmatized groups than non-narrative formats (Oliver et al., 2012). Messages targeting respondents' identities were more effective than information-based messages about organ donation, contributing to greater donor registration rates (Dillow and Weber, 2016). Though scholarship on personalized news about natural disasters is more limited, Maier et al. (2017) found that the use of personalized stories about large-scale distant suffering due to mass violence in Africa was more effective than non-personalized news. Personalization was also more effective than including photographs, mobilizing information, or statistical information in generating emotional responses similar to empathy (e.g., sympathy, sadness, anger, compassion) and, indirectly, charitable giving (Maier et al., 2017).

Understanding how to mobilize coordinated community response efforts is crucial considering the role that the public can play in hazard response, recovery efforts, and political action to encourage policies that mitigate the negative socioeconomic impacts of drought and water scarcity. The objective of this study is to examine the effects of personalized and non-personalized stories about drought to improve our understanding of how and when personalization can motivative emotional responses and prosocial action to support individuals suffering from drought. To do so, we apply Zhou and Niederdeppe's (2017) conceptualization of personalized narratives as stories that include (1) identifiable individuals, (2) individual experiences (i.e., rather than collective or shared experiences), and (3) an expression of the character's perspectives and emotions. Below we describe three theoretical constructs often described as critical antecedents of narrative persuasion—empathy, perceived suffering, and transportation. We then review theories and previous research examining the association between empathy and prosocial action. Finally, we the describe the results of an online survey assessing the effect of personalization on readers' cognitive and emotional responses, narrative engagement, and intentions to donate to farmers suffering from drought.

Empathy

There is growing attention in journalism and communication studies to the use of emotive storytelling in arousing sympathy (Maier et al., 2017) and empathy (Shen et al., 2014). Empathy is a multi-item contrast, that some argue differs substantially from emotions such as sympathy and pity (Gerdes et al., 2010). Definitions of empathy vary widely across disciplines. Communication researchers describe empathy as being either trait-based (e.g., an enduring characteristic of an individual) or state-based (e.g., a reaction to empathy-arousing messages; see Shen, 2010a). State-based empathy (or state empathy) is a construct that describes "actual automatic and somatic responses" (Preston and de Waal, 2002, p. 4) that are activated after exposure to specific media stimuli (Shen, 2010a).

State empathy is a process that includes physiological and intellectual dimensions, though scholars disagree about what to call these dimensions (Shen, 2010a). Using Shen's previous framework, we define state empathy as a multi-item construct composed of a physiological dimension (labeled as "affective"), an intellectual dimension (labeled as "cognitive"), and an associative dimension (called "associative"). The affective dimension of state empathy includes the observer's ability to physically mirror the experiences or feelings of others (Iacoboni, 2008). Cognitive state empathy is generally defined and measured as perspective taking, or the act of picturing oneself in another's shoes. The associative dimension is a measure of character identification, often as a result of perceived similarities between the audience and the message subject. The role of associative state empathy has received less attention than the other dimensions, contributing to questions about whether identification, due to perceived similarities between the audience and the message subject, can reliably generate an empathic response. Thus, we add to the existing body of literature by simultaneously evaluating the effect of personalized news stories on the cognitive, affective, and associative dimensions of state empathy.

Contemporary scholarship has developed interventions focused on both the affective (Decety and Jackson, 2006) and cognitive dimensions of state empathy, including efforts to induce perspective taking for people with AIDS, minority groups, and the homeless (Batson et al., 1997b; Stephan and Finlay, 1999; Finlay and Stephan, 2000). State empathy has been measured after exposing participants to media stimuli, such as pictures, videos, or audio recordings of harmful acts toward people or animals (Shelton and Rogers, 1981; Batson et al., 1997a,b, 2002; Schultz, 2000; Berenguer, 2007; Swim and Bloodhart, 2015), or after exposure to public service announcements (PSAs) (Stiff et al., 1988; Bagozzi and Moore, 1994; Finlay and Stephan, 2000; Campbell and Babrow, 2004; Shen, 2010a,b, 2011; Shen et al., 2014). Exposure to personalized narratives, including a newspaper account of someone else's emotional or physical experience, has also been used to arouse empathic responses (Stiff et al., 1988; Shen et al., 2014), though this format has received less attention than PSAs. Drawing on this work we posit that:

H1: Personalized news stories (vs. non-personalized news stories) will be positively associated with readers' state empathy.

Media Coverage and Perceived Suffering

Most people experience natural disasters through media coverage (Maier et al., 2017). Therefore, how the story is framed and the frequency of the media coverage can influence public perceptions of natural hazards. Indeed, frequent local-level newspaper coverage of drought conditions in California was significantly associated with greater public concerns about drought (Duffy, 2016).

To date, there is limited scholarship exploring media coverage of slow-onset hazards. However, a recent review of news coverage about the California drought found that news stories focused on slow-onset hazards (such as drought) are generally confined to episodic frames and focused on socio-economic impacts (Duffy, 2016). Episodic frames about hazards generally focus on individual suffering and impacts. Media representations of hazards that focus on suffering have the potential to arouse intense emotional responses (Aarøe, 2011). The emotional emphasis of media coverage of slow-onset hazards has been criticized for exaggerating risk and sensationalizing serious concerns, which can create problems for recovery efforts. Despite concerns about the use of dramatic narrative stories to boost readership, Solman and Henderson (2019) suggest that disaster reporting "is one of the few legitimate places for emotional expression in news journalism" (p. 1642).

Scholars who have examined the use of emotive storytelling in disaster reporting have suggested that news focused on others' suffering may carry more weight than reports focused on property damage or the severity of the disaster, and are more effective at capturing media attention and mobilizing public action (Joye, 2015; Solman and Henderson, 2019). Indeed, personalized stories about large-scale distant suffering heightened readers' emotional distress more than stories focused on statistical information or stories including photographs of victims (Maier et al., 2017). Yet previous work in this area has primarily focused on readers' emotional distress, not readers' perceptions of others' suffering. According to (Decety and Lamm, 2006), a prerequisite for communication and empathy arousal is the preservation of individuality. While making a link between the self and other though perspective taking is a critically important component of empathy, separating our own feelings from others' feelings and thoughts, or self-other awareness, is also essential to preventing ecocentric responses to others' feelings and thoughts (Segal et al., 2017). Therefore, this study will also examine how personalized news stories impact readers' perceptions of others' suffering and whether these perceptions are associated with state empathy.

H2: Personalized news stories (vs. non-personalized news stories) will be positively associated with readers' perceived suffering.
H3: Perceived suffering will be positively associated with readers' state empathy.

Narrative Engagement

Narrative engagement, also called absorption, is a popular umbrella concept used to describe a readers' immersion into the story world (Oliver et al., 2012; Appel et al., 2015). Transportation is a subtype of narrative engagement described as a psychological state that simultaneously involves attention, imagery, and emotions (Appel et al., 2015). Transportation relates to the experience of engaging with, or being transported into a narrative world (Green et al., 2004). Previous work has reported mixed results regarding the relationship between transportation and empathy. Oliver et al. (2012) found that story involvement, a subtheme in Green and Brock (2000) narrative transportation scale, influenced emotional reactions to a narrative news story and intentions to help stigmatized groups (prisoners and elderly persons). Transportation was a significant predictor of empathy arousal in response to a narrative but not a significant mediator of narrative impact on empathy and cognitive responses (Shen et al., 2014). Drawing on this work, we propose the following hypotheses:

H4: Personalized news stories (vs. non-personalized news stories) will be positively associated with readers' transportation into the story.
H5: Transportation will be positively associated with perceived suffering and state empathy.

The Empathy-Altruism Hypothesis

Much of the scholarship on empathy is grounded in the empathy-altruism hypothesis (Batson, 1991). Batson and colleagues (see Batson et al., 1989, for a review) tested this hypothesis through a series of experiments exploring the relationship between empathic feelings (e.g., sympathy, compassion, warmth, tenderness, etc.), positive attitudes toward others (Batson et al., 1997b; Finlay and Stephan, 2000), and behavioral intentions (Batson et al., 2002). Results indicate that participants prompted to imagine the subject's feelings (compared to those prompted to concentrate on being objective) were significantly more likely to express intentions to donate funds to support an addiction and counseling service (Batson et al., 2002).

Following Batson's work, empathy is regularly described as a key factor in social interaction (Gerdes and Segal, 2009), civic engagement (Miaskiewicz and Monarchi, 2008), and social tolerance (Segal et al., 2012). Indeed, researchers in the fields of psychology, social work, and business have identified empathy as a critical source of prosocial behavior (Grant and Berry, 2011; Segal et al., 2017; Batson, 2018), often defined as voluntary actions benefiting others or society (Eisenberg and Miller, 1987). Bagozzi and Moore (1994) exposed respondents to a "rational" appeal condition and an emotional appeal (called the high-empathy condition) and found that respondents in the latter group expressed greater intentions to help victims of child abuse. Participants reported greater distress and willingness to contribute to an organization that helps children with cancer when they were exposed to a stimulus with an identified victim rather than a non-identified victim (Kogut and Ritov, 2005). Guided by research in the tradition of the theory of reasoned action (Ajzen, 1991; Kim and Hunter, 1993), Oliver et al. (2012) found that empathic attitudes were associated with stronger intentions to help stigmatized groups dealing with health-related challenges.

As the examples above illustrate, most of the previous work considering the role of empathy-arousing messages in communication has focused on the health domain (e.g., Stiff et al., 1988; Shen, 2010a,b, 2011). There is also a substantial body of work in environmental contexts focused on arousing empathy for animals (Shelton and Rogers, 1981; Schultz, 2000; Berenguer, 2007, 2010) and assessing the relationships between empathy, pro-environmental attitudes, and pro-environmental behavior. For example, Swim and Bloodhart (2015) exposed participants to messages focused on climate change-related threats to polar bears, and found that participants prompted to take the perspective of the animals were more likely (than those prompted to remain objective) to donate to environmental advocacy organizations. Here, we expand this work by focusing on the impacts of drought—though this context has implications for climate change communication and messages about other natural hazards and disasters. Drawing on the empathy-altruism hypothesis and previous work in health and environmental contexts, we posit the following:

H6. State empathy will be positively associated with intentions to donate to farmers suffering from drought.

Assessing the Cognitive, Affective, and Associative Dimensions of Empathy as a Source of Prosocial Behavior

Early scholars debated whether empathy-driven prosocial action occurred in response to others' affective cues—as Hoffman (1981) posited—or as a result of a cognitive process driven by individuals' perspective taking abilities (Decety and Jackson, 2006). Proponents of the "affective assumption" have suggested that narratives generate an emotional involvement with characters (Slater and Rouner, 2002; Green et al., 2004; Busselle and Bilandzic, 2009) and that it is the emotional response to others' needs that produces the "other-oriented desire" to reduce perceived distress or suffering (Davis, 1994, p. 134).

Indeed, experimental research across a variety of contexts has found a strong association between readers' emotional responses (i.e., distress) and willingness to help victims in need (Kogut and Ritov, 2005; Maier et al., 2017).

There is also evidence to support the association between the cognitive dimensions of empathy, including perspective taking, and prosocial behavior—or the "cognitive hypothesis." Perspective taking has been associated with increased psychological closeness between individuals, helping behavior (Cialdini et al., 1997), and mimicking behavior (van Baaren et al., 2009; Müller et al., 2012).

Still, other scholars have suggested that the cognitive and affective dimensions are "sequentially and causally connected" (Stiff et al., 1988, p. 200) such that cognition enables people to take the perspectives of others, but it is affective empathy that generates the motivation to act. Keen (2010) has suggested that the affective, cognitive, and associative dimensions are complementary, especially in response to reading, because "When texts invite readers to feel, they also stimulate readers' thinking" (p. 69).

Others have suggested that identification, a key component of the associative dimension of state empathy, is critical for communication and behavior because: "you persuade a man [sic] only insofar as you can talk his language by speech, gesture, tonality, order, image, attitude, idea, *identifying* your ways with his" (Burke, 1969, p. 55). Thus, a character's identity, gender, socio-demographic characteristics, along with their expressed values may generate associative state empathy when they align with readers' values and identity. Identification is the process through which relationships develop and social bonding occurs (Shen, 2010a,b) and is necessary for message relevance (Campbell and Babrow, 2004) and reduced reactance, which can lead to the rejection of persuasive messages (Shen, 2010a). Shen (2010a) has suggested that identification is associated with Kelman's theory of attitude change and may therefore be, "more predictive of behavior" than the other dimensions of state empathy.

To date, scholarship on empathy in communication regularly treats the multi-item construct of state empathy as a single outcome variable, limiting current understanding of the underlying mechanisms associated with empathy arousal and helping behavior in response to narrative news stories. Indeed, we are not familiar with any study to date that has tested a tripartite model of state empathy, as proposed here. To address this gap, we use a structural equation model to simultaneously test the effect of the cognitive, affective, and associative dimensions of state empathy on prosocial behavior, asking the following research question:

> **RQ1:** To what extent do the cognitive, affective, and associative dimensions of state empathy influence intentions to donate to others?

METHODS

Stimuli

Data were collected using online surveys through the Qualtrics platform. The survey took 15 min to complete. Participants were assigned randomly to one condition (personalized or non-personalized). Both conditions included a simulated news story about drought conditions in the Southwestern U.S. in 2015 (Personalized = 392 words; Non-personalized = 387 words). Both stories were titled, "Arizona farmers burdened by the Megadrought" and formatted to resemble an AP-style article. We included a single image of drought conditions across the state of California from 2011 to 2015. The image came from the U.S. Drought Monitor and did not vary across conditions. We kept the introductory paragraph and the structure of the article the same across both stories to prevent the introduction of confounding cues. The articles were based on reports by the Associated Press and designed to avoid specific partisan cues. Both news stories are available in the **Supplementary Material**.

The focus of the articles in the two conditions differed. The personalized story included three components of personalized narratives: (1) an identifiable farmer, (2) direct quotes about the farmer's experience with drought, and (3) direct quotes about the farmer's economic and personal suffering due to drought conditions. The non-personalized story focused primarily on expert concern about the 2015 drought. It broadly addressed the social and economic impacts of drought conditions for farmers in the Southwest, though it did not include any direct quotes from individual farmers or descriptions of the character's emotional state or experiences.

The survey for this study began with an assessment of participants' trait empathy. Trait empathy refers an individual's unique ability to respond to another person's distress while state empathy is situation based. Following previous scholarship, we include trait empathy as a control variable likely associated with state responses to a stimulus (Bagozzi and Moore, 1994; Finlay and Stephan, 2000; Campbell and Babrow, 2004; Shen, 2010a,b; Shen, 2011; Shen et al., 2014). After completing the trait measures, participants read one of the two randomly assigned stories, rated their perceptions of the story, completed the perceived suffering, state empathy, and transportation measures, and intentions to donate to farmers affected by drought in the Southwest. Finally, participants completed demographic questions.

Participants

Eleven participants dropped out of the study before they could complete the survey and were removed from the data, resulting in a sample size of $N = 249$. Participants were undergraduate students enrolled in an introductory course on mass communication at a public university in the midwestern United States (M age = 20 years, SD = 1.4 years). We distributed surveys in a classroom setting and provided participants extra credit for participation. Most respondents were women (67%) who had completed some college ($M = 2.73$ and $SD = 0.68$) and self-reported as moderately wealthy growing up (1 = poor to 5 = wealthy; $M = 3.2$, $SD = 0.90$), with income in the range of \$50,000 to \$99,000 (1 = less than \$10,000 to 9 = over \$150,000; $M = 6.35$, $SD = 2.13$). While we didn't ask for information about race, the student population at this University is 70% white (Data USA, n.d.).

TABLE 1 | Factor solution for state empathy.

	Factor		
	Cognitive SE	Affective SE	Associative SE
	1	2	3
I can understand the points of view expressed in the article	**0.809**	0.121	0.084
I recognize the situation detailed in the article	**0.781**	0.045	0.136
Reactions to the drought are understandable	**0.642**	0.133	0.127
The emotions expressed in this story are genuine	**0.576**	0.316	0.041
I can understand what farmers in the southwest are going through	**0.589**	0.286	0.292
I experienced the same emotions as the farmer(s) when reading this story	0.202	**0.803**	0.368
I was in a similar emotional state as the farmer(s) when reading the story	0.148	**0.776**	0.421
I can feel the farmer's emotions	0.310	**0.704**	0.258
When reading the message, I was fully absorbed	0.230	**0.510**	0.410
I can identify with the farmers in the story	0.210	0.370	**0.800**
I can identify with the situation described in the story	0.145	0.236	**0.770**
I can relate to what farmers are going through in the story	0.146	0.449	**0.688**

Values above the cutoff criteria of 0.5 are indicated in boldface.

In our sample, 62 participants had a single missing value, resulting in a small portion (0.44%) of the total number of missing values over the total number of responses across all participants. Preliminary tests were conducted in SPSS 26 (IBM). For all analysis $p < 0.05$ was considered significant. Scale reliability was measured using Cronbach's alpha >0.65 was considered acceptable (Nunnally, 1978).[2]

Measurements

State empathy was measured using a previously validated scale (Shen, 2011). The scale included 12 items representing the affective, cognitive, and associative dimensions of state empathy and ranged from 1 = *not at all* to 5 = *completely*. Principal-axis factoring with varimax rotation identified a three-factor solution explaining 64% of the variance in state empathy (Factor scores and items listed in **Table 1**). The first factor labeled "cognitive" was associated with five statements pertaining to the reader's understanding of others' point of view and recognition of the situation detailed in the articles ($M = 3.61$, $SD = 0.70$, Cronbach's alpha = 0.84). The second factor, which we labeled "affective" was associated with four statements related to readers' emotional reactions to the story ($M = 3.07$, $SD = 0.94$, Cronbach's alpha = 0.89). The final factor we labeled "associative," and it was comprised of three statements about identifying with the topic and individual experiences detailed in the stories ($M = 2.97$, $SD = 1.02$, Cronbach's alpha = 0.88). In the following sections, we refer to these as cognitive SE, affective SE, and associative SE.

Perceived suffering was measured using three items asking participants to indicate whether the story portrayed the pain, suffering and distress associated with drought in the Southwest (from 1 = *strongly disagree* to 5 = *strongly agree*). The three items created a reliable scale and were collapsed ($M = 3.51$, $SD = 0.87$, Cronbach's alpha = 0.89).

[2]State empathy items with a factor loading of 0.50 or greater were retained (Matsunaga, 2010).

Transportation into the story was assessed using Appel et al.'s (2015) Transportation Scale – Short Form. The five-item items had seven-point response scales (from 1 = *not at all*) to 7 = *very much*) and were reliable ($M = 4.07$, $SD = 1.32$, Cronbach's alpha = 0.90).

Intentions to donate were measured after reading the newspaper articles. Participants read the following statement: "Lots of things come up that keep people from donating to social organizations even if they want to." Respondents then answered the question: "Would you be willing to donate money to help farmers in the Southwest affected by the drought?" by selecting one of two possible options: 0 = *no*, 1 = *yes*.

Trait empathy was measured using the affective and cognitive dimensions of the Social Empathy Index (SEI) (Gerdes et al., 2011; Segal et al., 2012). The full SEI includes 22 items measuring five dimensions of empathy and responses range from 1 = *never* to 6 = *always*. The scale included 9 items measuring the affective dimensions of trait empathy ($M = 4.53$, $SD = 0.67$, Chronbach's alpha = 0.83). Example questions included: "When I see someone receive a gift that makes them happy, I feel happy myself," "I am good at understanding other people's emotions." And "When I see someone being publicly embarrassed, I cringe a little." One item was removed to improve scale reliability ("When I see someone accidentally hit his or her thumb with a hammer, I feel a flash of pain myself").

Analysis

The theoretical model was tested in M*plus 8* using structural equation modeling (SEM) in Muthén and Muthén (1998-2017). We used the WLSMV estimator, recommended for models with categorical outcome variables. The chi-square value reported below is calculated using the DIFFTEST function in M*plus*. Trait empathy was placed in the model as a control on state empathy. Story personalization (0 = *non-personalized*; 1 = *personalized*) was an exogenous variable that influenced all of the other post-test variables in the model: perceived suffering, state empathy and prosocial intentions.

TABLE 2 | Correlations.

	1. Cog. SE	2. Aff. SE	3. Assoc. SE	4. Per. Suffering	5. Transport	6. Int. to Donate
1. Cog. SE	1.00					
2. Aff. SE	0.519**	1.00				
3. Assoc. SE	0.496**	0.751**	1.00			
4. Per. Suffering	0.612**	0.567**	0.429**	1.00		
5. Transport	0.579**	0.721**	0.601**	0.567**	1.00	
6. Int. to Donate	0.263**	0.232**	0.105	0.207**	0.170*	1.00

*$p < 0.05$. **$p < 0.01$.

TABLE 3 | Descriptive statistics for non-personalized and personalized stories.

	Story format			
	Non-personalized		Personalized	
	M	SD	M	SD
Cog. SE	3.46	0.70	3.75	0.67
Aff. SE	2.89	0.93	3.23	0.91
Assoc. SE	2.89	1.00	3.05	1.04
Per. Suffering	3.37	0.92	3.65	0.79
Transport	3.94	1.36	4.19	1.26
Int. to Donate	0.42	0.49	0.44	0.49

Model fit was evaluated using the comparative fit index (CFI), standardized root-mean-square residual (SRMR), and root-mean-square error of approximation (RMSEA) criteria identified by Hu and Bentler (1999): CFI > 0.90 and RMSEA < 0.05. We adopted a 95% confidence model in the bootstrapping procedure. All exogenous variables were correlated.

RESULTS

Because this research concerned both the impact of story type on behavioral intentions and the mediating role of state empathy, perceived suffering, and transportation, we followed O'Keefe's (2003) suggestion and did not conduct a message manipulation check as the messages differed on objective, modifiable features. We used a structural equation model to evaluate the direct and indirect effects of personification on state empathy, perceived suffering, transportation, and intentions to donate.

Preliminary Analysis

Correlations between key variables are presented in **Table 2**. To address H1, H2, and H4, we conducted ANOVA tests to evaluate the main effects of personalization on state empathy (SE), perceived suffering, and transportation. Descriptive results are reported in **Table 3**. There were significant treatment group effects on cognitive SE $F_{(1, 246)} = 11.73$, $p < 0.001$ and affective SE $F_{(1, 246)} = 8.54$, $p < 0.01$. Respondents' scores on perceived suffering also varied significantly between the personalized and non-personalized story versions $F_{(1, 247)} = 6.72$, $p < 0.01$. These findings provide support for H1 (i.e., personalization is associated with state empathy) and H2 (i.e., personalization is associated with perceived suffering). There were no significant differences in transportation between the personalized and non-personalized news stories $F_{(1, 246)} = 1.59$, $p = 0.21$. Thus, H4 was not supported.

Model Results

Based on the aforementioned results, the hypothesized model was reduced to **Figure 1** without associative SE and no direct association between story format and transportation. The final model fit the data well: χ^2 (4) = 29.0, $p < 0.000$, RMSEA (Root Mean Square Error of Approximation) = 0.035, CFI (Comparative Fit Index) = 0.93, and explained 87% of the variance in intention to donate (see **Figure 2**).

Story personalization was significantly associated with cognitive SE ($\beta = 0.17$, $SE = 0.06$, $p < 0.01$) and affective SE ($\beta = 0.15$, $SE = 0.07$, $p < 0.05$) (H1). Story personalization was also significantly associated with perceived suffering ($\beta = 0.17$, $SE = 0.06$, $p < 0.01$) (H2). The intensity of perceived suffering was positively associated with both the cognitive ($\beta = 0.37$, $SE = 0.09$, $p < 0.001$) and affective dimensions of state empathy ($\beta = 0.24$, $SE = 0.08$, $p < 0.01$), providing support for H3.

Transportation was positively and significantly associated with perceived suffering ($\beta = 0.56$, $SE = 0.06$, $p < 0.000$), cognitive SE ($\beta = 0.35$, $SE = 0.08$, $p < 0.000$), and affective SE ($\beta = 0.61$, $SE = 0.06$, $p < 0.000$), providing support for H5.

H6 was supported. There was a significant association between affective SE and intentions to donate ($\beta = 0.39$, $SE = 0.16$, $p < 0.05$). Cognitive SE, perceived suffering, and transportation were not directly associated with intentions to donate. This finding highlights the potential importance of affective responses to narrative stories as a critical pathway to promote prosocial intentions and provides limited support for the "cognitive hypothesis."

We used 1,000 bootstrap samples and bias-corrected confidence intervals to explore the specific indirect effects of transportation and perceived suffering on behavioral intentions. The specific indirect effects of transportation on donations, through affective SE, are significant ($\beta = 0.222$, SE = 0.10, $p = 0.025$) 95% CI [0.075, 0.375].

DISCUSSION

News coverage about climate change, and the natural hazards associated with it, represent an opportunity that challenges

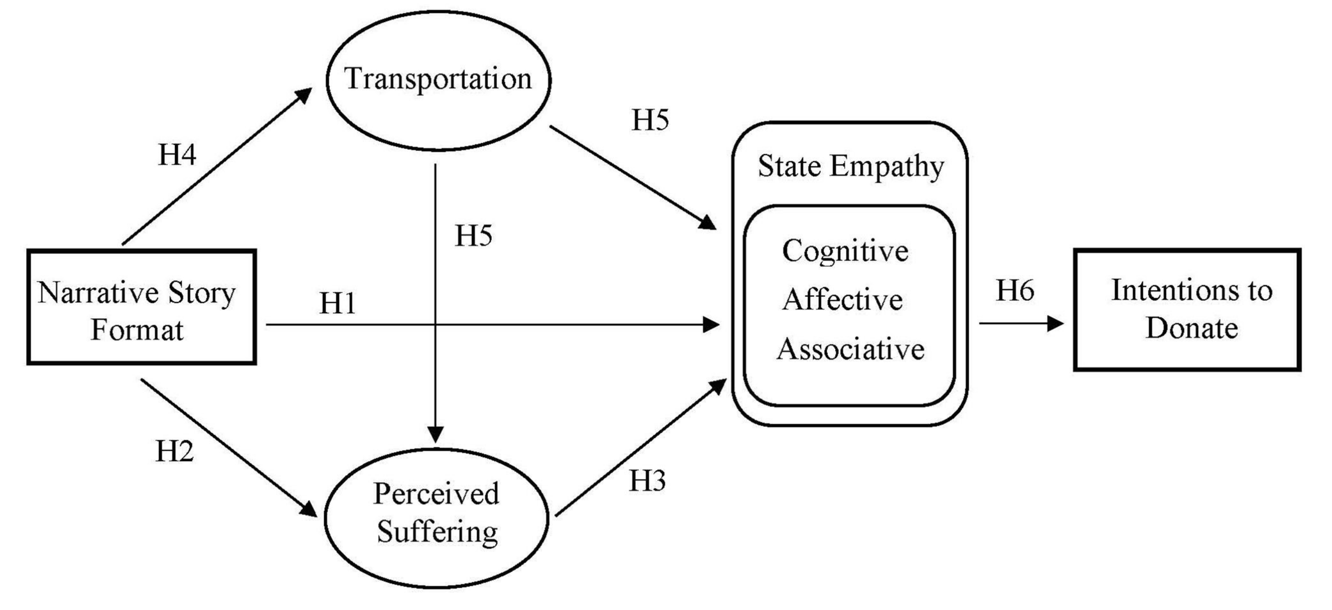

FIGURE 1 | Hypothesized model.

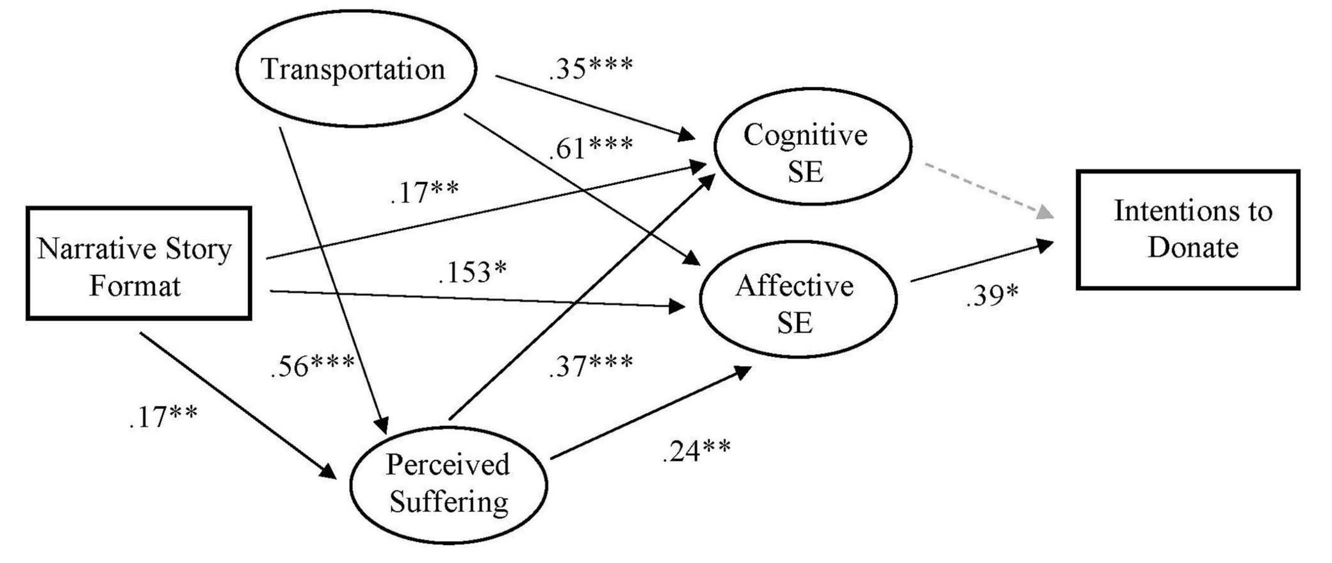

FIGURE 2 | Final path model. *P< 0.05, **P < 0.01, ***P < 0.001. Solid black lines indicate significant direct effects (P< 0.05); insignificant paths are indicated with dashed lines.

journalists' role as "critics of (nation) state power," tests journalism's "default position[s]," and demands "new ways of communicating" (Kunelius, 2019). This research sheds light on proposed patterns of causality between empathy-arousing messages and prosocial intentions and advances the use of empathy-arousing messages and emotional storytelling in the context of drought and natural hazards. This study's findings also illustrate the nuanced effects of state empathy on behavioral intentions and the importance of affective responses to narratives portraying human suffering. Overall, the expected relationships were observed in most cases, and the final model accounted for a large amount of the variance in respondents' intentions to donate to farmers suffering from drought.

Relative to participants exposed to the non-personalized news story, participants exposed to the personalized news story reported higher levels of perceived suffering, cognitive SE, and affective SE, confirming and building on previous evidence that narrative news stories about environmental hazards can engender emotional responses from readers that may in turn encourage prosocial action. While previous research has suggested that identification (associative SE) is a key dimension of state empathy, we were not able to verify these findings because our stimuli did not generate a significant associative response. It is possible that this is due to the nature of the sample and a story focused on an adult farmer instead of a younger subject.

Perceived suffering was directly associated with the affective and cognitive dimensions of state empathy. While previous work has used perceived suffering as a criterion for the selection of empathy-arousing messages (Shen, 2011), this study empirically tested the role of perceived suffering in activating state empathy and prosocial intentions. Our findings highlight the importance of perceived suffering in state empathy arousal, but fail to provide evidence of a significant effect of perceived suffering on prosocial behaviors. While Maier et al. (2017) found that news stories about large-scale distant suffering were more effective in generating emotional responses (e.g., sympathy, sadness, anger), and indirectly, charitable giving, we only found partial support for these associations in the context of drought. It is possible that perceived suffering is not as strongly associated with helping behavior as actual emotional distress or transportation. Indeed, the observed significant indirect effects from transportation to intentions through affective SE would appear to support this assertion. It is also possible that the use of younger participants, less able to regulate emotions (Somerville et al., 2010), also contributed to these results. We discuss the limitations of using a student sample in detail below. These findings may also be due to the fact that this study emphasized the economic impacts of drought on farmers. Previous scholarship in agro-environmental contexts has found that economic messages have a more muted effect on public opinions than environmental messages (Peterson et al., 2019). Future work could explore alternative frames with varying degrees of emotional arousal.

Oliver et al. (2012) found differences in one of the two transportation measures (differences in story involvement but no differences in story impact) between the narrative and non-narrative story formats. In this study, we found a strong association between narrative engagement and perceived suffering and narrative engagement and state empathy. These results appear to confirm Oliver et al.'s (2012) assertation that narrative engagement precedes compassionate and affective responses to narrative stories.

Previous research has revealed inconsistent effects of story manipulation on transportation when readers were assigned specific reading goals (e.g., proofreading vs. regular reading) or when stories were labeled as fact or fiction (Gnambs et al., 2014). Shen et al. (2014) also reported mixed results with transportation: narrative stories with an environmental frame led to greater transportation, but stories with an economic frame revealed no increase in audience transportation. Our results indicating no direct effect between personalization and transportation align with these previous findings. Similarly, the personified story used in this study focused on farmers' economic losses. Given these results, it is possible that economic frames are less effective in generating transportation and future work should explore this option. While our study revealed no significant differences in transportation between a personalized and non-personalized story, personalization is only one form that strategic narratives can take (Zhou and Niederdeppe, 2017). Future work could also explore how narrative dramatization, emotionalization, and fictionalization might influence readers' emotional and prosocial responses to news coverage about natural hazards.

In this study, only affective state empathy was directly associated with intentions to donate. This finding reinforces previous evidence suggesting that affective empathy is more proximal to action than the cognitive dimension (Singer and Lamm, 2009). Moreover, these results suggest that the connection between empathy and prosocial intentions may only occur with the arousal of the affective dimension of empathy, providing one potential explanation for the previously mixed results exploring the empathy-arousing ability of narratives (Keen, 2007). These results suggest that the current empathy-altruism hypothesis could be modified to better account for differences in the effect of the cognitive, affective, and associative dimensions of state empathy on behavioral intentions.

Limitations

Participants were limited to students at a public university in the U.S. It is possible that participants with more direct experience with drought or farming would be more likely to identify with the individual profiled in the personalized news story. It is possible that lack of experience with drought contributed to the lack of an observed direct relationship between identification and prosocial behavior. In addition, students' limited ability to make a financial contribution might be another reason for the lack of direct effects of story type or perceived suffering on prosocial behavior. Finally, participants were recruited as part of a class on media and society. Thus, this population may be more sensitized to different modes of communication and thus less affected by the stimuli used in this study. We recommend that future research replicate this study with adults.

Additionally, our measure of readers' donations, which we used to test Hypothesis 6 and Research Question 1, assessed participants' general intention to donate money, rather than asking them to make an actual donation or to specify how much they would donate. Although research related to the Theory of Planned Behavior (Ajzen, 1991) suggests that individuals' behavioral intentions are often highly correlated with their actual behavior, assessing actual donations would have been preferable. Additionally, the yes/no format of the donation intentions question may have obscured differences between participants in the degree to which they planned to donate, or made them more likely to select the "yes" option (given it did not have a monetary value attached to it). Future research that enables participants to make actual donations of differing amounts would be a valuable next step.

Finally, the approach used in this study tells only how respondents felt immediately after reading personalized and non-personalized articles about drought. This approach provides us with limited information about the potential cumulative effect of mass media disaster coverage or the long-term impacts of reading a personalized news story about large-scale distant disasters.

In spite of these limitations, these findings suggest that personalized news stories about drought events are one potential pathway to encourage readers' emotional responses, including perceived suffering and state empathy. Our results also suggest that transportation into a story, perceived suffering and state empathy may interact in important ways to contribute to intentions to support individuals during drought events. While intentions are important, social action around drought, water scarcity, and climate change will require significantly more direct action, including political lobbying, organizing, and public protests. While we found many important relationships between our primary measures, we found no direct relationship between personalization and behavioral intentions. Thus, additional work is needed to further explore the effect of emotional storytelling on the adoption of prosocial actions in response to drought and natural hazards.

In addition, we add a note of caution about the use of personalized stories to motivate action. Prior evidence from a variety of studies in health communication suggests that personalized stories are effective in encouraging individual attitudes and behaviors. However, previous research has also highlighted the limitations of using personalized narratives to generate collective action or promote specific social policies. For example, compared to depersonalized formats, personalized narratives generated more counterarguments in response to claims that social factors drive obesity (Zhou and Niederdeppe, 2017) and less support for school-based nutrition policies (Barry et al., 2013). Moreover, given the potential for psychological reactance to messages about climate change (Dixon et al., 2019; Ma et al., 2019), messages about drought must be carefully designed and tested to avoid responses that might undermine effective persuasion (Nabi et al., 2018). Future scholarship should explore the potential for personalized narratives in environmental contexts to encourage both individual-level attitudes and behaviors as well as collective action and policy support.

Given the potential for the frequency, duration, and severity of drought events to increase, there is a critical need for further study about the use of emotional storytelling for hazard coverage. Our work focused on personalized and non-personalized news stories about farmers, but future work could explore empathic and prosocial responses to stories about other groups (i.e., the elderly, immigrants). Previous research has suggested that reports about floods by Western-dominated global media are less likely to use personal stories about individual suffering when reporting about flooding in the developing world (Solman and Henderson, 2019). Future work could explore if readers' empathic responses to stories about individual suffering vary by subject location, nationality, gender, and race.

The extreme suffering produced by drought highlights the importance of understanding how to mobilize an effective collective response to slow-onset hazards such as drought and water scarcity. One potential tool for such mobilization is the media. Yet while "just-the-facts" reporting about drought, environmental hazards, or climate change, may raise awareness about these environmental issues, emotive storytelling and personalized narratives appear to be a promising tool to generate readers' empathic responses and, indirectly, intentions to support individuals suffering due to drought. In addition, our findings suggest that personalized stories designed to produce prosocial intentions may be more effective when they generate a combination of transportation, perceived suffering, and affective state empathy. In sum, these results point to ways that environmental writers and reporters can raise awareness and potentially mobilize social action around drought and water scarcity.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Review Board, Iowa State University Office of Research Ethics. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

DW led the development of the research design, oversaw the analysis, research interpretation, and writing. EJ and NW assisted with the development of the survey, data interpretation, and writing. JH assisted with data interpretation and writing. All authors contributed to the article and approved the submitted version.

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The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomm.2020.588978/full#supplementary-material

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frontiers in Environmental Science

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Regional Differences in Spatiotemporal Drought Characteristics in Great Britain

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Despite being one of the most damaging natural hazards, droughts and their spatiotemporal dynamics are typically not well understood. Great Britain, which is the focus of this work, has experienced many major drought episodes in the past, causing a range of socioeconomic and environmental impacts. Here, we apply a recently developed technique to identify and characterise past droughts, using space-time connectivity to extract events from a monthly gridded precipitation dataset covering 1862–2015, without imposing fixed geographical boundaries or time-frames. For each grid cell, the data was aggregated into four new time series using moving averages over 3-, 6-, 12- and 24-month windows. These reflect a range of response times for different types of drought impacts. Drought events were then extracted for each time window separately. In order to assess regional differences in drought characteristics, each extracted drought was assigned to one of three regions: the South-East (SE), the North-West (NW) and a "Transition" region in-between them. A frequency analysis of drought characteristics (duration, area, intensity and severity) highlighted differences between regions: for short and medium accumulation periods (3, 6, and 12 months), short and less severe droughts are more frequent in the NW than in the SE, whereas long, spatially extended and more severe droughts are more frequent in the SE than in the NW. However, for long accumulation periods (24 months), fewer differences are observed between the NW and the SE. In the "Transition" region, severe droughts are less frequent than in the other two regions. A timeline of historic drought events detected by our method included the vast majority of known drought events from previous studies, with a few additional ones, and we shed important new light on the relative severity of these historical drought episodes. Finally, an analysis of the spatial coherence between regions showed that the most extreme drought events presented little spatial coherence, whereas less severe droughts tend to be more spatially coherent. This has important implications for water resources planning and drought management strategies, particularly given the increasing emphasis on inter-regional water transfers as a potential solution in situations of extreme drought.

Keywords: spatiotemporal droughts, frequency analysis, return period, spatial coherence, drought area, drought duration, drought severity

INTRODUCTION

Globally, drought is one of the most damaging natural hazards (Blauhut, 2020). Droughts pose a major threat to lives and livelihoods across the world, and the impacts of drought are expected to increase in future on a global scale, due to anthropogenic warming (Prudhomme et al., 2014) and socio-economic changes (Arnell et al., 2019). As such, there is a growing demand for drought and water resources management systems that enable policymakers and practitioners to appraise the risk of drought occurring, under historical conditions as well as using future projections, to identify appropriate adaptation options. In addition, monitoring and early warning systems are needed to help identify the onset, development and recovery from droughts and to identify when appropriate mitigation measures should be applied to avoid impacts on society and the environment (Bachmair et al., 2016).

Such drought management systems rely on a proper understanding of drought occurrence and dynamics in the region in question. A key characteristic of droughts is that they tend to be large-scale phenomena, and typically evolve slowly, at least in comparison to other hazards (a "creeping" hazard, e.g., Wilhite et al. (2014)). In theory, this slow evolution should be an asset to drought managers, particularly for enabling early warning. However, the slow onset can make it challenging to define drought and identify onset of drought conditions (with a similar complexity occurring for drought termination; Parry et al. (2016)). The large spatial scale also presents a problem, as compared with other hazards such as flooding; quantifying drought severity is challenging as risk assessments need to capture duration and intensity, but also spatial extent. Assessment of flood rarity typically proceeds by examining a time series of levels or river discharge measurements at a point, but droughts can extend over hundreds of square kilometres and, moreover, given the often slow evolution of events, these properties all vary over the course of a drought event as the focal point of the event migrates in space (Lloyd-Hughes, 2012).

These properties of droughts call for drought severity assessment methods that explicitly take into account both the spatial and temporal component of drought. There have been many previous efforts to quantify the occurrence of meteorological droughts using spatiotemporal methods. Typically, fixed regions are selected and time series of e.g., rainfall or evaporative demand are analysed (e.g., van der Schrier et al., 2007; Spinoni et al., 2015). Other authors have analysed space and time in parallel using Severity-Area-Duration (SAD) methods (e.g., Andreadis et al., 2005; Sheffield et al., 2009) which quantifies droughts in terms of prescribed areas and durations. However, this does not allow temporal dynamics to be fully resolved – i.e., the method allows long-term statistics of drought severity and areal extent to be characterised, but does not allow events in time to be extracted, nor the analysis of trends over time. To this end, Lloyd-Hughes (2012) proposed a three-dimensional structure-based approach which quantifies the space-time evolution of droughts without reference to fixed regions. This allows the structure of individual events to be characterised as they evolve through space and in time. However, this method is primarily aimed at comparing the similarity in structure of such "extracted" drought events, and is less well suited to examining drought occurrence or historical evolution. Haslinger and Blöschl (2017), on the other hand, propose a new method of space-time evolution that enables extraction of drought event characteristics in terms of duration, severity and intensity, but also spatial extent – enabling return periods to be ascribed to these characteristics.

This work focuses on the United Kingdom, a comparatively wet country but one which is known to experience major meteorological drought episodes that have caused severe impacts on hydrology, water resources, the environment and society (Marsh et al., 2007; Barker et al., 2019). The climatology of meteorological droughts, in terms of duration, severity, etc. has been studied extensively in the past. However, this has typically been done for fixed pre-defined regions (Burke and Brown, 2010; Hannaford et al., 2011). The spatial coherence of drought has been documented without recourse to fixed regions, using high-resolution gridded precipitation datasets by Rahiz and New (2012) and Burke et al. (2010). However, while the former examined spatial coherence across the United Kingdom – quantifying how correlation between grid points decays with distance, and how this varies regionally and seasonally – it did not consider temporal dynamics, being focused on long-term drought statistics. The latter was focused primarily on providing a baseline for future climate change experiments, and did not analyse past drought characteristics or dynamics in detail. Furthermore, most studies have examined meteorological drought risk using relatively short records, although Rahiz and New (2012) and Burke et al. (2010) considered a gridded dataset available back to 1914 (but the density of gauges in the early period is low).

In summary, there have not been detailed studies of United Kingdom meteorological droughts that quantify the frequency of droughts in terms of their duration and intensity in parallel, using methods that enable droughts to be quantified from a spatiotemporal angle that dispense with fixed regions. Here, we aim to close this research gap by using the drought extraction method of Haslinger and Blöschl (2017) to a newly available gridded precipitation dataset extending back to 1862, which includes a wealth of newly digitised data to enhance the spatial coverage of the early period (MetOffice, 2019, 2020). The regional differences in these spatiotemporally extracted droughts are then analysed to better understand the physical and natural contrast in drought dynamics across Great Britain.

This work is necessary to provide a full understanding of meteorological drought occurrence, enabling water managers in the United Kingdom to undertake more informed drought risk assessments to support drought and water resource planning. Following recent policy changes, specifically the "duty of resilience" in the WaterAct, 2014 (WaterAct, 2014), United Kingdom water managers need to plan for droughts worse than those experienced in the historical record. This has prompted a widespread uptake of stochastic simulation to appraise drought frequency and severity, but this has often been done in different ways at different scales by the United Kingdom's many private water companies. There are growing calls for a nationally consistent dataset of spatially coherent droughts to support intra-regional planning and adaptation (Environment Agency, 2020). To support this, studies of drought space-time coherence as well as regional drought occurrence are needed. So far, most applied efforts have focused on specific regions for a very limited number of individual gauges with comparatively short records (e.g., WaterUK, 2016). Here, we provide a more comprehensive appraisal of meteorological drought risk at a national scale, using a long-term high-resolution precipitation dataset. We acknowledge that water resources planners also need to understand hydrological and water supply system drought risk. At present, this is done in a myriad different ways in different regions of the United Kingdom and different water supply systems. In the present paper our focus is on the meteorological inputs, which are of fundamental importance to all planners (as well as those non-statutory water users outside the water industry who are also concerned with drought), and are ultimately the primary input to hydrology/supply models. Furthermore, when considering meteorological drought there is an available high-resolution, gridded and spatially complete dataset extending back to 1862, which is not possible for hydrological variables. However, to reflect the different response times for different types of drought impacts, such as agricultural, hydrological and groundwater impacts, we aggregate the precipitation data into four new datasets, by applying moving averages over 3-, 6-, 12- and 24-month windows.

Specifically, four main research questions were addressed in this study:

(i) Where in Great Britain (GB) do droughts occur more frequently over the historical period?
(ii) How do the drought characteristics differ in different regions of GB in terms of area, duration, intensity and severity?
(iii) When and where did major droughts occur in the past?
(iv) How much spatial coherence of droughts is there between regions? In other words, does drought occur simultaneously in different regions of GB?

DATA AND METHODS

Section "Data and Methods" presents the precipitation dataset used for the analysis, and the methods applied (i) to identify the drought events, (ii) to define the geographical regions considered, (iii) to assign the identified drought events to the geographical regions, and (iv) to estimate the frequency of occurrence of events with respect to their spatial extent, duration, intensity and severity.

Data

The monthly GB precipitation dataset used in this study was derived by the United Kingdom Met Office as a result of a large data rescue and digitisation programme, carried out within the Historic Droughts project[1]. The 5 km gridded dataset, which covers the period 1862 to 2015, was derived using the same methodology as the UKCP09 data (MetOffice et al., 2017), with interpolation carried out using inverse distance weighting (Perry and Hollis, 2005). The value of each pixel corresponds to the precipitation at the centre of the cell.

The Met Office has invested a great amount of effort to rescue data and digitise precipitation data back to the second half of 19th century within the Historic Droughts project. This has substantially increased the density of the monthly raingauge network in the earlier period (1862–1910) compared with the raingauge density used to derive other datasets such as the CEH-GEAR (Keller et al., 2015; Tanguy et al., 2019) rainfall datasets. The data rescue and digitisation programme added over 200 monthly gauges to the network for the period 1862 to 1910 (MetOffice, 2019, 2020). However, reliability of the data, particularly for the earlier period, needs to be carefully considered, and this is being discussed in Section "Uncertainties in the Data" of the Discussion.

Identification of Drought Events

For the identification of drought events, the method developed by Haslinger and Blöschl (2017) was applied using the historic precipitation data. This method was first developed to investigate the historic spatiotemporal drought characteristics in the Greater Alpine region of Central Europe. The method consists in, firstly, calculating moving averages of monthly precipitation data for different accumulation periods (3, 6, 12, and 24 months) on every grid point in the domain. The different accumulation periods are useful for examining different types of drought; for example, short precipitation accumulation periods often reflect the response of river flows, and longer accumulations the response of groundwater, or groundwater dominated river flows (Barker et al., 2016). The longer accumulation periods are also of interest for reservoir levels and water resources planning, although in some areas such as the north-west of England, the 3-month accumulation period can also be relevant for reservoirs (e.g., in summer 2018, Parry et al. (2018)).

A Gamma distribution is then fitted to the averaged precipitation, separately for every month of the year and every grid point, in a similar way as in the Standardised Precipitation Index (SPI) (McKee et al., 1993). To separate dry from non-dry areas, a quantile value equal to 0.2 (i.e., corresponding to a non-exceedance probability of 0.2) was used as a threshold. Although this is not a very extreme value (equivalent to a 5 year return period, and an SPI−value of −0.84), it was initially proposed by Agnew (2000) as a threshold to define moderate droughts, and is commonly used to identify dry precipitation anomalies (e.g., Vicente-Serrano, 2006, 2007; Livada and Assimakopoulos, 2007; Santos et al., 2011; Ribeiro et al., 2020). For a more intuitive assessment of drought intensity, these non-exceedance probabilities are scaled in order to get higher values with higher drought intensity using the equation:

$$q_{int} = (\xi - p)/\xi \tag{1}$$

where the new scaled quantity, q_{int}, will be referred to as the quantile drought intensity, p is the probability of non-exceedance of the observation, and ξ is the 0.2 threshold. The intensity measure q_{int} ranges between -4 (probability of non-exceedance

[1] https://historicdroughts.ceh.ac.uk/

of 1) representing the wettest conditions and 1 (probability of non-exceedance of 0) representing the most severe drought of a particular location and month.

Lastly, once q_{int} is calculated for every grid point and every month, the algorithm detects *contiguous* areas with drought intensity values q_{int} larger than 0. The drought area (DA) detected in this way for this time step is compared with the DA of the next time step. If they overlap in space, they are considered as belonging to the same drought event. The same three criteria defined in Haslinger and Blöschl (2017) were applied for a space−time region to be considered a drought event: (i) single drought areas must be larger than 10% (~20,000 km^2) of Great Britain (mainland), this criterion was selected to ensure that only areas with a reasonable size and therefore impact are considered as drought event candidates; (ii) the overlap of the areas must be at least 50% of the smaller area; and (iii) the smaller area must be at least 25% of the larger area.

By using a quantile-based indicator for each pixel (rather than indicators based on absolute values of precipitation), the departure from "normal" conditions are described. Therefore drought events occurring at different places (e.g., NW and SE) can be compared.

The concept of drought severity is used to rank the drought events. We consider that the measure of severity should take into account drought intensity, area and duration, so that an event becomes more severe if (i) the quantile drought intensity q_{int} is large, (ii) the area under drought is large, and (iii) the duration of the drought is large (Haslinger and Blöschl, 2017). The first two components are combined into an intensity measure for every time step over the drought duration:

$$I = \sum_{i=1}^{n} q_{int}, \quad i \in DA \tag{2}$$

where I is the intensity, n is the number of grid points i within the drought area (DA), and q_{int} is the quantile drought intensity. Consequently, I increases with both the number of drought grid cells and their quantile drought intensity.

We calculate the overall drought severity as:

$$S = \sum_{j=1}^{m} I, \quad j \in DE \tag{3}$$

where S is the severity, which is the sum of all intensities I within the same drought event (DE), and m is the number of time steps j comprising the drought event.

The mean intensity is defined by severity divided by duration.

Geographical Clustering

In Great Britain, there is a very strong south-east to north-west rainfall gradient, with nearly an order of magnitude difference in annual rainfall between the driest parts of south-east England around the Thames estuary and the wettest parts of the mountains of western Scotland and north Wales. The scale of spatial variation in annual and seasonal rainfall implies a need to examine drought occurrence and dynamics on a regional scale rather than nationally. On average, the north-west is substantially wetter than the south-east and behave differently in terms of precipitation (Mayes and Wheeler, 2013), with the two regions often being anticorrelated with each other, meaning droughts in one region are unlikely to affect the other (Folland et al., 2015).

In this study, we aim at comparing the north-west and south-east in terms of their drought characteristics (including area, duration, intensity and severity), to understand the natural and physical differences in drought dynamics between these two distinct regions. To define the geographical extent of the North-West (NW) and South-East (SE), we applied the k-means clustering technique (e.g., Gordon, 1981; Raut et al., 2017) to monthly series of gridded precipitation, initially specifying two clusters. The monthly precipitation series in nearby grid cells are likely to be well correlated with each other, and can be expected to lead to similar drought characteristics within each region. The k-means clustering method is an unsupervised learning algorithm which aims to group the data into k groups where the data points are clustered based on feature similarity. In our case the feature is the monthly series of gridded precipitation.

The first k-means clustering attempt divided GB into two uneven regions, with the NW covering 1/3 of GB and the SE covering 2/3. This difference in size would have made a direct comparison of drought characteristics difficult. Therefore, a second k-means clustering analysis was carried out, this time specifying the use of three clusters. However, this also resulted in very different sized regions.

Instead, the strategy adopted was to use the k-means clustering technique applied in two successive steps: (i) first, the method was applied using two clusters, resulting in the two uneven regions described earlier (NW = 1/3 of GB and SE = 2/3 of GB); (ii) then, in a second step, the k-means clustering technique was applied again to the largest of the two regions (SE) to divide it into two sub-regions. Using this two-step process, three regions with very similar size were obtained and are shown in **Figure 1**. The NW and SE regions are now separated by a "transition region."

Assignment of Drought Events to a Region

To assign each identified drought event to one of the three regions, the concept of a Drought Core Region (DCR) was used. The DCR, initially proposed by Haslinger and Blöschl (2017), is defined as those grid points of an identified event with a time-average q_{int} of at least 0.5, which represents a non-exceedance probability of 0.1 or an SPI of −1.29. Consequently, the DCR identifies those areas of a particular drought event where the precipitation deficit is most pronounced.

Each drought event was assigned to the region containing the largest proportion of the DCR. If a drought event does not have a DCR (no area with a time-average $q_{int} \geq 0.5$), the drought event was assigned to the region containing the largest proportion of the total DA (i.e., the DA aggregated across all the time steps of the DE).

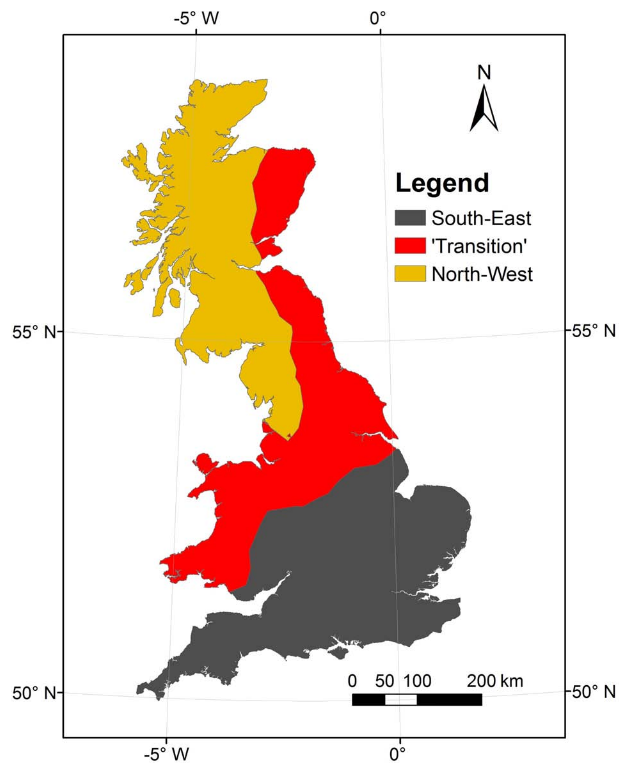

FIGURE 1 | Great Britain rainfall regions defined using *k*-means clustering technique applied in two steps.

Frequency Analysis

Return Periods

To compare the frequency of occurrence of drought events in the three regions, the concept of return period was used. A return period is defined as the inverse of the exceedance probability (generally expressed in %). For example, a return period of 100 years corresponds to a probability of 1 in 100, or 1%, that an event of a particular magnitude will be exceeded in any one year. Return periods of droughts for different characteristics (area, duration, intensity and severity) were calculated using the following approach:

The drought events, x, were ranked in ascending order according to the characteristic considered (e.g., area affected by a given drought) with ranks from 1 to N (i.e., the total number of events). In case of a tie, the average of the ranks was given to all events in the tie. The preliminary non-exceedance probability (or cumulative distribution function, CDF), $G(x_i)$ for the event with rank i is then defined as:

$$G(x_i) = i/(N+1) \tag{4}$$

Using $N+1$ rather than N means that we never get a non-exceedance probability of 1, it will always be slightly lower than 1 at most (Coles, 2001).

To account for the fact that we have a peak-over-threshold series (rather than an annual series of a maximum or minimum per year), with either more or fewer than n events (n being the number of years), we define the rate λ, which is the average number of events per year:

$$\lambda = N/n \tag{5}$$

Assuming that the events are independent, and that the probability of non-exceedance of x over a 1-year period is given by the Poisson distribution, we derive the final CDF, $F(x)$, for the corresponding annual maximum series, as described by Stedinger et al. (1993). $F(x)$ is the probability that the annual maximum for a year will not exceed x:

$$F(x_i) = \exp\{-\lambda\,[1 - G(x_i)]\} \tag{6}$$

The corresponding return period T is then calculated as:

$$T = 1/\,[1 - F(x_i)] \tag{7}$$

$[1 - F(x_i)]$ corresponds to the exceedance probability.

Trend Analysis

In order to analyse the change in drought frequency over time, we estimated the (changing) return period of a fixed drought severity for different 50-year windows within the total study period.

This was done in two steps:

- First, the drought severity corresponding to the 10-year return period based on the entire period of observation (154 years), called the "global 10-year return level," was calculated, for each accumulation period and each region. When applying the methodology described in Return Periods, once all the events were ranked, the observation with return period just above 10 years and the one with a return period just below 10 years were selected, and linear interpolation was used to calculate the "global 10-year return level."
- We then considered different 50-year periods within the full study period, shifted by 5 years at a time, and repeated the frequency estimation within each of these 50-year windows. In the ranked drought events within each period, the event with severity just larger than, and just smaller than the "global 10-year return level" were selected, and the corresponding return period was calculated using linear interpolation between the two. We call this new return period the "sub-interval return period."

If the "sub-interval return period" is smaller (larger) than 10 years, it indicates that droughts of the severity corresponding to the "global 10-year return level" in that 50-year window are more (less) frequent than over the whole period.

RESULTS

Drought Events Per Region

The first research question motivating this study was to find out whether there is a difference in frequency of drought events between the three regions of GB, with a particular focus on the differences between the SE and the NW.

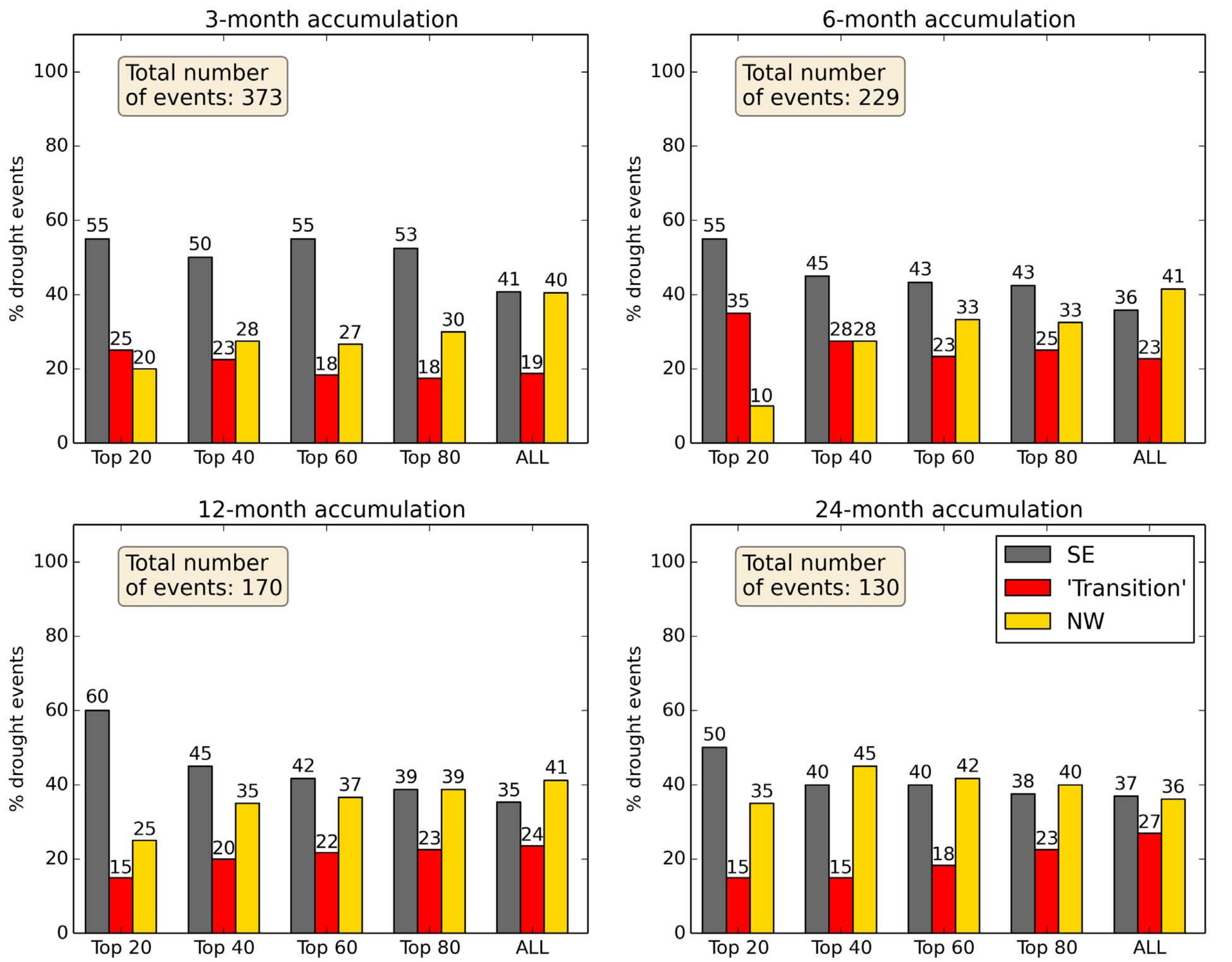

FIGURE 2 | Proportion (in %) of drought events in each region according to drought severity ranking for different accumulation periods. "Top 20," "Top 40," "Top 60," and "Top 80" correspond respectively to the 20, 40, 60, and 80 most severe droughts in GB during our study period (1862–2015). The last set of bars (labelled "ALL") on each graph include all drought events detected in GB. The events were ranked from most severe to less severe based on the drought severity as defined in Eq. 3.

Figure 2 shows the proportion of drought events (for the different accumulation periods analysed) assigned to each region when considering different ranking of events in terms of severity as defined in Eq. 3. For the most severe droughts (top 20 droughts), the SE region shows the largest proportion of events. For shorter accumulation periods (3 and 6 months), the "transition" region has the second largest proportion of most severe events, whereas for longer accumulation periods (12 and 24 months), the NW has a larger proportion of severe events than the "transition" region.

As the severity of events decreases (top 40, top 60, top 80 and all events), so does the proportion of events assigned to the SE region, particularly for longer accumulation periods. When all events are considered, the proportion of events occurring in SE and NW is almost equal for all accumulation periods whilst the "transition" region has fewer drought events than the other two regions. These results suggest that the majority of the most severe drought events take place in the SE, but a larger number of less severe events occur in the NW.

Frequency Analysis of Droughts

For the second research question, we looked at the differences in drought characteristics between the SE and NW, in terms of area affected, duration, intensity and severity. Return periods for these characteristics were calculated as described in Section "Frequency Analysis."

Return Periods

Mean area

Figure 3 shows the return period of drought events based on their mean drought area ($\overline{DA}$) for the three regions considered. For short accumulation periods (3 months), little difference is observed between the three regions. For medium accumulation periods (6 and 12 months), larger events are more frequent (shorter return period for the same mean area) in the SE compared with the other two regions. However, for long accumulation period (24 months), droughts affecting large areas are more frequent in the NW whereas droughts affecting smaller areas are more frequent in the SE.

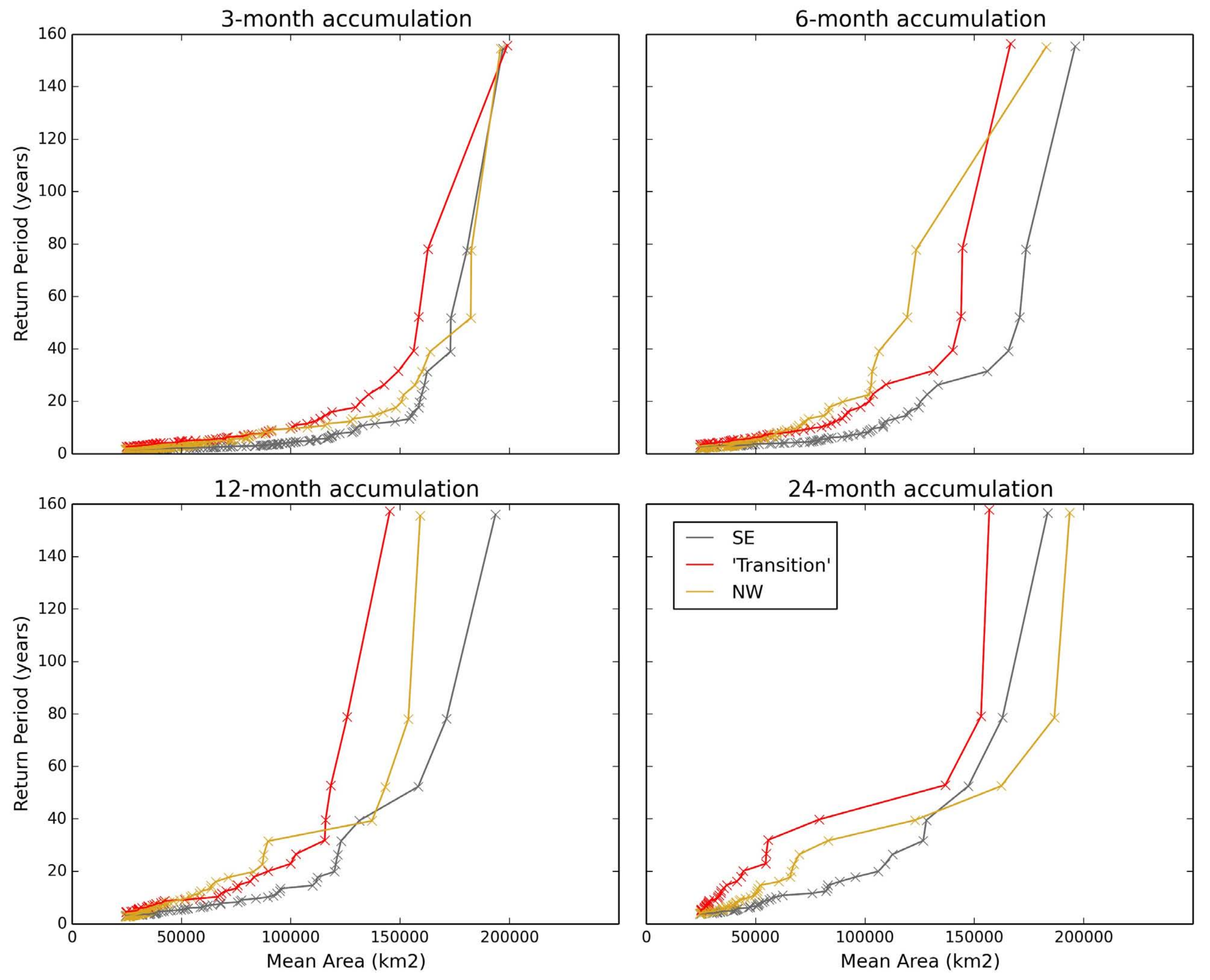

FIGURE 3 | Return period of drought events calculated based on their mean area for the three regions of GB, and for different accumulation period of precipitation (3, 6, 12, and 24 months).

Duration

Figure 4 shows the return period of drought events based on their duration for the three regions studied. Longer droughts are more frequent (i.e., have a shorter return period for the same duration) in the SE than in the NW for short and medium accumulation periods (3, 6, and 12 months accumulation period). The opposite is observed for long accumulation periods (24 months). The "Transition" region shows similar return periods to the NW for 3 and 6 months accumulation periods, whereas it shows larger return periods for longer accumulation periods.

Mean quantile drought intensity ($\overline{q_{int}}$)

Figure 5 shows the return period of drought events based on their mean quantile drought intensity ($\overline{q_{int}}$) for the three regions studied. $\overline{q_{int}}$ is a measure of how intense a given drought event is on average over each timestep and each pixel. From **Figure 5**, we can see that the local intensity of the drought events have similar return periods for the SE and NW for all accumulation periods. They are less intense for the same return period for the "transition" region, for all accumulation periods.

Severity

Figure 6 shows the return period of drought events based on their severity for the three regions studied. As shown in Eqs 2 and 3, the severity depends on q_{int}, the mean area and the duration of a drought. The results for drought severity are therefore a combination of the results in the three previous paragraphs, although the relationship is not necessarily straightforward, as the events with longer duration are not necessarily the more intense, or more extensive ones. However, as expected from the results in the previous paragraphs, we do observe that the most severe droughts are more frequent (shorter return period) in the SE compared to the other two regions for short and medium accumulation periods (3, 6 and 12 months), whereas for long accumulation periods they are more frequent in the NW.

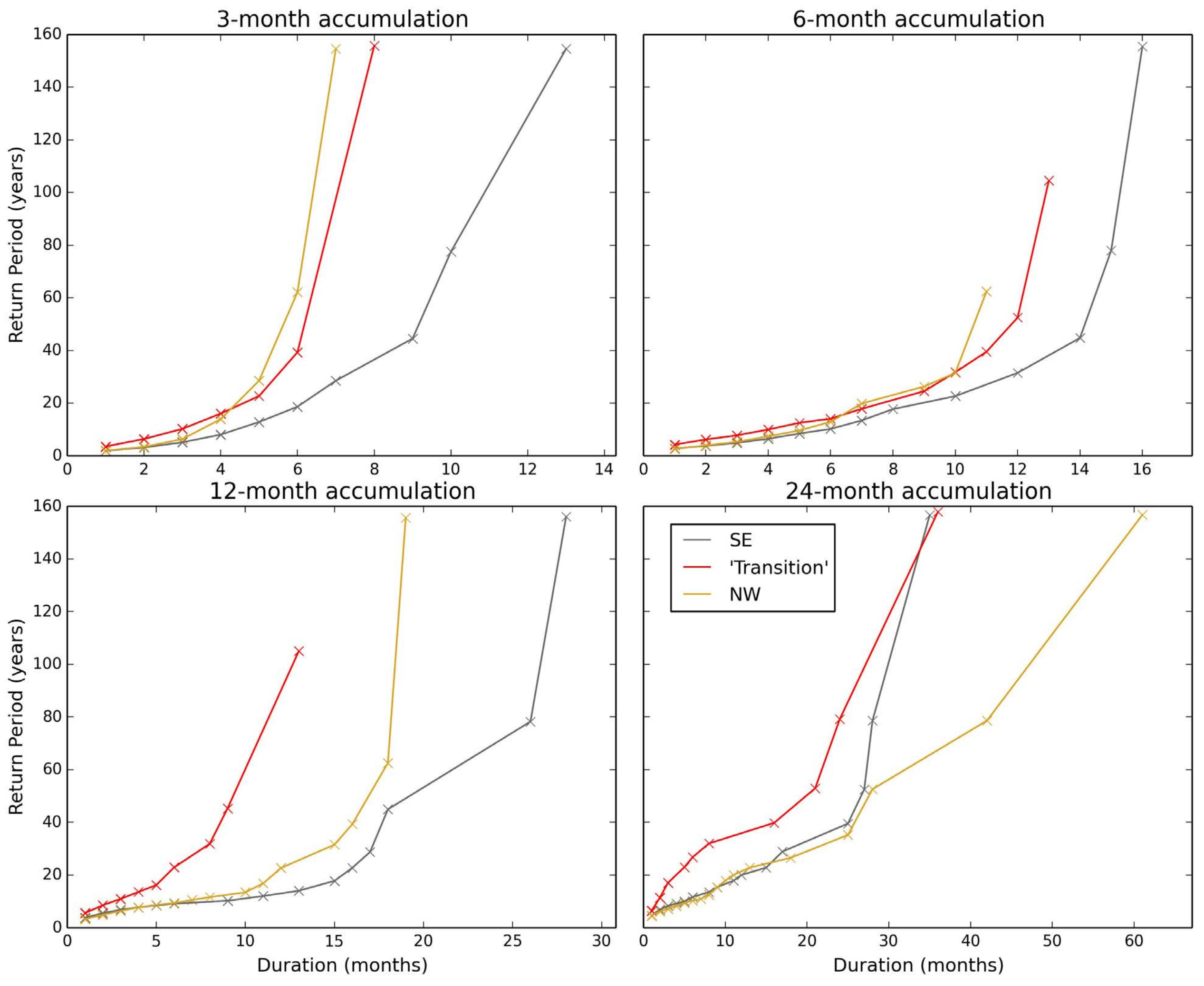

FIGURE 4 | Return period of drought events calculated based on their duration for the three regions of GB, and for different accumulation period of precipitation (3, 6, 12, and 24 months).

Trend Analysis

The change in drought frequency over time was estimated by calculating the "global 10-year return level" and the "sub-interval return period" as described in Section "Data and Methods - Trend Analysis." These calculations were carried out for each accumulation period and region, and for all 50-year windows shifted by 5 years at a time in the 1862–2015 period. **Figure 7** shows the temporal variation of the "sub-interval return period" in the three regions. For the shorter accumulation periods, the data is noisier, but for longer accumulation periods (12 and 24-months), a clear multi-decadal alternation between drought rich periods in the SE (grey line in **Figure 7** below 10-year) and drought rich period in the NW (yellow line in **Figure 7** below 10-year) can be observed. The pattern is less clear for the transition region (red line).

Droughts in SE and NW

Results in **Figures 3**, **4**, **6** showed that droughts are more spatially extensive, longer and more severe in the SE than in the NW for short and medium accumulation periods, whereas the opposite is true for long accumulation period (24 months). These results are summarised and represented spatially in **Figures 8**, **9**. **Figure 8** shows for the most severe droughts ("top 20") and for the four accumulation periods considered (3, 6, 12, and 24 months) the number of times each pixel belonged to the DCR of a drought event. We can see that the DCR of the most severe droughts are concentrated in the SE and "transition" regions, especially for short and medium accumulation periods. The most north-western part of GB shows particularly few occasions of belonging to the DCR of the most severe droughts.

However, when all droughts are considered (**Figure 9**), the north-western part of GB is where the DCRs seem to concentrate, especially for short to medium accumulation periods, suggesting that this area experiences a large amount of less severe droughts compared to the SE. For the 24 months accumulation period, a second cluster of pixels belonging to DCRs located in the

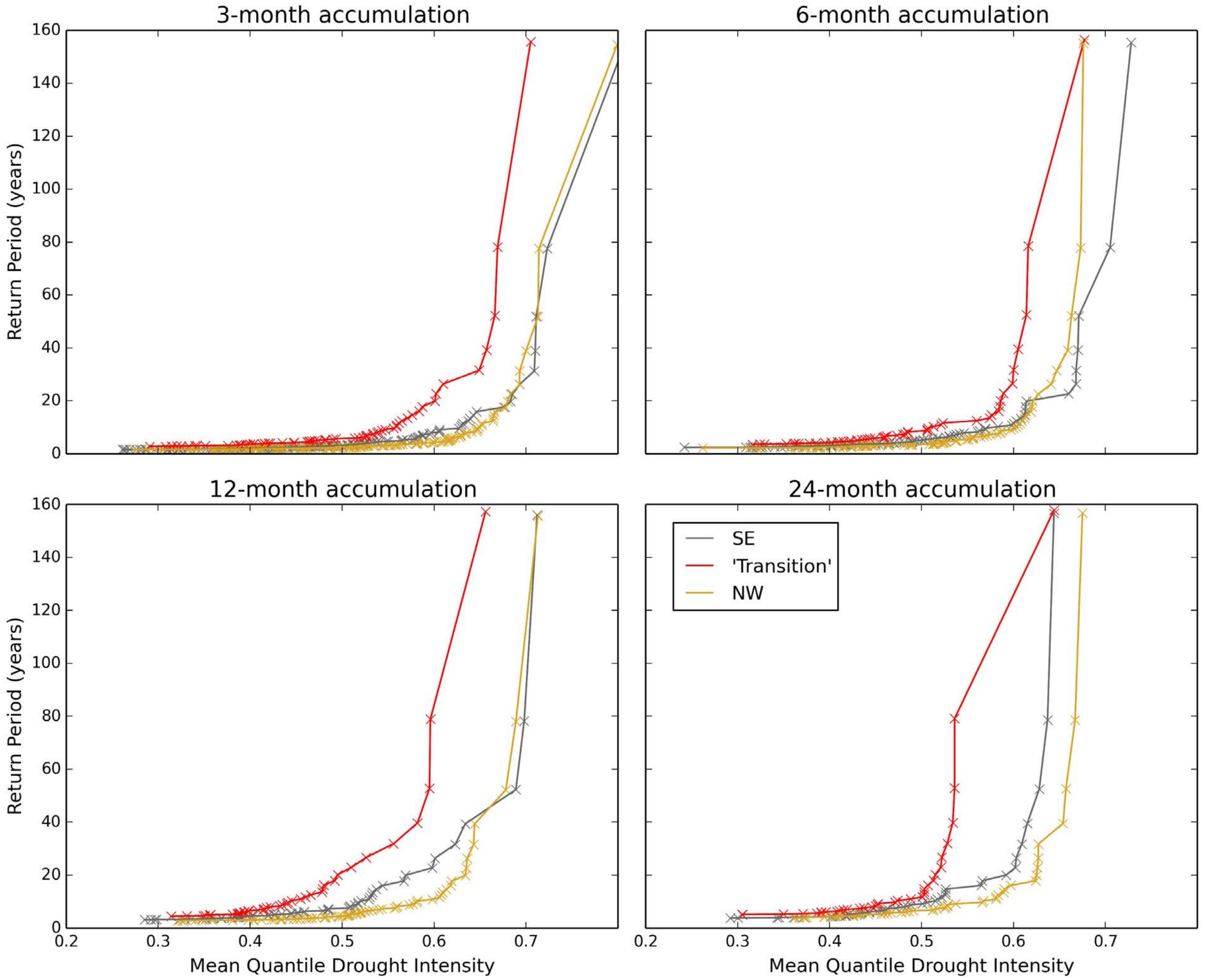

FIGURE 5 | Return period of drought events calculated based on their mean quantile drought intensity ($\overline{q_{int}}$) for the three regions of GB, and for different accumulation period of precipitation (3, 6, 12, and 24 months).

central part of southern England can also be observed, suggesting that this area also sees a large amount of less severe long-term droughts.

These geographical differences observed in the type of droughts (infrequent but severe vs. less severe but frequent) occurring in the SE and NW will have consequences for the challenges faced by water managers in each region. The droughts discussed so far are purely based on precipitation, but the impact that different type of meteorological droughts will have on water availability is closely linked to the hydrological properties of catchments in each region, which is discussed in Section "Discussion."

Historic Timeline of Droughts

To identify long-term trends in droughts, the timing and location of detected drought events were explored. **Figure 10** shows the "top 20" drought events based on severity. The plot shows simultaneously when the drought occurred (peak year on *x* axis and peak season on *y* axis, i.e. when the maximum mean intensity occurs), where it occurred (colour according to the region to which the event was assigned), and its ranking (size of the dot and number shown above the dot). We can see that the data rescue carried out by the Met Office United Kingdom in the earlier period (pre-1910) has allowed the identification and characterisation of some previously not well known severe droughts. As already shown by **Figure 2**, the majority of most severe droughts occurred in the SE for all accumulation periods, with particularly few observed in NW for the 6 months accumulation period.

However, for longer accumulation periods (12 and 24 months), the proportion of severe droughts occurring in the NW is higher (**Figure 10**). In fact, for these long accumulation periods there appears to be an alternation between severe droughts in the NW and the SE, with droughts in the SE occurring 1920–1940 and 1975–2000 and droughts in the NW occurring 1860–1900 and 1940–1975. This observed alternation echoes what was observed in **Figure 7**. **Supplementary Figure 1** is similar to **Figure 10**, but shows the timeline of all drought events detected,

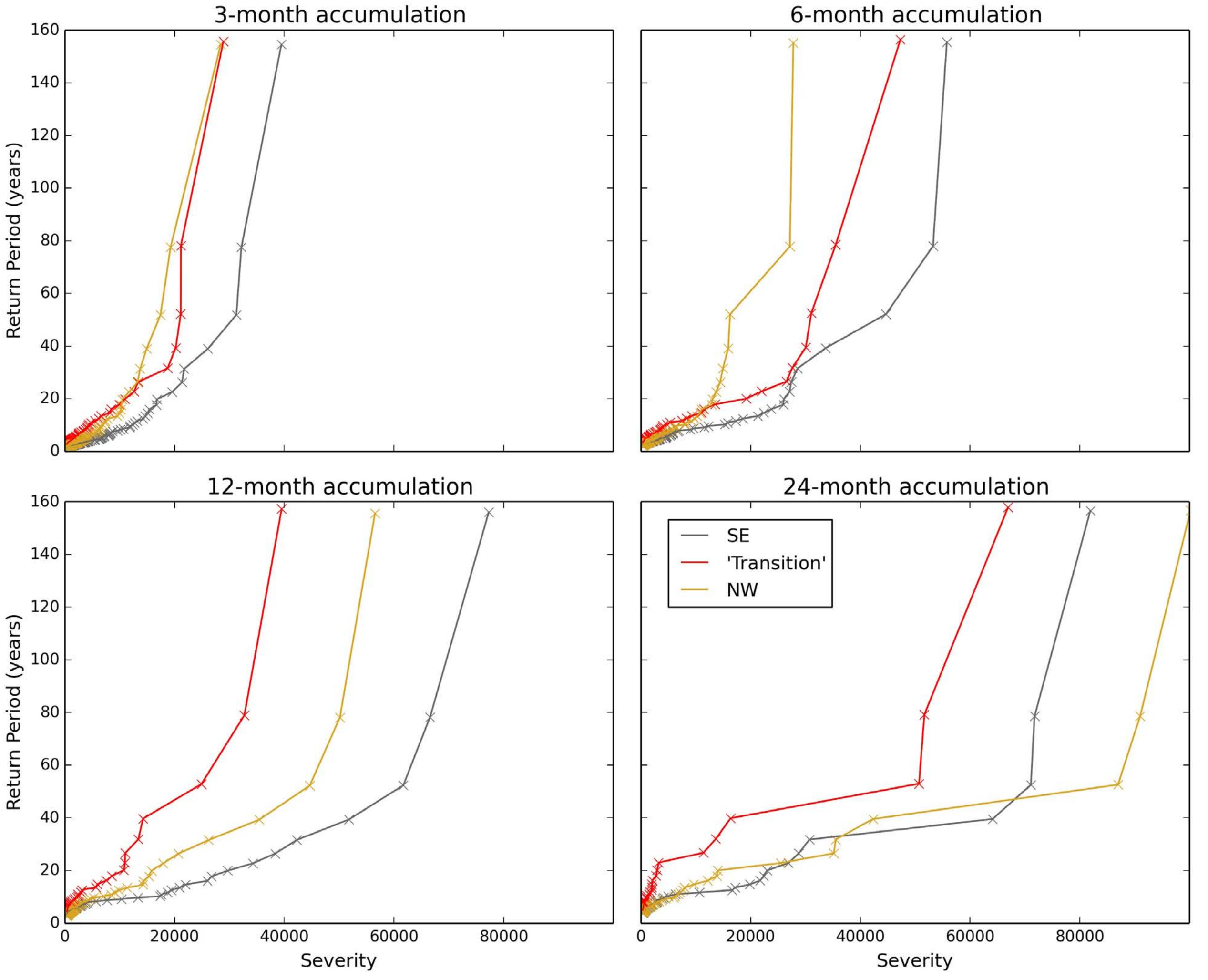

FIGURE 6 | Return period of drought events calculated based on their severity for the three regions of GB, and for different accumulation period of precipitation (3, 6, 12, and 24 months).

instead of only the 20 most severe ones and also shows severe droughts switching between the SE and the NW.

Comparison With Major Droughts Reported in the Literature

When comparing the drought timeline shown in **Figure 10** and **Supplementary Figure 1** with previous studies, as expected we find many parallels, but also some differences. Marsh et al. (2007) synthetized a range of datasets from 1800 to 2006 to study and characterise past droughts in the United Kingdom (mainly qualitatively), and identified nine major droughts (going from 1890 to 1997). Jones and Lister (1998) identified one additional severe drought (1887–1888) earlier than Marsh et al. (2007)'s first major drought. Two further droughts were reported by the National Hydrological Monitoring Programme in the period posterior to Marsh et al. (2007)'s study (2004–2006 and 2010–2012 droughts). Barker et al. (2019) have subsequently identified three additional drought rich periods (hydrological droughts) which were not previously documented (1940–1949, 1960–1966 and 1968–1975). The Historic Droughts project has produced a drought inventory[2] which brings together cross-sectoral descriptions of historic droughts and water scarcity in the United Kingdom. **Table 1** shows a list of the droughts catalogued in the drought inventory [with the additional 1888–1887 drought from Jones and Lister (1998)'s work].

Here we define an identified drought event as "major" if its rank in the historical record is within the 10 most severe droughts in at least one of the regions and for at least one of the accumulation periods (3, 6, 12, or 24 months).

Figure 11 lists all "major droughts" identified in our study following this criteria, and summarises the ranking based on drought severity for all regions and accumulation periods. All of the known past droughts from **Table 1** can be found among these "major droughts," with six additional ones also identified. The

[2]https://historicdroughts.ceh.ac.uk/content/drought-inventory

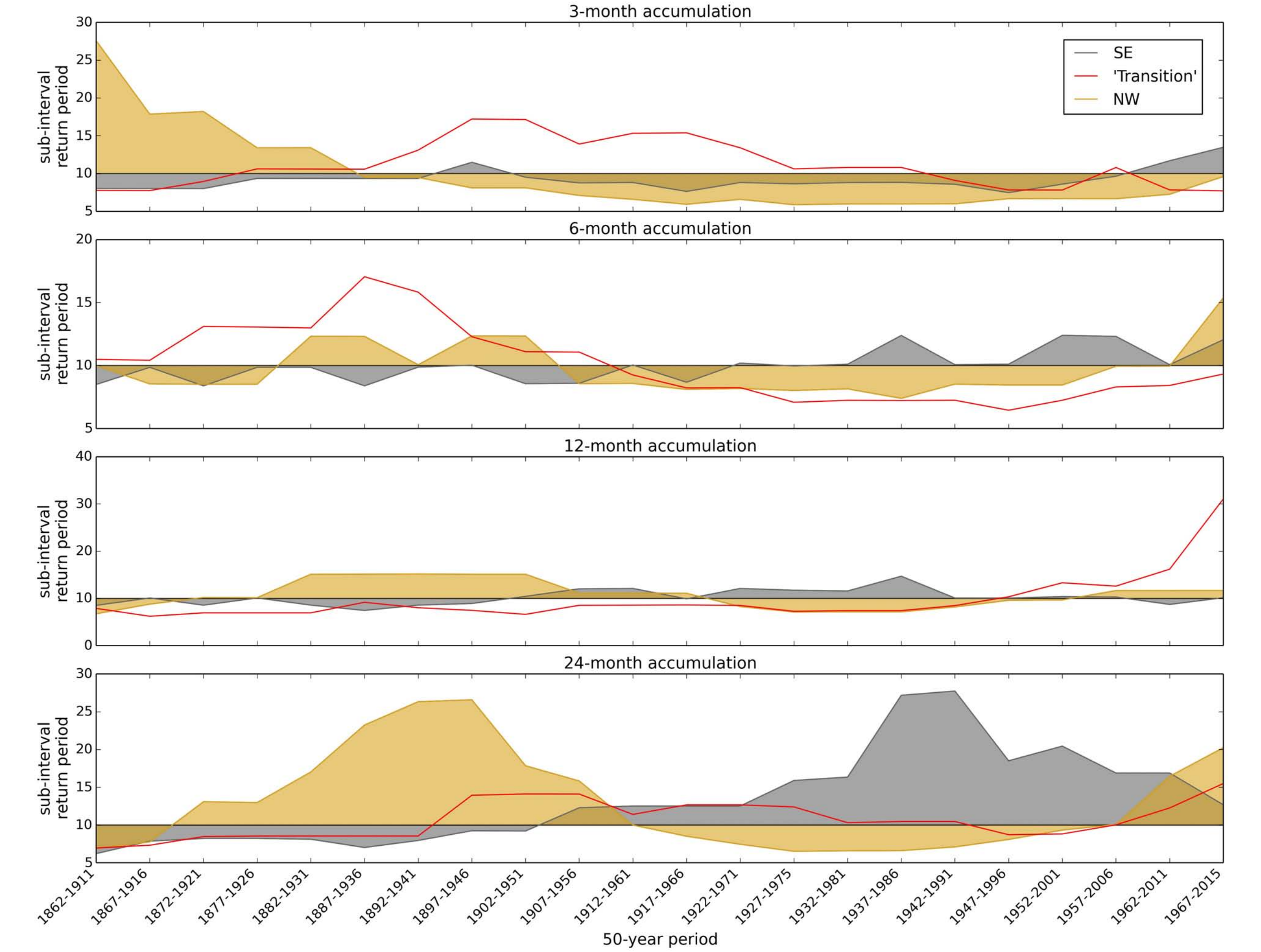

FIGURE 7 | Temporal evolution of the "sub-interval return period" for a "global 10-year return level" as defined in Section "Data and Methods - Trend Analysis" for different 50-year time windows.

droughts previously reported (from **Table 1**) are marked in pink on the left hand side of **Figure 11**, whereas the newly identified ones are marked in blue.

From the "major droughts" previously reported, the 1887–1888, the 1920–1921, the 1933–1935, the 1973 and the 1976 droughts are particularly severe at the national scale (GB), affecting multiple time scale with their rank being within the top 5 most severe droughts for more than one accumulation period. The 1933–1935 drought was particularly severe in the SE where it ranked as the most severe drought for the 6, 12, and 24 months accumulation periods. Although Jones and Lister (1998) used reconstructed river flows in England and Wales to identify the 1887–1888 drought, interestingly, it is the transition region (for short accumulation periods) and the NW region (for longer accumulation period) which are most affected by this drought. The 1929 drought affected the SE, and ranked highly (top 3) at national scale for short accumulation periods.

Some of the other known major droughts have a lower ranking at the national scale, but ranked highly regionally. For example, the 1891–1910 "Long Drought" affected the transition region more severely for long (12 and 24 months) accumulation periods and the NW region for mid-length (6 months) accumulation period. The 1940s drought affected more severely the NW for long accumulation periods, whereas the 1959 and 1962–1964 droughts mostly affected the transition region. The 1995–1998 drought affected the transition region for short accumulation periods and the SE for long accumulation periods. The 1988–1993 and the 2010–2012 droughts both mainly affected the SE. The 1984 and 2003 droughts both affect the NW region at 3- and 6-month accumulation period, ranking second and third most severe droughts respectively in that region. According to the methodology used here, the 2003 drought was more severe than the 2004–2006 drought.

The 1911, the 1913–1914 and the 2004–2006 droughts do not appear as severe as the rest of the "major" droughts using our methodology. The 1911 drought only affects the transition region at 12-month accumulation period, whereas the 1913–1914 drought was only severe at short accumulation period (3-month)

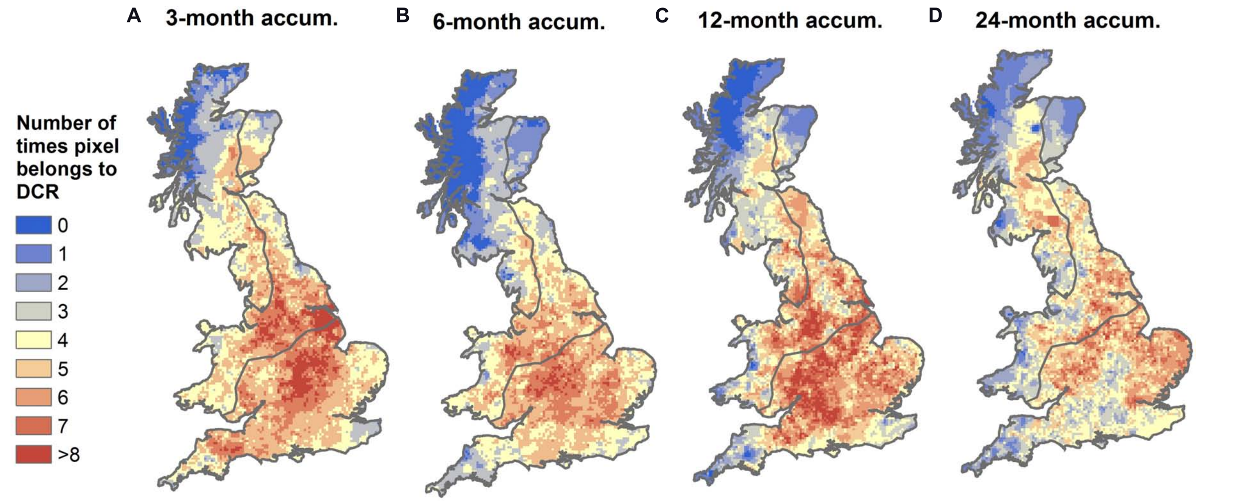

FIGURE 8 | Number of times each pixel belonged to the DCR of a drought event in the top 20 drought events (based on severity) for accumulation periods of **(A)** 3 months, **(B)** 6 months **(C)** 12 months, and **(D)** 24 months.

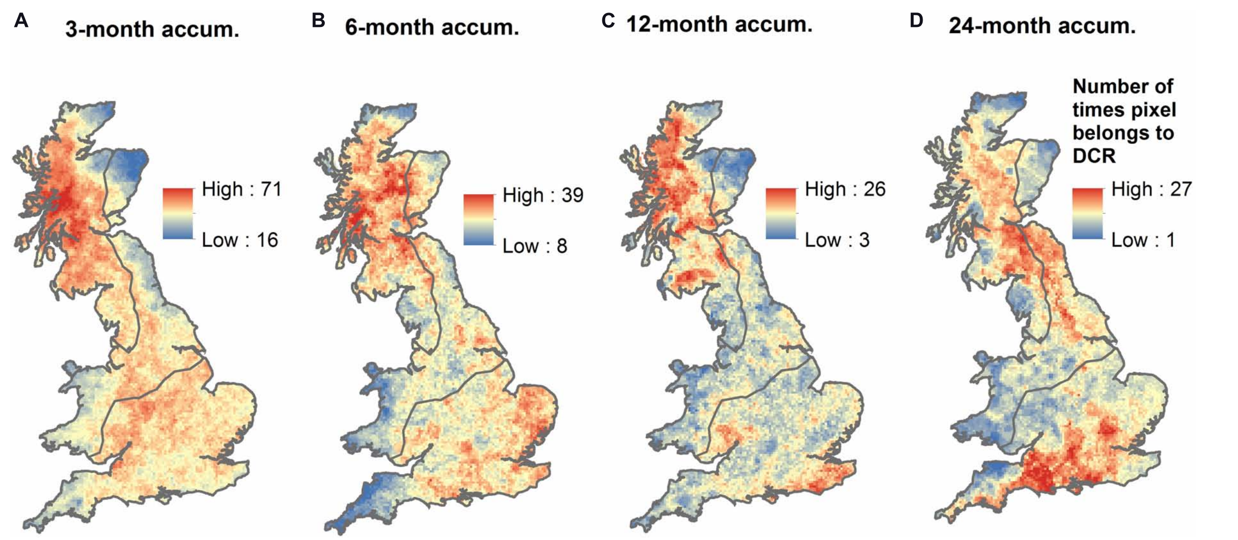

FIGURE 9 | Number of times each pixel belonged to the DCR of a drought event in all drought events detected between 1862 and 2015 (based on severity) for accumulation periods of **(A)** 3 months, **(B)** 6 months, **(C)** 12 months, and **(D)** 24 months.

for the NW. As to the 2004–2006 drought, it is only in the NW for 6-month accumulation period that it ranks as the 7th most severe droughts. This observation is discussed further in Section "Historic Droughts."

Six new "major" droughts were identified in this study:

- A cluster of four droughts from 1864 to 1881, with the 1870 one particularly severe in the NW (number one drought for the 6-months accumulation period). This illustrates the value added by the newly digitised historic raingauge data which has allowed the extension of the precipitation data back to 1862, although caution is required when interpreting these results due to data uncertainties as discussed in Section "Uncertainties in the Data."
- The 1937–1938 drought was severe in the transition region, and
- The 1955–1956 drought affected the transition region for short accumulation period and NW for medium and long accumulation period.

Synchronisation of Droughts Between Regions

The final research question aimed at looking at how often different regions are simultaneously in drought. This can be two distinct droughts occurring simultaneously in two regions, or

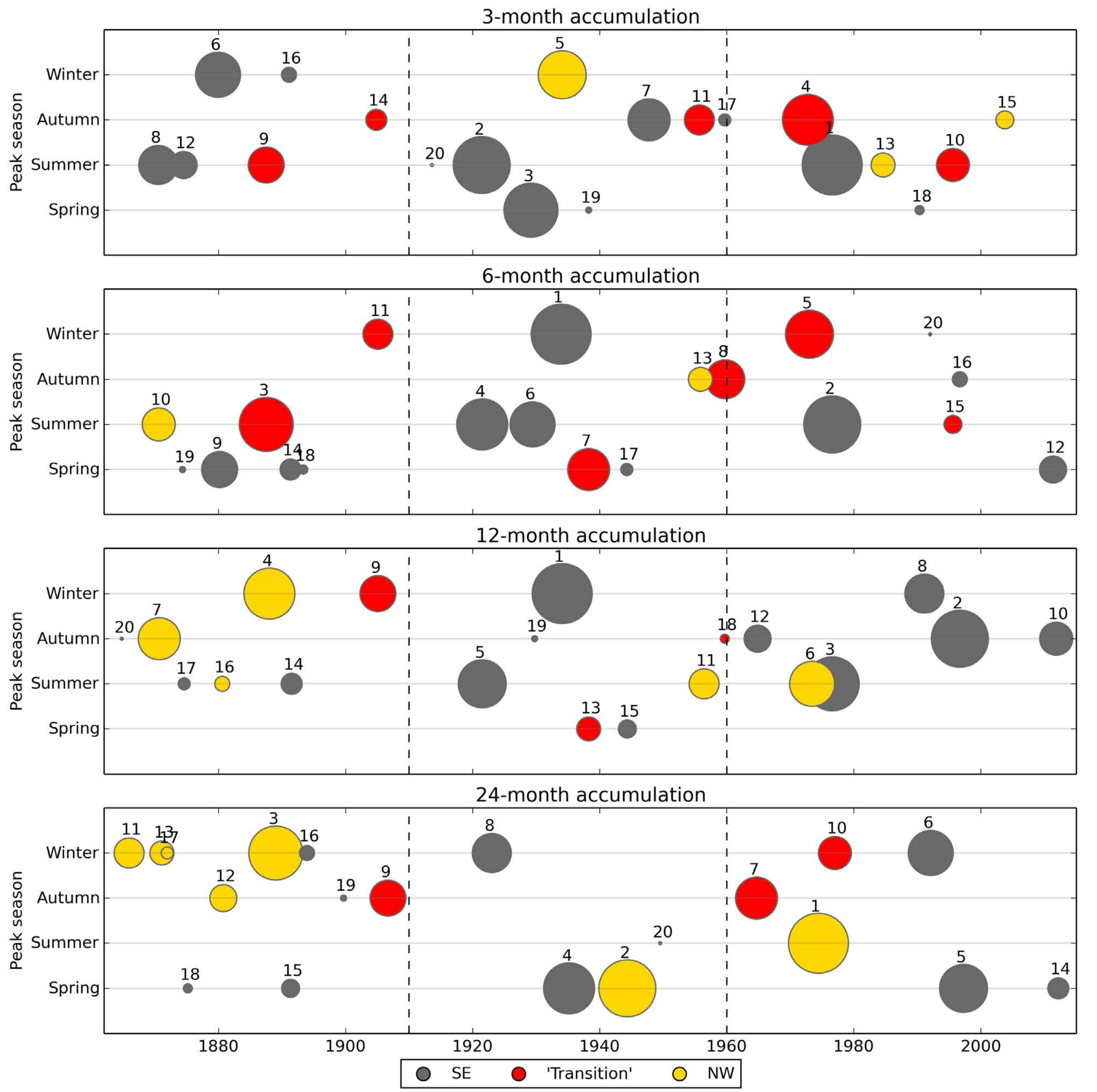

FIGURE 10 | "Top 20" events based on severity for accumulation periods of 3, 6, 12, and 24 months (from top to bottom). The *x* axis shows the year of the peak of the drought (i.e., when the drought was most intense); the *y* axis shows the peak season of the drought event; the ranking is shown by the size of the dot (the bigger the dot, the more severe is the drought) and the number on top of each dot; and the colour of the dot indicates the region to which the drought event has been assigned.

the same drought affecting various regions. Whenever a drought assigned to a given region had at least 25% of its extent in another region, this second region was considered to be "affected" by said drought. Note that the threshold 25% is arbitrary and a different value could have been chosen.

Figure 12 shows the percentage of months in drought where only one region was in drought, or multiple regions were in drought simultaneously. The hatched areas in the stacked bars represent months where drought was occurring simultaneously in multiple regions, whereas the non-hatched areas show the months where drought was occurring in a single region. It shows that most SE droughts also affect the Transition region, which is not that surprising, as in the initial clustering based on precipitation with two regions only (as described in Section "Geographical Clustering"), these two regions (SE and Transition) belonged to one single region. It

TABLE 1 | List of droughts reported in the Historic Droughts Drought Inventory (https://historicdroughts.ceh.ac.uk/content/drought-inventory), with the additional early drought identified by Jones and Lister (1998).

Drought	Years
Early drought	1887–1888
The Long drought	1891–1910
The 1911 Drought	1911
The pre-war Drought	1913–1914
The Roaring Twenties Drought	1920–1921
The Late Twenties Drought	1928–1929
The Locked Pump Drought	1933–1935
The Wartime Drought	1940s
Testing the Water Act	1959
The big Freeze Drought	1962–1964
The Forgotten Drought	1973
The Standpipe Drought	1975–1976
The Northern Drought	1984
In and Out of Drought	1988–1993
The Tanker Drought	1995–1998
The Hot Summer	2003
The Media Drought	2004–2006
From Drought to Flood	2010–2012

Events after 2015 are not considered in this study.

also shows that a significant proportion of droughts affect all three regions simultaneously. For example, if we look at the 3-month accumulation period (first stacked bar in **Figure 12**), all three regions were simultaneously affected in 16% of all months in drought. When the SE is in drought, in 31% of the cases the NW is also in drought ([intersection between SE and NW]/[total of SE]*100 = [16+2]/[16+24+16+2]*100). When the NW is in drought, 36% of the time the SE is also in drought ([intersection between SE and NW]/[total of NW]*100 = [16+2]/[16+2+8+24]*100).

In **Figure 13**, only the "top 20" most severe droughts in each region were selected, the results look quite different to when all events are considered (as shown in **Figure 12**). We can see that when only the most severe events are considered, there is very little overlap between the NW and the SE. This means that when the SE is in an extremely severe drought, very rarely is the NW also in a drought at the same time, and vice-versa. The Transition region, however, is often affected by severe droughts at the same time as one of the other regions.

DISCUSSION

Precipitation over Great Britain is characterised by large disparities in absolute precipitation between the NW and SE. There are also significant differences in variability. However, droughts are generally seen as a deviation from the norm, and in this study we therefore extract drought events below a particular quantile threshold (= 0.2), which makes comparisons between regions possible. We take the approach of extracting droughts as a spatiotemporal feature from high-resolution gridded data, enabling us to look at area, duration, intensity and severity. Using these characteristics of the extracted events, we were able to compare past droughts between the regions.

To our knowledge, this is the first study for Great Britain to derive drought events independently from spatial boundaries and without fixing any temporal window. This is unique as we allow space and time to vary freely to self-define the droughts, although for the purposes of visualising drought occurrence, frequency and characteristics, we also classify these events as belonging to one of three regions, allowing us also to look at synchronicity of drought occurrence between regions.

In this section, we first reflect on the uncertainties in the data and how these should be carefully considered when interpreting the results. We then discuss the results including their implication from a water management point of view focusing on (i) historic droughts, (ii) the differences in drought characteristics between regions, and (iii) the spatial coherence of droughts.

Uncertainties in the Data

As mentioned in Section "Data," thanks to the data rescue and digitisation efforts from the Met Office within the Historic Droughts project, a substantial increase in monthly raingauge density was achieved in the earlier period of the data (1862–1910), where over 200 monthly gauges were added to the network (MetOffice, 2019, 2020). However, despite this significant increase in number of raingauges, the network is still much denser from 1961 onwards compared with pre-1961, where there is a jump from 526 stations to 4259 across Great Britain. The current network comprises around 2700 raingauges. It is therefore important to consider the uncertainties caused by the density of the raingauges used to derive the underpinning gridded rainfall data used here, especially in the earlier period.

To address this issue, Legg (2015) extensively analysed the effect of thinning the raingauge network density on the uncertainties in the derived gridded precipitation product. They concluded that the interpolation error increases only slowly as more stations are removed from the network. From their analysis, the increase in root-mean-square errors (RMSE) when comparing the current raingauge network density (∼2700 raingauges) with the network during the earliest period (∼250 raingauges) would go from about RMSE≈16 mm to RMSE≈23 mm on average which is considered an acceptable increase in the error. The Met Office has digitised enough new raingauge data in the earlier period to keep the error in the precipitation grids within an admissible level.

However, additional caution is required when considering results in the NW, as the drop in density of raingauges prior to 1961 is more dramatic in Scotland than elsewhere in GB. In addition, Scotland is also one of the areas of GB displaying the largest variability in precipitation. **Supplementary Figure 2** shows the spatial distribution of the raingauge network collated by the Met Office just before the large jump in number of raingauges (in 1960) and immediately after (in 1961). We can see that the density of the network is particularly affected in Scotland, and to a lesser extend in Wales, the north-east and central England. Therefore, when looking at spatial extent of droughts before 1961, it is possible we see a false signal of greater drought coherence in the NW due to scarceness of

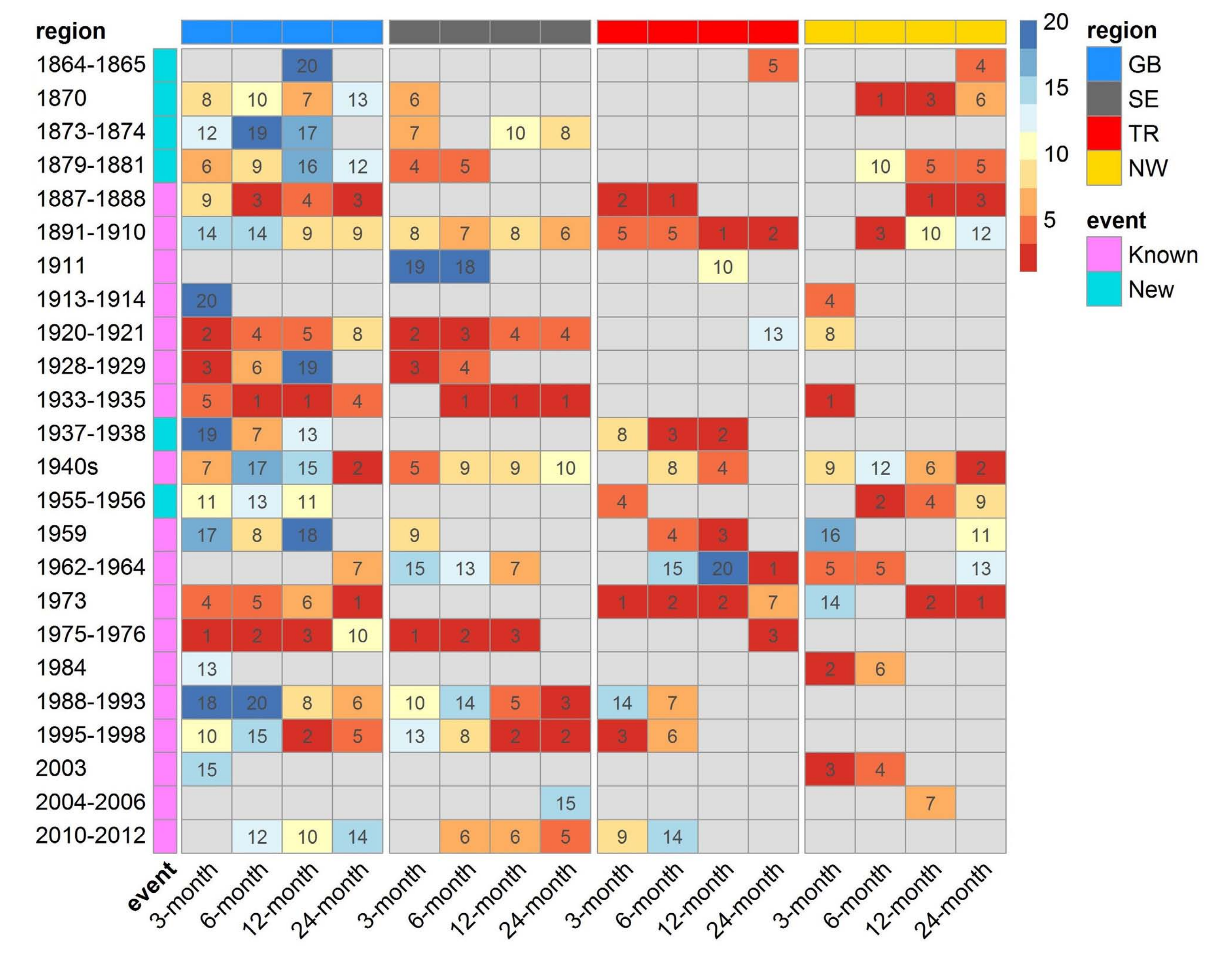

FIGURE 11 | List of major droughts identified in this study. Each line in the plot corresponds to a major drought event identified in this study. The drought events marked in pink (on the left hand side of the plot) are major droughts previously reported in the literature, the ones marked in blue are new ones identified in this study. The plot is organised in four vertical blocks corresponding to Great Britain and the three regions (i.e., SE, Transition region, and NW). Each of these four blocks are in turn divided into four columns corresponding to the accumulation periods considered in this study (i.e., 3, 6, 12, and 24 months). The colour (and number) in each cell shows the ranking of the drought based on severity. For cells that are greyed out, the rank of the drought is greater than 20.

raingauges resulting in less spatial detail in the rainfall pattern. As a result, there is a risk of overestimating the drought area in that region, and consequently, the severity of droughts prior to 1960, and increasingly so as we go back in time, as the density of raingauges decreases.

In addition to the question of the raingauge network density, the degree of confidence we can have in the actual raingauge data quality – particularly for the earlier period in some remote areas such as the Scottish highlands – is to be carefully considered. The earlier instruments were installed before international standards for precipitation measurements were defined and widely adopted (Rodda and Dixon, 2012), and issues such as snowfall under-catch in winter or the effect of wind are likely to overestimate the severity of droughts. However, Murphy et al. (2020) found that winter under-catch was identified as being significant mainly for data prior to 1850 in the British Isles, and that observed and reconstructed precipitation time series strongly agreed for the period going from 1870 to present. This gives us confidence in the underlying raingauge data underpinning the gridded dataset used in this study, which starts in 1862, and although we acknowledge the greater uncertainty in the data in the earlier period, this is the best dataset available at the time this study was carried out and is a clear improvement to what was available before.

Historic Droughts

As we would expect, most of the severe droughts previously reported in the literature (**Table 1**) were picked up as major droughts in our study; well-known droughts such as the 1976 and the 1933–35 droughts ranked highly in the results. However, there are a few exceptions: the 1911, the 1913–1914 and the 2004–2006 droughts (**Figure 11**) are not found to be exceptionally severe here. The apparent lack of severity for these particular

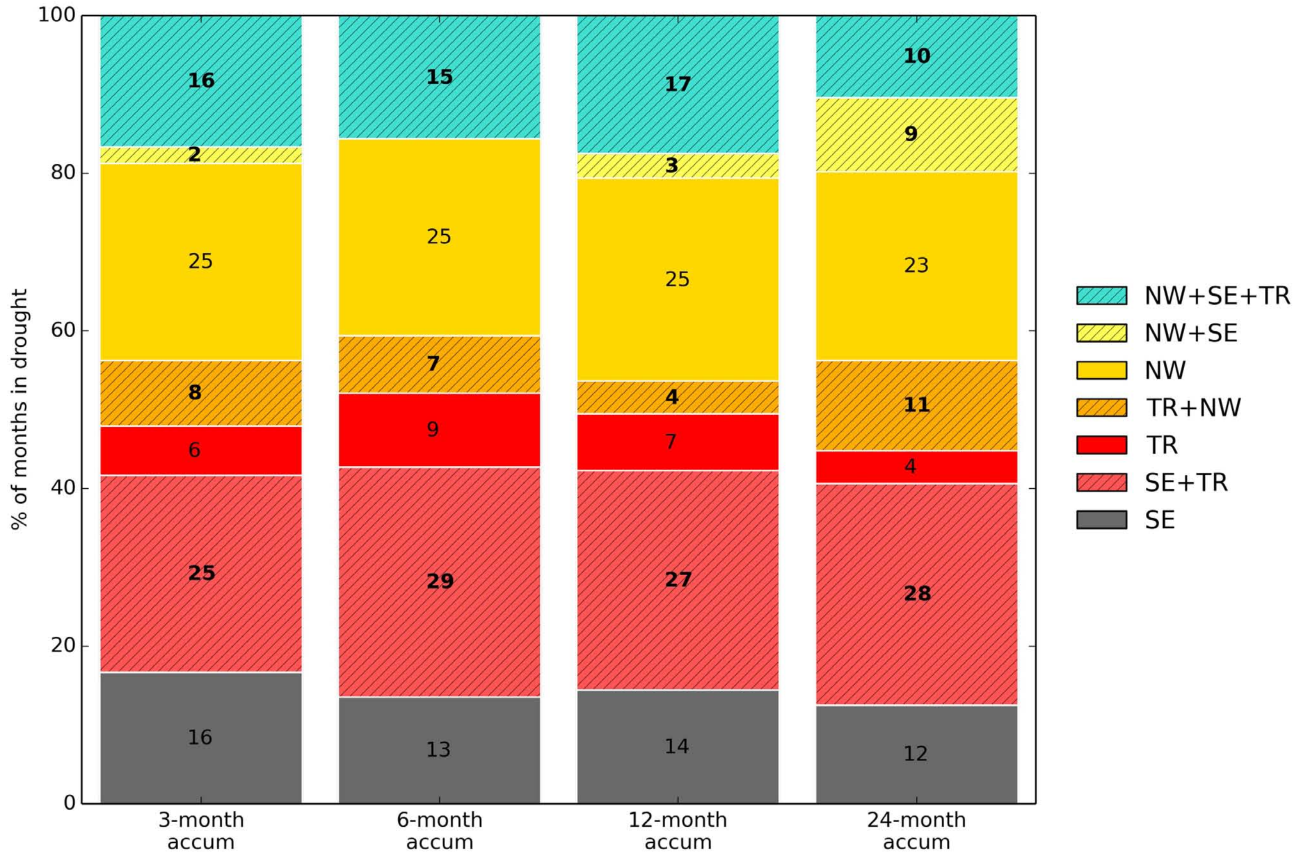

FIGURE 12 | Percentage of months in drought affecting the three regions. The hatched area represents months in drought where multiple regions were affected simultaneously. "TR" in the legend stands for the Transition region. This includes all drought events detected between 1862 and 2015, for accumulation periods of 3, 6, 12, and 24 months.

events – despite having historical evidence of drought impacts (as illustrated in the drought inventory) and having been identified as a severe event by other methodologies (e.g., Barker et al., 2019) – could be explained by the inherent nature of the methodology used. Here the method is based on a connectivity approach, where the pixels identified as being in drought must be contiguous, and the area between two consecutive time-steps must overlap in order to be considered as belonging to the same drought event. Consequently, in case of a "patchy" rainfall pattern, we can end up with simultaneous smaller drought events very close one to the other, but considered as separate events due to their discontinuity in space or time. The advantage of not having fixed boundaries or a fixed time window to define the droughts in our method becomes a drawback in this case. This limitation in the methodology had already been highlighted by Haslinger and Blöschl (2017), who pointed out that the risk of applying the method to high-resolution data was that small-scale features may interrupt a coherent space-time region. Merging multiple droughts occurring simultaneously and in close proximity could be a way to overcome this issue and avoid missing some severe events due to this feature. Our study has also identified six additional droughts not well known until now: an early drought rich period in the 1860s and 1870s particularly in the NW, a severe drought in the "Transition" region in 1937–38, and a severe drought in the NW in 1955–56. Five out of these six "new" droughts were also identified in the recent study by Murphy et al. (2020) as "severe" droughts (12-month SPI > -1.5), with the exception of the 1870–1873 one which fell into the category of "moderate" drought. Murphy et al. (2020) use single long national-scale rainfall time series for England, Scotland and Ireland (albeit each being a combination of multiple gauges) so the current study adds value by characterising the spatiotemporal signature of these events.

The study of drought frequency trend analysis (Section "Results - Trend Analysis," **Figure 7**) and the timeline of historic droughts (Section "Historic Timeline of Droughts," **Figure 10** and **Supplementary Figure 1**) highlighted the existence of an apparent alternation between severe droughts in the NW and the SE for long accumulation periods (12 and 24 months), with clusters of droughts in the SE occurring 1920–1940 and 1975–2000 and droughts in the NW occurring 1860–1900 and 1940–1975. This pattern coincides with decadal fluctuations in the winter North Atlantic Oscillation (NAO) index (Hurrell, 1995; Visbeck et al., 2001), proven to be correlated to precipitation levels in the NW (Wilby et al., 1997; West et al., 2019). Negative winter NAO indices are known to be linked to lower

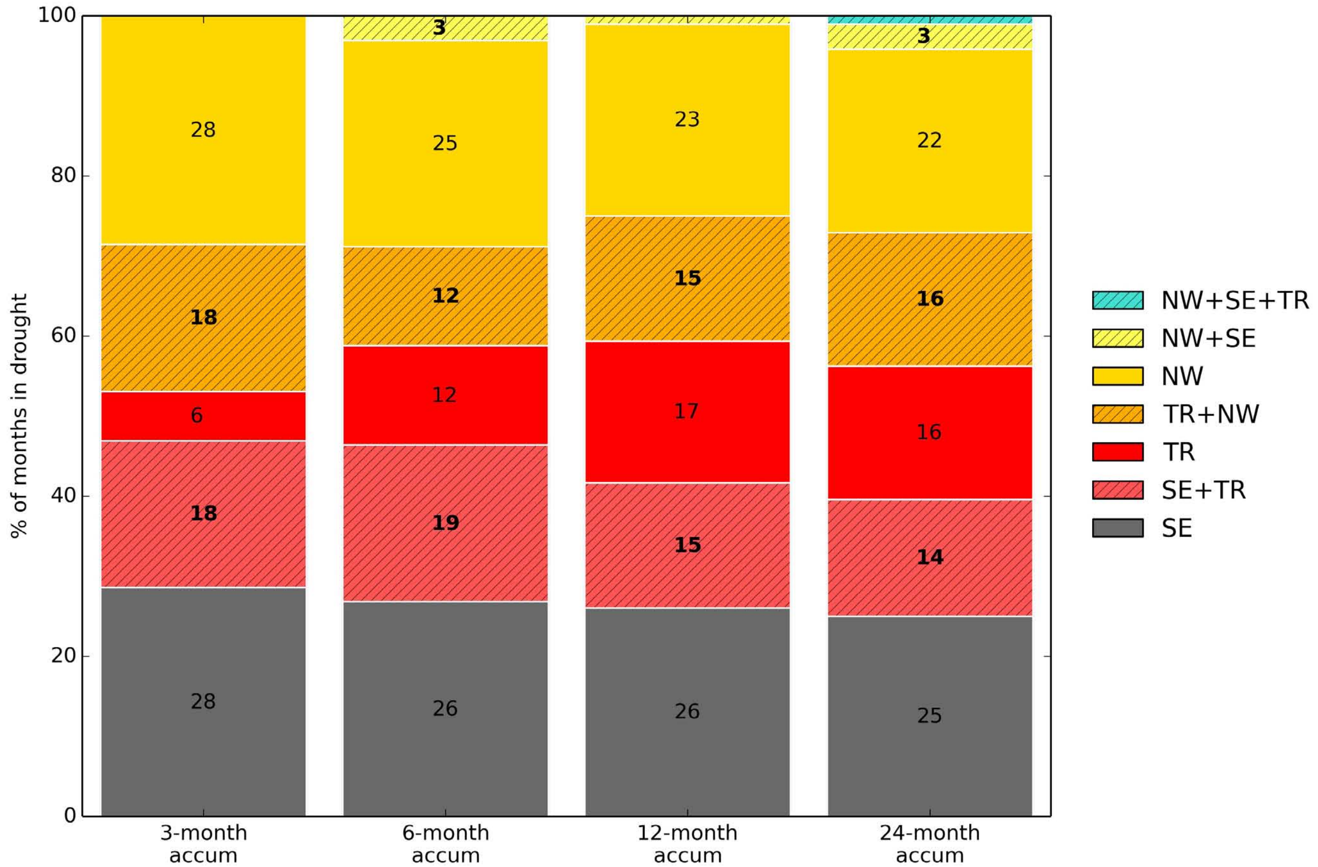

FIGURE 13 | Percentage of months in the most severe droughts affecting the three regions. The hatched area represents months in drought where multiple regions were affected simultaneously. "TR" in the legend stands for the Transition region. The "top 20" most severe droughts detected between 1862 and 2015 in each region were considered, for accumulation periods of 3, 6, 12 and 24 months.

precipitation in the NW, which is consistent with the cluster of severe droughts observed in that region in 1860–1900 and 1940–1975, both periods experiencing persistent negative winter NAO index. The smoothing involved in the long accumulation periods suggest that the NW-SE drought alternation is related to this well-established low frequency variability in the climate system associated with the NAO, and ultimately its larger-scale drivers. Previous studies (e.g., Folland et al., 2015; Svensson and Hannaford, 2019) have described the NW-SE rainfall gradient in the United Kingdom and the various Atlantic to global scale ocean-atmosphere drivers of these patterns.

Regional Differences in Drought Characteristics

Our findings confirm that the NW is generally affected by shorter duration, less severe, albeit more frequent droughts. This might be explained by generally more variability in precipitation in the NW compared to the SE. However, for long accumulation periods, droughts were found to also be extended and severe in the NW. This might be because over that timescale, we are dealing with moderately dry years that might consist of a run of several droughts with wetter interludes, rather than a true extended drought. The NW is characterised by plenty of rainfall in absolute terms and hydrologically is dominated by rapidly responding catchments with little storage capacity. Consequently, even during long-term rainfall deficits, impacts on water resources may not be so dramatic if there are short periods of wetter weather which can "reset" the drought conditions and allow the water resources to recover in between the drier spells. It is also possible that, to a certain extent, the lower density of raingauges pre-1961 is contributing to overestimation of the spatial extent, and hence the severity, of droughts in the NW (see Section "Uncertainties in the Data").

Short intense droughts are potentially more damaging for the NW as no stored water is available to compensate for this short-term deficit. Our study shows that severe droughts at short accumulation period are less frequent in the NW than in the SE, however, short-term deficits can have severe impacts on water resource availability in the NW due to the limited water stored within catchments.

This study has highlighted that the NW suffers overall more frequent short and less severe droughts. Although these events are unlikely to cause major impacts, because the catchments are so responsive, they could still locally and temporarily threaten water supply – moreover, even short, summer "flash" droughts in responsive parts of western England can rapidly cause other social and environmental impacts (e.g., on aquatic ecosystems, due to low river flows, and terrestrial systems (e.g., dry soils leading to wildfires and agricultural impacts)). The heatwave driven drought of 2018 was one such example (Parry et al., 2018).

In the SE however, slow-responding, groundwater-dominated catchments and water resources prevail. This trait makes the SE generally resilient to short-term droughts, even if intense, in terms of water resources availability. They can still be problematic for ecosystems and many sectors (e.g., non-irrigated agriculture) if the soil moisture is depleted, but it is prolonged rainfall deficits that are likely to result in impacts on water availability. Typically, multiannual droughts with multiple dry winters (winter being the water recharge period) have the greatest impact in this groundwater-dominated region (Marsh et al., 2007; Folland et al., 2015). Population density, and hence water demand, is higher in the SE, and is expected to increase over the coming decades. Many areas of the SE are already water stressed and this is expected to deteriorate further with the combined effect of increasing water demand (Environment Agency, 2020) and changes in water availability as a result of climate change, which will alter the distribution of evapotranspiration and precipitation (Prudhomme et al., 2012). Water managers are facing unprecedented challenges, and the understanding of drought dynamics provided by our study will be a useful foundation for informing effective planning for future drought mitigation.

Spatial Coherence of Droughts

Regarding spatial coherence of droughts, it is interesting to see that, when all drought events are considered, for a significant proportion of months in drought (between 15 and 20% depending on the accumulation period considered), the SE and NW are simultaneously in drought (**Figure 12**). However, when only the most severe droughts are considered (top 20 droughts in each region, **Figure 13**), seldom are the SE and NW simultaneously in drought (less than 4%). This corroborates the findings by Folland et al. (2015) that for fifteen major long droughts in the United Kingdom there was a significant anti-correlation in the average precipitation anomaly between the NW and the SE, in particular for winter months (i.e., droughts in one region are unlikely to affect the other). Our study shows that this relationship is not observed for less severe drought events, for which droughts tend to be more spatially coherent. This, in turn, confirms the observations by Rahiz and New (2012) that drought events with moderate severity and short duration have greater spatial coherence. However, they also found that events taking place during the hydrological wet season (October to March) had greater spatial coherence than during the dry season (April to September), which was not clear in our results (**Supplementary Figures 3–6**). Here we observe a higher spatial coherence in spring and summer for long accumulation periods only (**Supplementary Figure 6**). It should be noted though that unlike Rahiz and New (2012), we have considered four seasons (Spring = MMA, Summer = JJA, Autumn = SON, Winter = DJF), which might partly explain the differences in results.

Spatial coherence, or lack thereof, has important implications for drought management, especially as the tendency is now to consider inter-region drought planning in a more integrated way (e.g., Environment Agency, 2020). The fact that historically, when the SE has suffered an extremely severe drought, the NW was (almost) never in drought, and vice-versa, has important implications for example for the prospect of inter-regional water transfer – a method in which water is supplied to a region in drought from areas not experiencing drought. In reality, for practical applications the regions used for water resources planning do not map onto the statistically defined regions used herein, so these results are more indicative rather than pertaining to particular transfers. Such transfers are normally predicated on a donor area in the wetter, upland areas like Wales (transition region) transferring to a drier lowland area in the south-east – as for example in the Severn-Thames transfer. Our results demonstrate that for the top 20 most severe droughts, when the transition region is in drought, 33–40% of the time (depending on accumulation period), the SE is also in drought. Therefore in situation of extreme droughts, about 60% of the time, water transfer could be considered. Such information could provide important probabilistic information for water resource planners considering the viability of transfers over the long-term.

Moreover the set of extracted drought events could be used for similar coherence analyses using different, operationally aligned regions in future. Importantly, however, here we only consider the possibility of coherent historical meteorological droughts but water resources planning requires future climate change to be considered and hydrological modelling and water supply system simulations to be undertaken (as in e.g., Dobson et al. (2020)). Some studies suggest the likelihood of coherent droughts across regions is likely to increase in future under anthropogenic warming (Rudd et al., 2019) whereas others do not show such large changes in coherence (Dobson et al., 2020). However, such studies have mostly used fixed regions and quite simple definitions of the likelihood of regions jointly being "in drought." The spatiotemporal extraction approach suggested here could be used in future studies to extract droughts from climate projections before running them through hydrological and supply system models.

CONCLUSION

In this paper, we employ a novel approach used for the first time in GB for identifying meteorological drought events based on connected space-time areas for a historic period from 1862 to 2015. We characterise these events based on their spatial extent, duration, average intensity and severity, and compare events occurring in three main regions of GB: the SE, the NW and a "Transition" region in-between them. For long accumulation periods (12 and 24 months), the timeline of historic drought events showed an alternation of drought rich multi-decadal periods between the SE and the NW, which coincides with the fluctuations in the NAO index. Our results also show that less severe and short droughts are more frequent in the NW than in the SE for short and medium accumulation periods (3, 6, and 12 months), whereas more severe and long droughts with larger spatial extent are more frequent in the SE. However, for long accumulation periods (24 months), fewer differences are observed between the NW and the SE. Our results provide insight on the frequency of drought characteristics such as extent, duration and severity for different regions in GB. By highlighting and quantifying these differences, our study informs water managers to help them tailor their drought management strategies to the specific characteristics of droughts in a given region. Most known major droughts rank highly in the results, and a few additional droughts are identified. This method allows a full spatiotemporal characterisation of these droughts in a way not previously done for GB.

Regarding the spatial coherence of droughts, the results showed that most of the time, the "Transition" and the SE regions are simultaneously in drought. Furthermore, when the SE is in drought, about a third of the time the NW is also in drought (and vice-versa), when all droughts in the historical record are considered. However, if we only select the 20 most severe droughts, then very few events occur simultaneously in the SE and NW. This opens up the possibility of regional water-transfer as a potential water management solution to face extreme drought situations. Overall, the present study has great potential to inform water management strategies for future drought planning exercises in Great Britain.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception and planning of the analysis. KH ran the analysis to extract the drought events from the gridded rainfall time series. CS performed the clustering analysis to define the study regions. MT did the frequency analysis, timeline of droughts events, and spatial coherence analysis. All authors contributed to the interpretation of the results. MT took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.639649/full#supplementary-material

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Barriers and Opportunities for Actionable Knowledge Production in Drought Risk Management: Embracing the Frontiers of Co-production

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Drought risks pose serious threats to socio-ecological systems, built environments, livelihoods and human wellbeing. Managing these risks requires long-term collaboration between diverse groups with different values, interests and forms of knowledge. Funders, researchers and practitioners have increasingly advocated for collaborative models of knowledge production in which all participants recognise the multiple ways of understanding drought risk and strive to co-create knowledge for decision making. Such transdisciplinary research approaches aim to develop and sustain more equitable and meaningful interactions between scientific and societal actors, and have been shown to increase knowledge use and build resilience to climate variability. In practice, however, collaborations around drought remain largely science-driven and, as a result, can struggle to produce actionable knowledge necessary to better manage drought risk. This article draws from drought studies and related transdisciplinary fields to highlight common barriers inhibiting actionable knowledge production across a broad range of drought risk management contexts. We also propose opportunities for improved knowledge production that can guide researchers, practitioners and funders seeking to engage in transdisciplinary work. Diverse understandings of drought risk have hindered widespread advances in knowledge production and resilience building. We argue for multi-disciplinary researchers to come together with stakeholders and focus on creating inclusive and context-driven environments. While not appropriate or cost-effective in all situations, co-production between researchers, practitioners and other stakeholder groups offers opportunities for actionable management plans and policies that reflect the complex and contested problem framings and socio-ecological contexts in which droughts impact society.

Keywords: co-production, actionable knowledge, drought risk management, drought impacts, transdisciplinarity

RECENT PROGRESS IN KNOWLEDGE PRODUCTION FOR DROUGHT RISK MANAGEMENT

Droughts are the result of complex interactions between physical, biological and social systems (Wilhite and Pulwarty, 2017). In this human-dominated era, prolonged droughts pose serious threats to economies, societies and the environment (Wilhite, 2012; Van Loon et al., 2016a). Their impacts are difficult to observe and quantify as they affect sectors in myriad ways (Van Loon et al., 2016b; Vicente-Serrano et al., 2020). Drought risks are a function of both the probability and severity of events (exposure) and underlying vulnerability of the exposed system, community or society (Vogt et al., 2018). Prolonged dry conditions can increase the risk of wildfires and water shortages which can have adverse effects on ecology, water supplies, public services, infrastructure, agriculture and industry. At an individual level, these impacts can affect people's recreational activities, livelihoods and ultimately their well-being. Historically, droughts have traditionally been managed using reactive, crisis-driven approaches (see Pulwarty and Sivakumar, 2014). In recent decades, numerous studies have argued for proactive approaches to managing drought risk based on long-term monitoring and multi-actor engagement (see Wilhite et al., 2014; Bachmair et al., 2016a; Finnessey et al., 2016).

Understanding where, when and how drought conditions evolve can give those affected time to prepare and act to minimise harm. In recent decades, there have been significant advances in drought monitoring and early warning, seasonal forecasting and data processing (Wilhite and Pulwarty, 2017; Hannaford et al., 2018). Monitoring and early warning systems (MEWS) have been developed to continuously track and, in some cases, forecast hydrometeorological variables at different scales (Wilhite, 2006; Hannaford et al., 2018). There have also been considerable efforts in repackaging these data in the form of drought indicators or indices (e.g., Hao and Singh, 2015). Several studies have assessed the links between different drought indicators (e.g., Vicente-Serrano and López-Moreno, 2005; Vicente-Serrano et al., 2012), and drought impacts in different sectors (Bachmair et al., 2016b).

However, while data-driven MEWS can characterise environmental conditions, they have limitations when it comes to connecting with how drought is locally experienced and recorded by impacted sectors and communities (Bachmair et al., 2016a; Ferguson et al., 2016). For example, drought is often scientifically defined, based on standardised indices that have little meaning for those impacted. Consequently, MEWS can struggle to produce actionable knowledge necessary to reduce vulnerability and enhance long-term resilience (Kirchhoff et al., 2013). There remains a simplistic belief in some literature (see e.g., Finnessey et al., 2016) that producing and simply communicating scientific information can depoliticise complex and highly contested societal problems such as climate change, loss of biodiversity and drought. In reality, such top-down approaches can reinforce existing unequal relationships (Murphy et al., 2016) and the perception that science alone can produce and deliver the knowledge needed to address complex social problems (Pohl et al., 2010; Turnhout et al., 2020). For example, creating narrow definitions of drought that suit empirical scientists from meteorology, hydrology, engineering, economics or agricultural science automatically marginalises less technical sectors and types of knowledge. In response, a growing body of literature has emerged (see Cash and Borck, 2006; Kirchhoff et al., 2013; Lemos et al., 2018a), advocating instead for transdisciplinary research that seeks to create meaningful knowledge for decision makers, communities and organisations through inclusive and interactive approaches (see Norström et al., 2020).

Transdisciplinarity can be defined as a commitment by academics and non-academics to integrate multiple forms of knowledge and perspectives within a collaborative research process (Suldovsky et al., 2018). There is growing evidence, particularly in the context of addressing complex socio-ecological challenges, that transdisciplinary approaches (e.g., knowledge co-production, post-normal science, action research) increase the likelihood of producing actionable knowledge (i.e., knowledge that is perceived as sufficiently credible, salient and legitimate to be used in decision making) (Cash et al., 2003; Lemos et al., 2018b). As a result, funders, researchers and practitioners are turning to more collaborative models of knowledge production and management to build resilience to intractable climate-related hazards such as drought.

While drought literature on transdisciplinary knowledge production is limited, recent drought studies draw from social sciences to argue for improved understanding of transdisciplinary knowledge-making practices and for stakeholders to play a more prominent role in the development of open and transparent MEWS (Van Loon et al., 2016b; Hannaford et al., 2018). For example, while exploring drought impacts and MEWS development in Europe, North America, and Australia, the "DrIVER" project incorporated learnings from stakeholder workshops to develop collective insights into different perspectives of drought impacts and MEWS needs (Collins et al., 2016; Hannaford et al., 2018). In a Mediterranean context, Turco et al. (2019) developed a fire forecasting system that merged user relevant information with seasonal climate forecasts to provide tailored outlooks for fire managers in Catalunya. Ferguson et al. (2016) collaborated with a Native American community in the United States Southwest on a drought information system that combined local observations and knowledge with scientific monitoring data. Experiences in sub-Saharan Africa have also shown that ignoring the cultural and power dynamics of different ways of knowing (traditional and scientific knowledge) can reinforce tensions within communities and enhance vulnerability to drought (Murphy et al., 2016). Such endeavours are pioneering integration of scientific tools and data with local understandings of drought impacts, towards shared or "co-produced" definitions of drought. With drought research taking this turn and attempting to operate in a transdisciplinary space, it is important to reflect on some inherent challenges of knowledge production for drought risk management and how they can potentially be addressed.

In this focused review, we draw on drought specific and related literature from more mature transdisciplinary fields that share similar epistemic foundations and risk-based decision-making

TABLE 1 | Barriers to and opportunities for actionable knowledge production in drought risk management.

Barriers	Opportunities
Droughts have different meanings	Deliberately co-produce
Droughts can be perceptually challenging	Understand stakeholder context and needs
Droughts are context specific	Explicitly recognise diverse drought meanings
Droughts are difficult to predict	Create enabling environments and be transparent about uncertainties

contexts (e.g., water governance, climate services, climate risk management and sustainability science). We also draw upon our own insights and practical experiences collaborating with societal actors on climate risk, drought and water resources decision making. Our objectives are to 1) identify common barriers to the production of actionable knowledge and 2) propose opportunities for improved knowledge production that can guide researchers, practitioners and funders seeking to engage in transdisciplinary drought work across diverse drought contexts and scales (**Table 1**). We conclude by elaborating some of the benefits and potential pitfalls of co-production, discussing the important role of social science in drought research, and recommending some future research directions.

BARRIERS TO ACTIONABLE KNOWLEDGE PRODUCTION FOR DROUGHT RISK MANAGEMENT

Drought affects different parts of the hydrological cycle, environment and society in ways that are highly subjective, pervasive and difficult to quantify (Bachmair et al., 2016a). The complexity of drought as a hazard, and contestation over how drought impacts society prevents more nuanced understandings of drought and knowledge exchange (Wilhite and Glantz, 1985; Redmond, 2002; Kallis, 2008; Ferguson et al., 2016). This section identifies some of the fundamental barriers inhibiting actionable knowledge production for drought risk management.

Droughts Have Different Meanings

At their most abstract, droughts are periods characterised by adverse effects from insufficient water. Drought impacts are often framed from an agricultural, economic or ecological perspective. Farmers may associate reduced yield or loss of harvest or livestock with dry conditions; economists may only consider conditions to be drought-like when demand for water exceeds supply; ecologists may focus on the impact of dry conditions on ecological health and water quality (Wilhite and Glantz, 1985; Mishra and Singh, 2010). Drought can also be defined in operational terms based on agreed criteria that help planners decide when to declare an event and activate response plans (Estrela and Vargas, 2012; Bachmair et al., 2016a; Maia and Vicente-Serrano, 2017). However, there can be no universal definition that relates to how droughts impact social systems (Lloyd-Hughes, 2014; Kohl and Knox, 2016). Drought and its impacts mean different things to different people depending on their specific interests, experiences and context. Moreover, thresholds and descriptions of event severity (moderate vs. severe) often differ depending on how drought impacts are framed by dominant voices, emphasising the importance of facilitating integrative assessments and perspectives that draw on diverse experiences. How we define drought can draw out pre-conditioned biases and a priori alienate or empower different stakeholders, indicating which impacts, sectors and types of knowledge have greater legitimacy in a policy or decision-making process.

Droughts Can Be Perceptually Challenging

Droughts are typically associated with drier than normal weather (meteorological drought). Reductions in precipitation can drive soil moisture deficits (agricultural drought) and in time lower surface and sub-surface water levels in a catchment (hydrological drought). However, drought evolution depends on the magnitude, timing and duration of the precipitation anomaly, the type of soil and land cover, dominant runoff pathways, geology and increasingly engineering and management interventions.

Drought impacts can propagate slowly without being immediately seen or experienced (Wilhite, 2012). As a result, impacts on public services, businesses and communities may also not immediately be attributed to drought conditions. Purely conceptual or scientific characterisations of drought have limited relevance for many stakeholders, particularly when the spatial and temporal resolution of the information provided does not match with their context (Ferguson et al., 2016). Drought planning is a particular challenge where recent societal and institutional experiences of drought may not be reflective of actual risk due to long-term climate variability (Murphy et al., 2017). Rivers or reservoirs in a region may appear to be at normal levels due to careful management, but low soil moisture may be impacting rain-fed agricultural production. In fact, hydrological droughts can persist even after heavy rainfall or flooding.

Droughts Are Context Specific

A particular socio-ecological and historical context will influence drought risk perception (Gil et al., 2000). Seven days without rainfall might be considered a meteorological drought in traditional agricultural societies that rely on precipitation on almost a daily basis during the rainy season. However, in desert societies where rainfall is scarce, such occurrences would be unremarkable.

How people perceive and respond to drought is strongly related to past experiences and memories (Taylor et al., 1988). Throughout history, drought-prone societies have developed culturally embedded rules of thumb or heuristics derived from experiential knowledge and mental models of their local environment (Courkamp et al., 2019). In some places, increases in extreme climate events are likely to have an effect on risk perception and on how people and societies understand seasons and climate variability in the future. Recent attention has been drawn to "flash drought" events in humid regions, characterised by their sudden onset, rapid intensification and severe impacts (Pendergrass et al., 2020).

At a societal level, droughts may be downgraded or "forgotten" entirely if they occur around the same time as a heat wave or prior to a significant flood event (Ciais et al., 2005; Marsh et al., 2013; Shepherd et al., 2018). It can be difficult to communicate drought risk in cultures with a perennially wet climate, associated with green landscapes (Weitkamp et al., 2019). In northern European countries, droughts are usually associated with hot weather which, in turn, evokes positive memories of being outdoors and enjoying the sunshine (Bruine de Bruin et al., 2016). As a result, droughts are not always seen as major hazards that require long-term planning. Perceptions of drought risk can also change as a function of socio-economic conditions and dynamic policy landscapes (Gil et al., 2000). For example, in the mid 20th century, Spanish society moved from a focus on meteorological droughts to hydrological droughts as their economy became less reliant on rainfed agriculture.

Droughts are Difficult to Predict

It is difficult to develop confident meteorological forecasts of drought more than two weeks in advance. With the exception of some tropical and subtropical regions in which climate variability is strongly determined by sea surface temperature variability (Vicente-Serrano et al., 2011), in the majority of the world regions the skill of seasonal forecasting is still very low to be effective in developing accurate seasonal drought forecasts (Bechtold et al., 2008; Dutra et al., 2013). Such capacity would be very useful to anticipate possible impacts and to allow preparedness of economic sectors to associated losses, hydrological managers to improve dam operation and optimization of available water resources and environmental managers to prepare for possible hazards (e.g., fire risk) and to reduce soil erosion and land degradation (e.g., with management of livestock grazing). While recent studies have suggested some improvement in skill (e.g., Davini and D'Andrea, 2020; Smith et al., 2020), current drought forecasting systems (e.g., https://www.drought.gov/drought/data-maps-tools/outlooks-forecasts) are still subject to large uncertainties.

OPPORTUNITIES FOR ACTIONABLE KNOWLEDGE PRODUCTION FOR DROUGHT RISK MANAGEMENT

There are a number of opportunities for researchers, practitioners and funders seeking to overcome these barriers. These are neither comprehensive nor prescriptive but offer insights from drought and related literature that can inform a pragmatic approach to producing actionable knowledge in a range of drought-sensitive decision-making contexts.

Focus on Co-Producing Rather Than Translating Knowledge

Public-facing drought information systems tend to focus on translating scientific knowledge for a wide range of stakeholders (Hannaford et al., 2018). Integration of scientific and non-scientific knowledge remains rare (Giordano et al., 2013; Solano-Hernandez et al., 2020), with some exceptions (e.g., Estrela and Vargas, 2012). This centralised, technocratic model of knowledge production is ineffective because it creates a disconnect between monitoring networks, scientists and sector-specific drought planning (Hannaford et al., 2018).

Collaborative knowledge production (commonly referred to as "co-production") can be defined in normative terms, as a learning process that deliberately brings together diverse perspectives to co-create actionable knowledge and new practices (Bremer and Meisch 2017; Lemos et al., 2018b). Co-production should be interactive, iterative, context-driven, problem-focused and involve deep engagement with non-scientific knowledge systems (Norström et al., 2020). Co-produced knowledge is more likely to be perceived as credible, salient and legitimate (Cash et al., 2003). While systematic assessments are rare (Mach et al., 2019; Arnott et al., 2020; Jagannathan et al., 2020), co-production has been shown to increase the likelihood of knowledge use in decision-making (Lemos et al., 2018b).

However, assembling a sufficiently broad group of actors, while keeping the process practically and strategically manageable requires considerable time, resources and expertise (Page and Dilling, 2019; Norström et al., 2020). Potential participants may not have sufficient capacity or motivation to engage in co-productive processes (Page and Dilling, 2019). Many academics are still primarily incentivised to conduct disciplinary science that cannot directly address societal challenges (Dilling and Lemos 2011). Conversely, practitioners and other stakeholders may work within professional contexts that do not reward iterative learning, innovation and critical reflection (Norström et al., 2020).

Successful co-production is predicated on including a plurality of perspectives, which often requires the disruption of established roles and routines (Vincent et al., 2018; Turnhout et al., 2020). Deep rooted power imbalances can prevent engagement, reproduce knowledge hierarchies and, consequently, undermine the co-production process (Mobjörk, 2010; Reed et al., 2014; Brandt et al., 2018). To avoid such pitfalls, it is important that all actors involved in the co-productive processes are committed to achieving a common goal and able to regularly and systematically reflect on and discuss the extent to which their understandings and values are being represented (Reed et al., 2014; Norström et al., 2020).

Iteratively Analyse Stakeholder Needs and Context

Given the complex and multi-sectoral nature of drought it is vital that a thorough analysis of potential stakeholders and their decision-making contexts is conducted prior to and throughout collaborations. Top-down, "loading dock" approaches that focus solely on information provision often fail to consider the complexity and dynamism of local cultural sensitivities around the legitimacy of different types of knowledge systems (Cash and Borck, 2006). This can create friction between local stakeholders and ultimately result in mal-adaptative decision making (Murphy et al., 2016). Uncritical mapping and selection of potential stakeholders (e.g., just targeting water managers) can reinforce existing narrow perceptions and power structures. It is important to know whether stakeholders are already used to dealing with hydrological variability or other climate-related hazards such as flooding. Businesses may also have to prioritise other stressors/threats above drought preparedness (e.g., the COVID-19 pandemic) when making decisions.

Contextual analysis and participatory design approaches can inform the development of tailored communications and interactions (Hannaford et al., 2018; Grainger et al., 2020). Some stakeholders may require technical information (SPI, severities, probabilities), others might just want high-level information about the general hydrological trend. An appraisal of the 2009 United Kingdom Climate Projections (UKCP09) highlighted that scientists often assume that users will be highly numerate and able to handle technical information (Porter and Dessai, 2017). This often leads to parachuting default or familiar approaches when interacting with stakeholders. Our experiences would suggest that, despite the inclusion of stakeholder analysis and engagement within some drought projects, researchers from the social and behavioral sciences are rarely involved in framing, planning and designing these interactions. Funders and natural scientists should acknowledge how valuable their contribution could be to knowledge production and reach out to these disciplines as early as possible in the project creation process.

Explicitly Recognise Diverse Understandings of Drought

It is crucial to recognise that plurality of perspectives make drought an inherently complex and context-differentiated hazard (Collins and Ison, 2009; Lange et al., 2017; Hannaford et al., 2018). As a result, no single perspective can presume superiority over another, and claim to have a definitive understanding of drought and potential solutions. The inclusion of multiple forms of knowledge has the potential to enhance knowledge use and build trust between researchers and drought-sensitive sectors.

Any characterisation of drought that strives for societal relevance must consider what makes drought socially relevant in that particular context (Ferguson et al., 2016). We would therefore encourage researchers to support drought sensitive decision makers to develop their own drought definition tailored to their own context. This can be achieved through collaborative ground-truthing of drought indicators with stakeholder knowledge (Bachmair et al., 2016a) and with an understanding of their specific needs (Estrela and Vargas, 2012).

Create Enabling Institutional Environments

Effective knowledge production requires collaboration between different sectors and knowledge systems operating at various spatial and temporal scales. Currently, links between community, national and global-scale drought management are weak (Pulwarty and Sivakumar, 2014). This fragmented management context is exacerbated by science and institutional systems that are grounded in top-down modes of knowledge production and mobilization. Drought researchers and planners might benefit from working through organisations operating at the interface between science and policy [known as boundary organisations (Guston, 2001)] to help connect different sectoral drought plans and knowledge systems (e.g., water supply and agricultural sector) (Hannaford et al., 2018). Page and Dilling (2019) suggest taking advantage of existing intra-sectoral communities of practices or local "champions" that may be influential within broader stakeholder groups (e.g., water managers/farmers).

The use of climate information and related services within drought risk management has been promoted by several key international initiatives including the United Nations' Global Framework for Climate Services and Integrated Drought Management Programme (Finnessey et al., 2016). However, Turnhout et al. (2020) show that these types of science-led initiatives are often dominated by depoliticisation dynamics that reinforce rather than mitigate existing uneven post-colonial politics. It is, therefore, vital that the drought research community reflect upon important institutional questions around who should instigate and drive collaborations (Hannaford et al., 2018).

Openly Discuss and Characterise Uncertainty

Drought management is beset by scientific and socio-economic uncertainties that require joint knowledge and problem solving by researchers, practitioners and other societal actors. Decision makers should have awareness of the uncertainty associated with different forms of knowledge and knowledge production processes (Fischhoff and Davis, 2014). However, this can be problematic, particularly when dealing with inherently uncertain processes in risk averse cultural contexts driven by institutional expectations for precision and accuracy (Taylor et al., 2021). Overlooking uncertainty in response to these expectations may result in a false sense of certainty, potentially leading to mal-adaptive decision making and loss of trust in scientific partners (Macintosh, 2013; LeClerc and Joslyn, 2015). It is therefore important to manage expectations carefully, and characterise uncertainties in a manner that is transparent, relevant and understandable to all stakeholders. When engaging with broader and non-scientific audiences, storylines or narrative approaches can help connect with people's innate understanding of future uncertainty and reveal important points of commonality (Shepherd et al., 2018; Jack et al., 2020).

CONCLUSION

Despite decades observing and quantifying changes in hydrological extremes, drought remains intractable in clear scientific terms and as a risk for societies to manage. Recent drought research has taken the first steps towards connecting with, and making actionable knowledge for, those communities and sectors impacted by drought impacts. In this focused review, we have reflected on this progress by highlighting some key barriers to knowledge production and proposing potential opportunities for strengthening drought knowledge.

Drought perceptions are strongly differentiated among scientific disciplines, stakeholders and economic sectors, and are subject to change as a function of hazard severity, socioeconomic and environmental conditions. Context is crucial, with drought having very different meanings and experiences in time and space—from humid and semi-arid regions to local differences within the same catchment. These scientific, perceptual and contextual challenges have made it difficult to engage with different sectors on anything other than a reactive basis (Wilhite, 2012).

To overcome these barriers, we urge those involved in drought risk management to embrace co-production as a model of engagement and knowledge production. This will require that researchers become partners in knowledge creation rather than solely producers of knowledge and to recognise multiple ways of understanding drought risk. In the right collaborative environment, explicit interaction with different knowledge systems can help to build trust, develop shared understandings and enrich knowledge outcomes (Tobias et al., 2019). Creating an enabling environment that accommodates a diverse understanding of drought is far from straightforward, requiring skills not typically required in natural science.

As we have stated earlier, drought literature on co-production is limited. Further exploration of the challenges raised in this article require future research into current knowledge production practices and use in specific drought risk management contexts to better understand the implications of "silo-ed" knowledge on decision making. The social sciences and humanities need to play a more prominent role in co-produced drought research not only as facilitators but also as action researchers so that we can better understand the cultural, political and institutional dimensions that influence drought understandings and risk management processes.

We should expect individual, disciplinary and organisational resistance to new ways of working as power dynamics and knowledge hierarchies are slowly revealed and dismantled. There are inevitable trade-offs between the time and resources required to co-produce research and the expectation on researchers to publish and advance in their careers. Transdisciplinary research will not be appropriate in all drought contexts and all parties will need to carefully consider whether the costs outweigh the expected benefits. Success criteria for co-production will differ greatly and evaluations will need to reflect the complexity of stakeholder expectations, motivation and capacities (Wall et al., 2017; Bremer et al., 2021). Funders, researchers and practitioners have unique ways of assessing whether to use a co-production approach and collaborators need to explicitly acknowledge differences in motivations early in the process. However, a common goal running through transdisciplinary research should be the emergence of a shared purpose and learning in groups (or social learning), both collectively and individually. Proactive approaches to monitoring and evaluation, adaptive project programming and participant flexibility are also critical within co-production processes (Vincent et al., 2018). While collaborative efforts may not immediately provide solutions, mutual exchange of experiences, ideas and values can, in the long-term, facilitate collective action and develop the vital capacities, networks and social capital needed to manage drought risk.

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SG: Article conception and design, drafting of manuscript; CM: Article conception and design, critical revision; SV-S: Critical revision.

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frontiers in Environmental Science

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Science-Narrative Explorations of "Drought Thresholds" in the Maritime Eden Catchment, Scotland: Implications for Local Drought Risk Management

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Drought in the United Kingdom is a "hidden" pervasive risk, defined and perceived in different ways by diverse stakeholders and sectors. Scientists and water managers distinguish meteorological, agricultural, hydrological, and socio-economic drought. Historically triggers in drought risk management have been demarcated solely in specialist hydrological science terms using indices and critical thresholds. This paper explores "drought thresholds" as a bridging concept for interdisciplinary science-narrative enquiry. The Eden catchment, Scotland acts as an exemplar, in a maritime country perceived as wet. The research forms part of creative experimentation in science-narrative methods played out in seven United Kingdom case-study catchments on hydro-meteorological gradients in the Drought Risk and You (DRY) project, with the agricultural Eden the most northerly. DRY explored how science and stories might be brought together to support better decision-making in United Kingdom drought risk management. This involved comparing specialist catchment-scale modelling of drought risk with evidence gathered from local narratives of drought perceptions/experiences. We develop the concept of thresholds to include perceptual triggers of drought awareness and impact within and between various sectors in the catchment (agriculture, business, health and wellbeing, public/communities, and natural and built environments). This process involved developing a framework for science-narrative drought "threshold thinking" that utilizes consideration of severity and scale, spatial and temporal aspects, framing in terms of enhancing or reducing factors internal and external to the catchment and new graphical methods. The paper discusses how this extended sense of thresholds might contribute to research and practice, involving different ways of linking drought severity and perception. This has potential to improve assessment of sectoral vulnerabilities, development of adaptive strategies of different stakeholders, and more tailored drought communication and messaging. Our findings indicate that drought risk presents many complexities within the catchment, given its cross-sectoral nature, rich sources of available water, variable prior drought experience among stakeholders, and different quantitative and perceptual impact thresholds across and within sectors.

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Fuzziness in identification of drought thresholds was multi-faceted for varied reasons. Results suggest that a management paradigm that integrates both traditional and non-traditional "fuzzy" threshold concepts across sectors should be integrated into current and future policy frameworks for drought risk management.

Keywords: indices, drought, decision-making, narrative, thresholds, Scotland, knowledge, memories

INTRODUCTION

Drought is a pervasive, diffuse, slow onset and hidden risk in the Anthropocene (Van Loon, 2016), presenting specific management challenges in different national contexts. In contrast, water scarcity – or lack of fresh water resources to meet standard or required water demand – can occur due to physical (drought), institutional and/or infrastructural reasons. Drought and water scarcity have distinct connotations, however, political concerns can also determine whether "drought" or "water scarcity" is used in the language of some statutory bodies. For example, the Water Resources (Scotland) Act (2013) makes no mention of drought but instead sets out arrangements for water shortage orders.

Traditional Western evidence bases, drawn on to support environmental and hydro-meteorological decision-making for climate resilience, have tended to prioritize specialist science (Mazzocchi, 2006; Nakashima, 2016). This applies in the evidence used in statutory drought risk management with its focus on the science and statistics of rainfall, soil moisture, river flows, groundwater levels and water supply systems. There is an accompanying drive both to monitor current conditions and prepare for future scenarios through drought risk modeling (e.g., in the United Kingdom—Scottish Environment Protection Agency (hereafter SEPA), 2015; Environment Agency, 2017). Specialist academic science prioritizes research into the relative merits of various drought indices (e.g., Standardized Precipitation Index (SPI); Reconnaissance Drought Index (RDI); see, for example, Zargar et al., 2011 for a review). Its focus is on the identification of index-based drought severity thresholds as trigger points for operational needs at a particular point or spatial scale. However, academic and operational methods of threshold characterization can differ. Water supply companies use threshold values in operationally-focused variables such as "supply days" in reservoir stocks while environmental regulators, concerned with maintaining river flows, use thresholds in deviations from the norm in 30, 90 and 180 days rainfall and river flow data (Scottish Environmental Protection Agency, 2020).

In establishing such thresholds, a nexus of different uncertainties exists, including length and quality of data-series (Link et al., 2020), and threshold selection relative to local impacts (e.g., critical precipitation levels for tree die-off, Clifford et al., 2013; oxygen depletion in rivers and the risk of fish-kill, Scottish Environmental Protection Agency, 2020). Alongside this, drought itself is a nebulous concept with its emergent impacts, developing over space and time, defined in different ways within a hydrological process cascade. For example, the Nebraska Drought Center's typology (Wilhite and Glantz, 1985) differentiates meteorological drought (rainfall deficit); agricultural drought (soil moisture drought), hydrological drought (rivers and water bodies), and socio-economic (water supply and use) drought (see definitions in **Table 1**). Scale is important; drought can be regional and in extreme cases, national and transnational. This contrasts with a frequently more spatially limited local or regional hazard such as floods, which are visible and bounded, for example, by a river floodplain or a zone within a pluvial flood event. Drought, as it plays out, is complex and hidden, with varying duration, intensity and spatial extent. For example, drought during a very hot dry summer contrasts with several years of below-average winter rainfall, with complex relationships, feedback loops and trade-offs.

Drought is also a social and cultural construct (Taylor et al., 2009). This makes drought risk management a challenging arena

TABLE 1 | Drought definitions and indices adopted for science-narrative engagement work in DRY (adapted from Mishra and Singh, 2010).

Drought category or stage	Definition	Indices used in DRY
Meteorological drought	Lack of precipitation over a region for a period of time.	SPI SPEI
Agricultural drought	Refers to a period with declining soil moisture and consequent crop failure without any reference to surface water resources.	RDI SPEI SMD Wetness index
Hydrological drought	Lack of water in the hydrological system, manifesting itself in abnormally low streamflow in rivers and abnormally low levels in lakes, reservoirs, and groundwater.	RDI Q_{95}
Socio-economic drought	Failure of water resources systems to meet water demands and thus associating droughts with supply of and demand for an economic good (water).	Not used
Groundwater drought	Reductions in groundwater recharge, levels and discharge, on a timescale of months to years.	Not used

Q_{95}, 95 percent exceedance flow; RDI, Reconnaissance Drought Index; SMD, Soil Moisture Deficit; SPEI, Standardized Precipitation-Evapotranspiration Index; SPI, Standardized Precipitation Index.

normally controlled by statutory agencies with limited concern for social interaction (Bryan et al., 2019). In the United Kingdom, recent droughts have not escalated to full socio-economic droughts, which means that only those publics whose activities are directly affected by prolonged dry periods have been aware of these different (early) drought stages (e.g., gardeners, farmers, anglers, recreational water users). For many people, "the hosepipe ban" ["Temporary Use Ban" (TUB) in current terminology; e.g., Gavin et al., 2014] is generally the most significant, formally declared, consequence of United Kingdom droughts (Bell, 2009), and is a key focus of the water saving measures listed as Appendix 2 to the Water Resources (Scotland) Act 2013.

The public's role in determining water allocations is limited. Water resources interests are generally represented by water utilities, hydro operators and irrigators, as well as distilleries, quarry operators, and paper works. These practices are generally informed by quantitative characterization of water availability and demand, where the concept of thresholds is critical to the possible exercise of abstraction restrictions by a regulator. However, ensuring meaningful public participation in water resources planning is a growing concern in international research and practice, with all the challenges this brings including power and language issues (e.g., Cook et al., 2013). For example, public participation, as a contribution to River Basin Management Planning process, is required under Article 14 of the EU Water Framework Directive (2000/60/EC), applying to all European catchment areas. Researchers are already exploring issues and opportunities in how lay and specialist scientific knowledge come together in drought risk decision-making in specific national contexts (e.g., Dagel, 1997 with drought severity indices and perception in marginal settings). This includes, more recently, Solano-Hernandez et al. (2020) on convergence between satellite information and farmers' drought perception in the Patagonian rangelands of *Argentina*; and Nguyen and Nguyen (2020), comparing potential biases in measured extreme weather data with those in self-reported weather shocks from rural households in Vietnam. This poses questions about how different publics and other stakeholders in the temperate maritime United Kingdom perceive more hidden drought and its different thresholds, with the implications for their action to increase resilience. This concern for identifying "thresholds," as a bridging concept for interdisciplinary exploration within our research, provides valuable potential for science to learn from narrative approaches and meaning making (drawing on life experiences, oral histories, stories, diaries etc.), and for narrative to learn from science.

AIMS

Using an interdisciplinary approach that involved co-working between natural and social sciences, and arts and humanities, this paper investigates interactions between different types of knowledge (specialist science; local knowledge) in determining meaningful drought indices and thresholds in a maritime country perceived as wet. It takes as its case-study the agricultural catchment of the River Eden in Fife, east-central Scotland, United Kingdom. The paper asks how looking at drought from both scientific and narrative perspectives adds to fuller and deeper understanding than could be achieved by either in isolation. It aims:

1. To explore the concept of "drought thresholds" from scientific and narrative perspectives and their comparison, in the context of spatial and temporal variations in drought in the catchment.
2. To evaluate the perceived thresholds for drought impacts by different stakeholders across sectors and their connection, and how this maps against scientific indices and thresholds.
3. To explore the potential for a framework for science-narrative drought "threshold thinking," as a way of bridging different types of drought knowledge.
4. To reflect critically on how this focus on "threshold thinking" might inform the policy and practice of public/community involvement in local drought risk management, including communication and messaging about drought risk.

The Fife Eden catchment, Scotland was chosen as one of seven case-study catchments across different gradients (hydrological, socio-cultural) in the United Kingdom within the Drought Risk and You (Drought Risk and You; hereafter "DRY") project[1]. This selection was because of its long hydrometric record and low rainfall in a United Kingdom context, providing contrast with other dry catchments in eastern England (Blake and Ragab, 2014) and in terms of governance. Governance of water resource planning for public water supply in Scotland is the statutory responsibility of a publicly owned utility, Scottish Water, unlike in England where water services are provided by privatized utility companies.

BACKGROUND CONTEXTS

Here we briefly appraise the theme of "thresholds" within the research literature from hydrological science and social science perspectives.

Drought Indices and Thresholds: Science Perspectives

Indices and thresholds are commonly used tools within the earth and environmental sciences (e.g., in hydrological, ecological and landscape change; e.g., Sivakumar, 2005; Kelly, 2015). Such indices attempt to quantify a particular system variable of interest, often over a specified time window, while thresholds are particular points or levels in system response, beyond which the system enters an alternative mode of response. If the change in system mode of response is irreversible, the threshold can be considered a "tipping point." Many drought indices exist that

[1]dryproject.co.uk.

could potentially be used to identify different kinds of drought severities that might affect different sectors and particular groups of stakeholders, and be compared with their drought perception. However, it is recommended that stakeholders consult more than one index in order to form a well-founded assessment of conditions, given varying responses of individual indices and varying data requirements that may be an issue in real-time assessments (Morid et al., 2006). Among the available indices are the Standardized Precipitation Index (SPI; Paulo and Pereira, 2006), the Normalized Precipitation Index (NPI), and the Normalized Flow Index (NFI) (Scottish Environmental Protection Agency, 2020) and Reconnaissance Drought Index (RDI) (Tsakiris et al., 2007). RDI, which is the ratio of precipitation to potential evapotranspiration over a certain period, has broad implications in terms of drought risk assessment as it provides a robust indicator for describing meteorological, agricultural, hydrological and socio-economic drought. RDI (annual and summer) is calculated using potential evapotranspiration and gross rainfall, as in Tsakiris et al. (2007). If the output (losses) exceed the input (normally over a period of months or years), drier conditions and eventually drought would occur. This drought index is considered as more robust than, for example, the SPI, which is solely based on precipitation. Therefore, the advantage of applying RDI is that the index is calculated using the rainfall relationship to the evapotranspiration, which is itself partly a function of temperature. This drought index has been used in several academic studies (Zarch et al., 2015). Comparisons in the literature tend to focus more on differences in index performance and suitability to geographic regions (e.g., Jain et al., 2015) rather than focusing on the needs of particular groups of users.

Gosling et al. (2012) validated robust indices and identified severity thresholds for appraising drought risk situations in Scotland by testing the efficacy of these indices using case studies from the Scottish drought catalog 1976, 1984, 2003 and 2010. This determined the most appropriate selected indices, index durations and severity thresholds to best capture past drought events to support decision-making (see also Zaidman et al., 2012). Hence NPI and NFI are used by Scottish Environmental Protection Agency (2020)[2]), to improve planning and response during "prolonged dry periods" (p18). Other indices routinely used to capture low river flows include Q_{95} (the river flow exceeded 95 percent of the time), "a significant low flow parameter particularly relevant in the assessment of river water quality consent conditions."[3]

For major water users such as public water supply undertakings, responses are triggered by threshold crossings using a control curve (Thorne et al., 2003). For any particular supply system, threshold values of water storage are identified on a seasonal basis, and are used to trigger responses ranging from monitoring, through leakage management and use of additional supplies to demand management and applications to reduce environmental flows. Operation of different sources, as parts of a linked network, makes for greater operational flexibility and system resilience. Thresholds are also used by environmental regulators in the identification and management of low flows. SEPA uses a 6-class water scarcity scale for operational management, with responses ranging from increased monitoring and planning through to limiting abstraction rates, protecting key water supplies and the use of alternative water sources (Scottish Environmental Protection Agency, 2020).

Social Science Aspects of Drought as a System: Threshold Thinking

Here we briefly consider applications of the concept of thresholds in two inter-related areas: risk perception and hydro-social systems.

Thresholds (1): While systems parameters, quantified through indices and critical thresholds, might be more embedded in the physical sciences, the concept of thresholds, or "the level or point at which something starts to be experienced," is well established in perceptual and behavioral sciences (Grothmann and Patt, 2005; Joseph et al., 2015). Such thresholds influence relationships between event memory, lay knowledge and resilience (McEwen et al., 2016) and guide peoples' decision-making (e.g., risk perception or awareness, coping appraisal and action). Models of people's perceptions linked to index thresholds are also increasing in popularity in environmental studies (of climate change, wildfires, flooding; e.g., Papagiannaki et al., 2019). These thresholds are typically based on "expectancy value" theories, which include frameworks that are used to explore relationships between people's attitudes and their choice and adoption of environmental behaviors (Rogers, 1975). Generally, in these theories, a coping appraisal toward a specific environmental threat (e.g., flooding, drought, climate change etc.) only starts if a specific cognitive threshold of threat appraisal is exceeded (Schwarzer, 1992). Furthermore, the coping appraisal must also cross a certain threshold to influence protective decision-making (Maddux and Rogers, 1983; Bubeck et al., 2013). Ultimately, the decision to implement a coping measure in response to a threat or hazard, such as drought, is highly dependent on not only the perceived risk of the degree of negative consequences, but also the perceived efficacy of, and costs associated with, the measures in abating or reducing negative consequences. These studies are well established in flooding with application of various theories such as Protective Action Decision Model (PADM) (Lindell and Perry, 1993) and Protection Motivation Theory (PMT) (Grothmann and Reusswig, 2006; Zaalberg et al., 2009; Poussin et al., 2012; Bubeck et al., 2013).

Studies in drought management have also seen emergence of application of similar methods (e.g., Mankad et al., 2013; Gebrehiwot and Van der Veen, 2015; Bryan et al., 2019). Mankad et al.'s study (2013) of Queensland, Australia households found that thresholds in perceptions of threat and perceived effectiveness and costs of

[2]SPI and NPI are broadly similar, just using slightly different assumptions about rainfall distribution to express deviation from normal. An equivalent for NFI (Normalized Flow Index) would be SSI (Standardized Streamflow Index). RDI is more focused on soil moisture/agriculture as it looks at ratio of rainfall to *PE*. SPI is more well-known than SEPA's NPI.

[3]https://nrfa.ceh.ac.uk/derived-flow-statistics

protective behaviors accounted for a significant proportion of explanatory power in participants' intentions to engage in adaptive behavior toward water shortages. Both studies by Gebrehiwot and Van der Veen (2015; rural Ethiopian farmers) and Bryan et al. (2019; south west England households) found that there were different decision stages toward implementing drought coping actions based on a combination of thresholds in perceived vulnerability, severity of consequences, self-efficacy, and response efficacy. Perceptual thresholds and decision thresholds of drought may vary with a complexity of socio-cultural and economic factors, given variable vulnerabilities and impacts, with scale of analysis and sectoral focus potentially masking or highlighting impact. They can also vary with people's memory and thresholds of awareness.

Thresholds (2): Interdisciplinary, systems thinking about drought impacts requires understanding of the interface between hydrological, social and technical systems, the physical and social thresholds, and integration of this knowledge. Swyngedouw (2009) "hydrosocial *cycle*" foregrounds the local circulation of water, knowledge, and power, deliberately focusing on water's social and political nature (see Linton and Budds, 2014). Looking at this concept and the interactions between nested systems at varied spatio-temporal scales, through the lens of "thresholds," we see this framing used in socio-hydrological modeling to support resilience (Fernald et al., 2015; Blair and Buytaert, 2016). For example, Fernald et al. (2015) co-worked with United States communities to translate the multidisciplinary dimensions of hydrological and social systems using causal loop diagrams. These in turn comprised an evidence base for system dynamics modeling turning narratives into future scenarios to help identify thresholds and tipping points for sustainable practices. Blair and Buytaert (2016, p452) argue that significant learning can occur from "the manner in which characteristics such as feedback loops, thresholds, time-lags, emergence and heterogeneity" are dealt with in socio-ecological studies, citing Liu et al. (2007).

These two approaches represent different ways of identifying indicators and thresholds in the social sciences. They have been applied in drought and water scarcity studies to explore threshold thinking in different ways than the technologically sophisticated analyses applied in hydrology. These challenges of definition highlight the need for interdisciplinary systems-based research framing around thresholds and feedback in drought risk management.

RESEARCH SETTING

The Fife Eden, a 300 km^2 rural catchment in east-central Scotland, has an average annual rainfall of 800 mm (**Figure 1**). The highest hills rise to 520 m above sea level and are used for sheep grazing and some forestry. Most of the 40 km length of the river flows through the flat Howe of Fife lowland, underlain by fluvio-glacial sands and gravels and supporting deep, fertile soils.

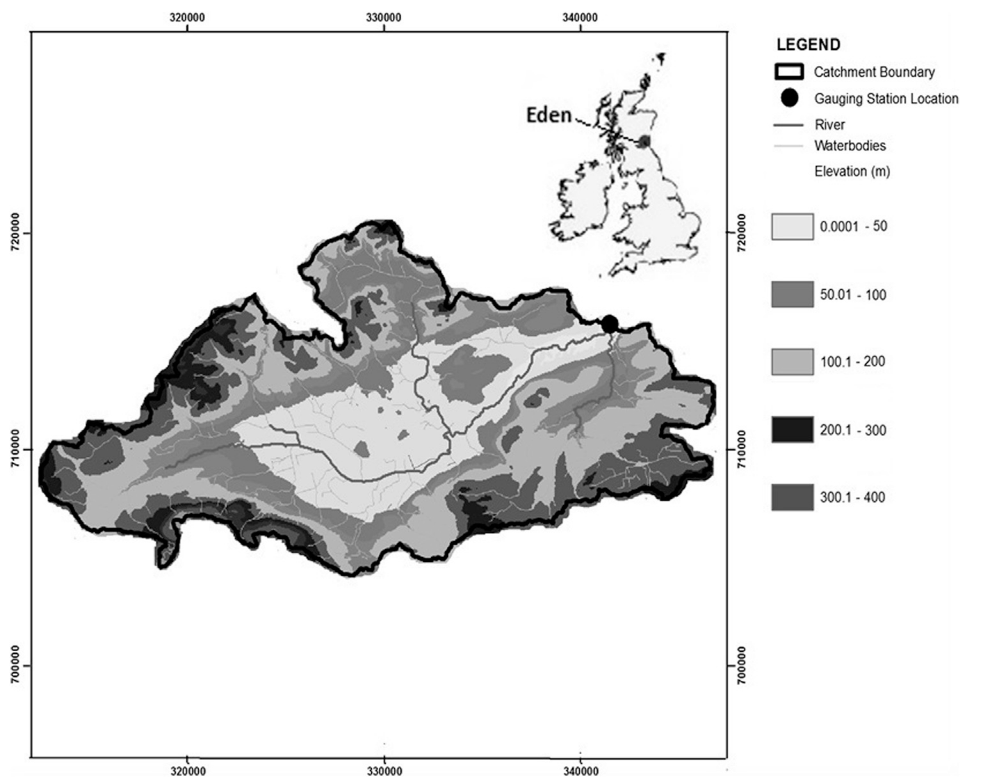

FIGURE 1 | Catchment location, stream route, gauging station position, and elevation. Source: catchment boundaries (Morris et al., 1990; Morris and Flavin, 1994). Elevation data courtesy of Intermap Technologies Inc. (Nextmap 50 m Digital Terrain Model).

The area was incrementally drained between the 17th and 19th centuries, including the drainage of a former lake, Rossie Loch. Agriculture in the Howe today is among the most productive in Scotland, supporting barley, oats, potatoes, vegetables and soft fruits.

The Eden river flow has been measured continuously at Kemback, 2.5 km from the tidal limit, since 1967. It rises and falls more slowly than neighboring rivers, with 63% of annual flow being delayed flow (National River Flow Archive, 2020) thought to originate mostly in a sandstone aquifer and in the valley sediments (Ó Dochartaigh, 2004). This means the river maintains its flow in extended dry periods, and provides security of water supply to water users sited along its banks. The main town, Cupar, sits on the banks of the lower Eden, with a population of 8,506 (2011 census). 21.8% of the population are aged 65+ years, compared with a Scottish average of 19.1% (National Records of Scotland, 2020a). In Fife as a whole, the 65–74 age group is the fastest-growing, with 40.6% increase from 1998 to 2019 (National Records of Scotland, 2020b). A new strategic development of 1,400 homes is included in the local structure plan (Tayplan, undated). Public water supplies originate from surface reservoirs in the Lomond Hills within the catchment, and also 15 km to the west in the Glendevon regional water supply scheme.

Agriculture is the largest water abstraction beyond public supply. Potatoes and root vegetables, as drought sensitive crops (Obidiegwu et al., 2015), in particular need irrigation to provide the required quality for buyers, but these and vegetables and soft fruits all need irrigation for yield. Grass, used as a forage crop, is also occasionally irrigated on some farms. Grass growth can be severely restricted during long dry periods, making it difficult to maintain good grazing and also conserve silage and hay for the winter months. Water shortage can be an issue in the catchment, but very much depends on location within the area.

Water abstraction in Scotland is governed by the Water Environment and Water Services (Scotland) Act 2003 (as amended) and the Water Resources (Scotland) Act 2013, the latter introducing "water shortage orders" in place of the drought orders which continue to apply in England. Under the legislation, the Scottish Environment Protection Agency (SEPA) is empowered to restrict abstractions in times of water shortage, and implements a system of river basin management planning in compliance with the European Water Framework Directive. These powers were introduced to Scotland 40 years after the Water Resources Act became law for England and Wales in 1963, giving rise to the impression that the need for water management in Scotland was much less than in England.

Under the licensing regime following the 2003 Act [particularly the Water Environment (Controlled Activities) (Scotland) Regulations 2005, as amended], farmers working on high value land became incentivized to build water storage lagoons (off-line ponds)[4] as a means of achieving security of supply and potentially large financial returns on investment, while avoiding abstraction controls in drought periods. These lagoons are subject to licensing under the same regulations to ensure best practice and protect the water environment.

The most serious water supply drought in the Eden catchment occurred in 1984 (Scottish Development Department, 1986). The section on Fife (4.6) mentions a hosepipe ban in August and a drought order for Glendevon. The report also refers to Clatto reservoir in the Eden catchment, with its outflow flowing eventually into the Ceres Burn, which joins the Eden near Kemback. However, Clatto Reservoir, and Cameron Reservoir (also referred to) are no longer operational sources (Bramwell, pers. comm.).

RESEARCH DESIGN AND METHODOLOGY

The four-year, interdisciplinary DRY (Drought Risk and You) project aimed to support improved the evidence-base to support better catchment-based drought risk decision-making in the United Kingdom. The team involved drought risk modellers, ecologists and agronomists working with specialists in narrative methods from the arts, humanities and social sciences. DRY's research design was focused around a series of creative experiments that brought together science and narrative iteratively into the same frame (McEwen and Blake, 2020). DRY considered six sectors (business, agriculture, natural environment, built environment, health and wellbeing, public/community) across seven case-study river catchments, the most northerly being the Fife Eden, Scotland described here. The notion of a "catchment" was construed flexibly to embrace both hydrological flows but also people who move across the catchment boundary for work and leisure. The science involved an open reconstruction of the past drought series for the Eden at Kemback flow gauge, setting up and calibrating/validating a hydrological model of the catchment, using DiCaSM—a spatially distributed catchment system hydrology model (Afzal and Ragab, 2020). The model simulates the key components of the terrestrial hydrological cycle (rainfall, evapotranspiration, changes in soil moisture, groundwater and rivers flows) within a catchment using a 1 km regular grid and daily time-step. A detailed description of the drought risk modeling approach involving past reconstruction and future scenario-ing is provided in Afzal and Ragab (2020). This specialist scientific information, in the form of graphs, maps and catchment-scale animations of specific drought indices like SPI and RDI (**Table 1**), was iteratively explored with local stakeholders. This was carried out alongside sharing UKCP09 climate change projections (Murphy et al., 2009) for the 25 km grid square centered on the Eden catchment, providing potential future seasonal average precipitation and temperature data (**Figure 2**). DRY's processes also involved co-developing drought climate and land use change scenarios with local and regional stakeholders (Liguori et al., 2021).

This scientific evidence was shared in diverse settings for narrative engagement, with the aim of gathering "science-stimulated narratives" across different stakeholders and sectors. The narrative approach used combined insights from

[4]https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/agri-environment-climate-scheme/management-options-and-capital-items/water-use-efficiency—irrigation-lagoon/

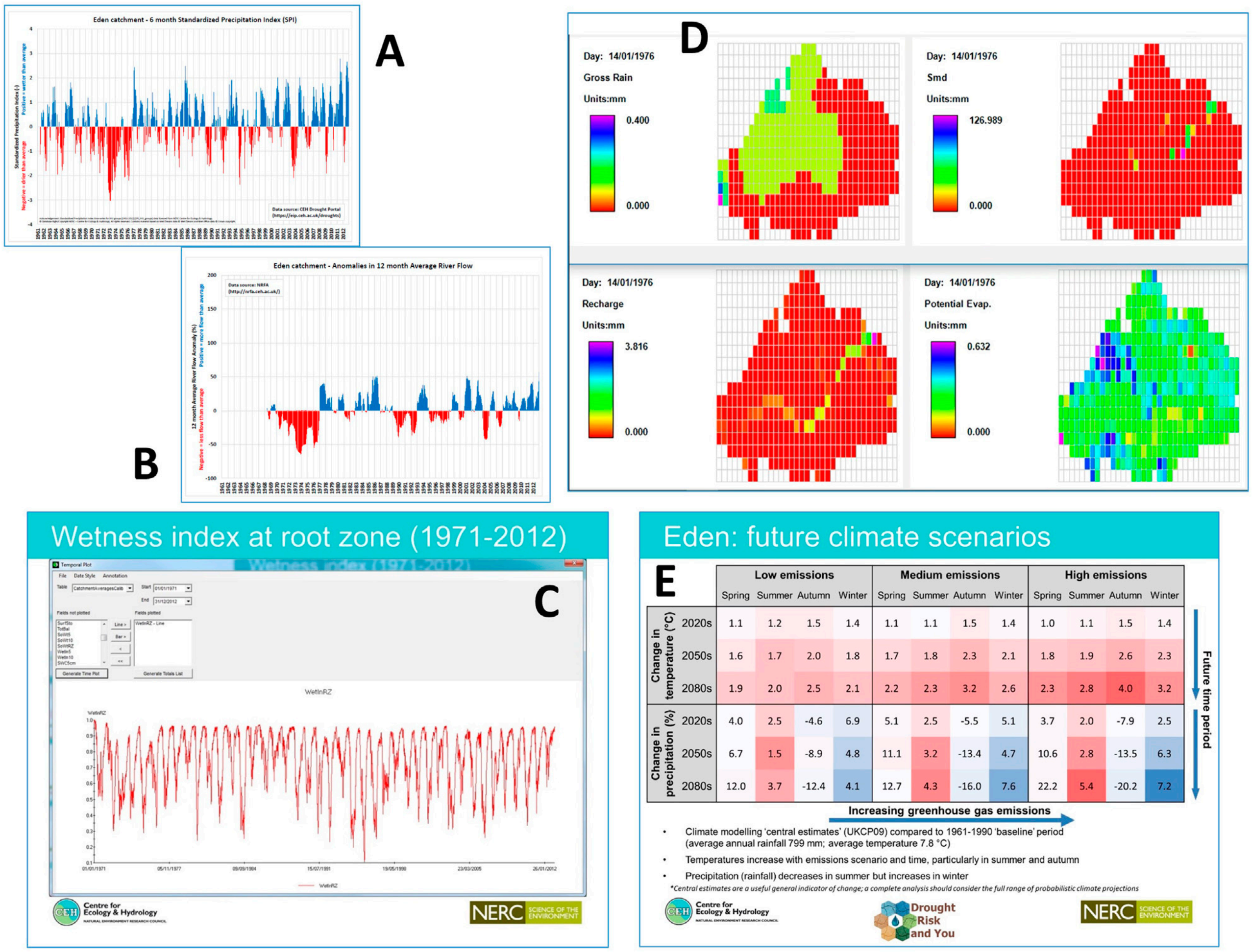

FIGURE 2 | Indicative composite of the scientific graphs and figures used in the various stakeholder engagement activities within the Eden catchment (for other examples, see Afzal and Ragab, 2020). **(A)** Time-series rainfall anomaly plot (SPI; 6 months); **(B)** Time-series—average river flow anomaly plot **(C)** Wetness index times-series generated by DiCaSM **(D)** Animation of drought indices through 1976 as front end to DiCaSM; **(E)** Example distillation of bite-sized science – UKCP09 scenarios.

different disciplinary ways of narrative working and storying practice (Lewis, 2011; Bourbonnais and Michaud, 2018; Liguori et al., 2021) and participatory methods (McEwen et al., 2016). This way of working recognized that within the United Kingdom, it was challenging to get local people to talk about local drought risk and experience, with the frequent need for researchers to go in more obliquely around wider water behaviors and environment (see Liguori et al., 2021). This issue was particularly acute in Scotland, a country perceived as wet. To meet this storying challenge, DRY developed an emergent suite of Adaptive Participatory Storytelling Approaches for storying work tailored to different settings. These accommodated, for example, different numbers of participants, lengths of engagement, depth of science shared during the research process, with self-selection of participants.

Within DRY's work in the Eden catchment, settings and multi-methods for narrative data collection are captured in **Figure 3**. These involved: narrative interviews (11), a focus group with local government (1), a farmer-facing participatory workshop (1), themed public river walks (2), Local Catchment Advisory Group meetings (6) and "off-road" engagements with the public at the Fife Agricultural Show, a local community events (2), a participatory visit to DRY's droughted grassland experiments and a walking interview by the River Eden. "Off road" engagements allowed the environment to act as an "interview-prop" to scaffold remembering *in situ* with better ease of recall of unique local knowledge (Slim et al., 2006). This prompted interviewees to talk in ways that might not occur in formal settings when trying to gain insights into a hidden risk like drought. These different approaches were used to collect and record narrative reflections, some of which were identified for production as "micronarratives" (MN; short audio reflections) and co-produced digital stories (DS; 2–3 min audio with images selected by the author (Meadows, 2003; Holmes and McEwen, 2020). These MN/DS are shared within the DRY Story Bank (https://dryutility.info/story-bank/).

The research process underwent ethics approval for work with human participants at the lead research institution. All narrative

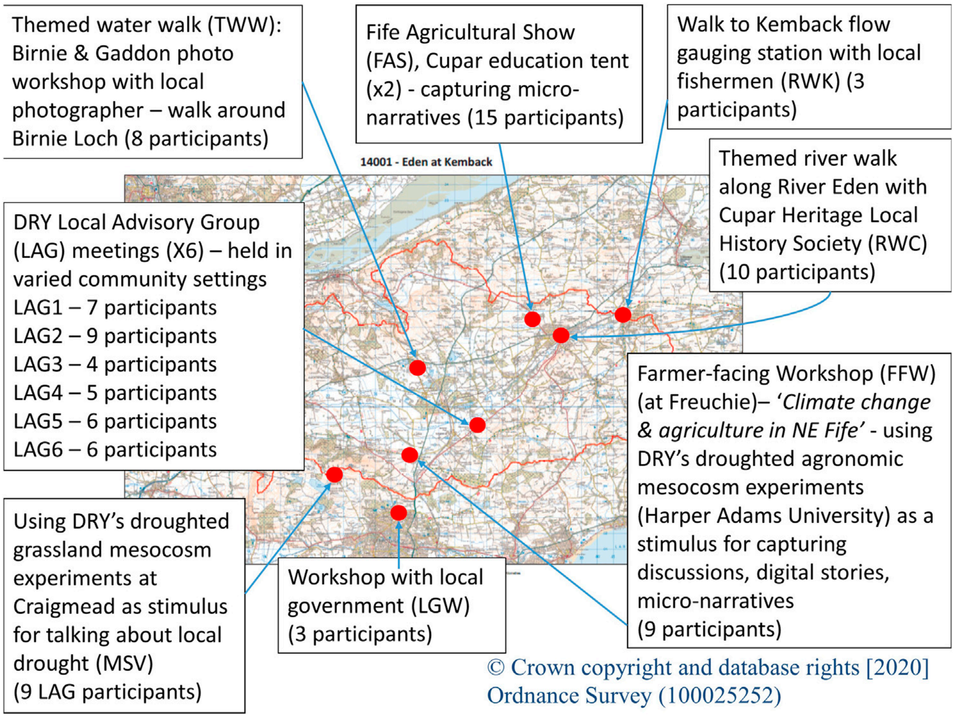

FIGURE 3 | Map of the participatory science-narrative approaches and activities undertaken by DRY, and their location within the Eden catchment.

types were recorded and transcribed for analysis. Analysis of the interviews, digital stories and micro-narratives involved thematic coding using QSR-Nvivo to conceptualize, classify, categorize, and identify emergent themes relating to the aims and scope of the paper. Further analysis included identifying sub-themes within themes to provide further in-depth understanding of the narratives and establish linkages with the aims. Additionally, thematic mapping was undertaken to highlight and triangulate these key themes and sub-themes within different sectors. This was followed by a mapping of the connections and trade-offs across sectors, and identification of thresholds, tipping points and trade-offs within past (and future) narratives.

RESULTS

Past Drought and Drought Thresholds: What the Science Says

Changes in precipitation and potential evapotranspiration (which increase with increasing temperature, along with decreasing humidity, increasing wind speed, and increasing solar radiation) over time, control soil moisture conditions and hence groundwater recharge and streamflow in a catchment. As soil moisture decreases, the actual evaporation will fall below the potential rate. In this study, drought severity was analyzed using past and anticipated changes in precipitation and evaporation within the Eden catchment. Temporal changes in precipitation over the catchment, revealed a significant decrease ($p < 0.05$) in precipitation for the period 1961–1976, and a slight increase in precipitation overall for the 1961–2012 studied period. During the 1961–1976 period, a decrease in precipitation of over 16 mm/year was found, and after 1976 rainfall slightly increased by 2 mm/year which was statistically non-significant. During the 1961–1975 period, potential water losses due to the potential evaporation were significantly higher than the 1976–2012 period (**Figure 4**). The effect of precipitation decrease and increase in evaporation for the 1961–1975 period can be seen where the RDI, calculated using potential evapotranspiration, and gross rainfall, revealed two extreme drought events when RDI was below -2 in 1973 and 1976 (highlighted in red; **Figure 5**). Drier than average spells (RDI less than -1) were also observed in 1974, 1976, 1989, 1996, and 2003. It was also noticed that based on the RDI, the total percentage of the wet years equaled the total percentage of dry years, but extreme dry events occurred twice as often as extreme wet years (RDI >2 once in 1985, extreme wet year), RDI < -2 (twice, in red, extreme dry)) (see Azfal and Ragab, 2020). **Table 2** shows a list of droughts (1961–2012) in the Eden catchment from scientific evidence, based on scales and indices (here annual and summer RDI). Different indices provide different pictures; the summer RDI index picks out the short-term 1984 drought, while annual RDI does not.

Thresholds for Drought: What Local Stories say

Our story narratives across all the various engagement events/ activities revealed that drought memories in the Eden

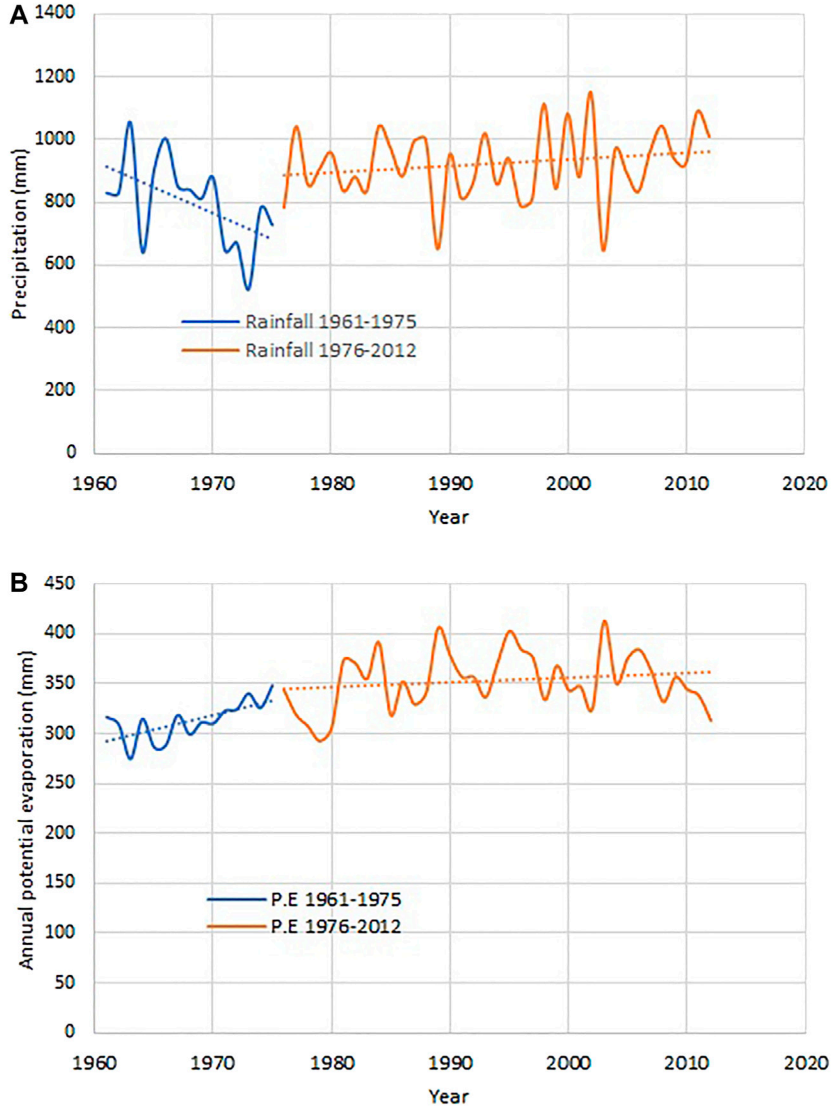

FIGURE 4 | (A) Average annual precipitation; and **(B)** average daily potential evaporation over the Eden catchment for pre-1976 for the period (1961–1975), and post-1976 periods (1976–2012).

catchment exhibit some measure of "fuzziness" over time, especially over decades (**Figure 6**). This fuzziness is often manifest in the precise time when events occurred, and less so where past impacts are concerned. Hence, we find that for high profile nationwide droughts like 1976, narratives often depicted similar impacts across DRY's catchments, for example, potato farmers remember that potato yield and quality were significantly reduced locally and nationally. Interestingly, although several decades ago, the 1976 drought was the "event" where the largest number of people (11 who specifically mentioned 1976) across various narrative settings and sectors could remember a distinct year. This corresponds with both the SPI and RDI data. It is noteworthy, however, that over the baseline period, both indices showed the lowest value in 1973, but drought memories started to present in 1975 and 1976. This could be an indicator of the need for two or more successive dry winters to impact water supplies, or that the memories are collective due to the persistent national media influence of 1976. More recent dry periods, such as spring 2017 and summer 2018, were also discussed more and with less temporal fuzziness as these memories were more recent (**Figures 6**, **7**).

Local residents in the Eden catchment and wider Fife area had very varied views about what drought meant for them and their local area, and how some of the indicators in their own sector of interest are identified and quantified. Although there was a strong memory of the 1976 drought among older narrative participants in general and members of certain sectors (e.g., agriculture), drought was perceived as a rare and speculative hazard from a Scottish perspective, and was

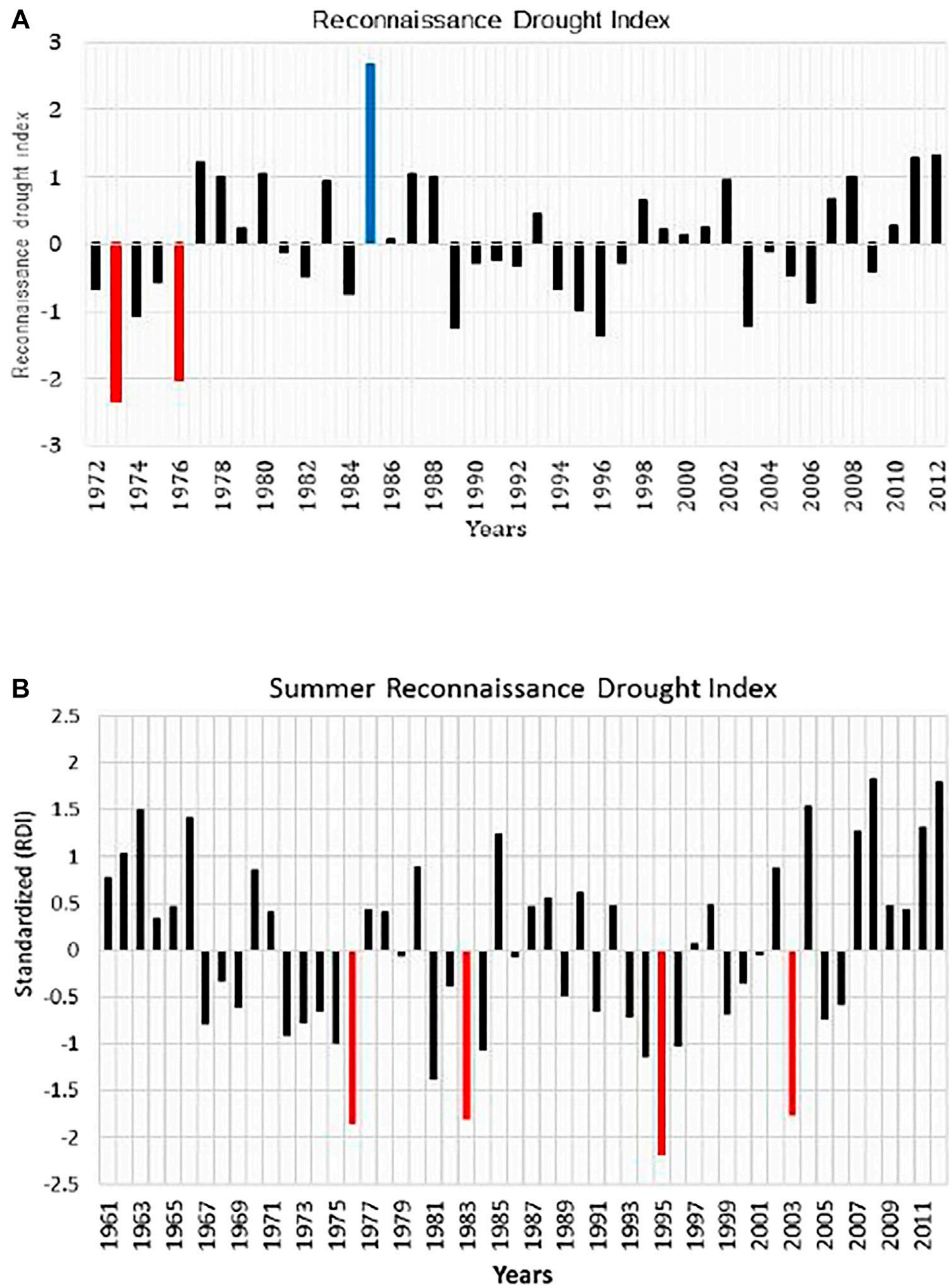

FIGURE 5 | (A) Annual reconnaissance drought index calculated using the potential evapotranspiration with gross rainfall (RDI); **(B)** Summer reconnaissance drought index calculated using the potential evapotranspiration with gross rainfall (Summer RDI). For both plots, the blue/red bars represent extreme wet and extreme dry years.

not necessarily on most publics' radar throughout the various narrative settings. Drought was also frequently "othered"- often seen as a problem for African countries, Australia, United States and even England. Some narratives also revealed that participants thought the catchment was getting wetter rather than drier and hence local flooding (rather than drought) was mentioned in various narrative settings. This belief of the catchment becoming wetter appears to correspond to the scientific findings above (though statistically non-significant).

When the idea of drought in Scotland was discussed as a local community issue, many participants tended in the rehearsal of memory to associate drought with warm, sunny weather illustrating their memories of summer droughts (see Participant #4 in **Figure 8**). Community members generally had nostalgic positive memories of the 1976 drought:

TABLE 2 | Most notable droughts in the Eden catchment from 1961 to 2012, based on (A) annual RDI; (B) summer RDI.

No.	Year of drought	Severity of drought	Annual RDI	No.	Year	Summer RDI
1	1973	Extreme	−2.327	**1**	1995	−2.178
2	1976	Extreme	−2.024	**2**	1976	−1.841
3	1996	Moderate	−1.342	**3**	1983	−1.795
4	1989	Moderate	−1.233	**4**	2003	−1.754
5	2003	Moderate	−1.214	**5**	1981	−1.374
6	1974	Moderate	−1.065	**6**	1994	−1.134
7	1995	Minor	−0.976	**7**	1984	−1.055
8	2006	Minor	−0.872	**8**	1996	−1.026
9	1984	Minor	−0.728	**9**	1975	−0.983
10	1994	Minor	−0.678	**10**	1972	−0.905
11	1975	Minor	−0.566	**11**	1967	−0.783
12	1982	Minor	−0.467	**12**	1973	−0.771
13	2005	Minor	−0.458	**13**	2005	−0.735
14	2009	Minor	−0.410	**14**	1993	−0.705
15	1992	Minor	−0.314	**15**	1999	−0.677
16	1990	Minor	−0.274	**16**	1991	−0.652
17	1997	Minor	−0.271	**17**	1974	−0.647
18	1991	Minor	−0.222	**18**	1969	−0.608
19	1981	Minor	−0.119	**19**	2006	−0.575
20	2004	Minor	−0.103	**20**	1989	−0.481

"*I grew up in the sixties, and in the seventies I remember dry wonderful warm summers, every day was a lovely hot day.*" (Local resident, Participant #23 - FAS1).

Others recalled hosepipe bans (TUBs) (**Figures 9**, **10**) and the environmental impacts of the drought, such as brown grass in areas usually known for their lush green scenes, low flowing rivers or burns and lochs, and lack of access to certain outdoor activities. Hence drought could be seen as a hindrance to regular or desired activities but not necessarily a major hazard from a Scottish point of view:

"*If you said there's a drought, I would imagine Sudan, in Africa, or Ethiopia. That where crops are dying. Livestock's dying. That's what I imagine drought as. You know, life changing sort of. Not it's a bit dusty when we're lifting potatoes or the yields not as good as we had last year. That's an inconvenience.*" (Local farmer, Participant #14 - INT).

Nonetheless, some narratives did indicate that there is an awareness of drought and dry weather conditions within and around the catchment. Some revealed that perceptual drought thresholds often varied between sectors, and also appeared to depend on individual stakeholders and their local baseline conditions (e.g., specific soil type or location of their abstraction for irrigation along the main Eden) prior to a drought. Based on the narratives gathered, agricultural and environmental stakeholders appeared to illustrate the most noticeable thresholds from past droughts compared to business and community stakeholders, which implies that historically droughts in the Eden rarely prolong to the stage of socio-economic drought. Some west coast island communities on private water supply in Scotland are arguably more vulnerable, with records of distillery shut-downs in 2013 (see Historic Droughts Portal[5]). Additionally, there were often stories of conflicts across sectors in droughts which impact certain thresholds. In the subsections below, we will present some of the perceived thresholds of drought across sectors within the transitions between different drought stages.

Transition: Meteorological – Soil Moisture Drought

Several participants in different narrative settings (e.g., LAGs or interviews) indicated that the spring season can sometimes be accompanied by dry, windy conditions in the Eden catchment, where meteorological variables, such as precipitation and wind speeds, are below and above average respectively. When these conditions combine with spring tillage, soil moisture is reduced, thereby illustrating a type of meteorological-soil moisture drought, with systemic effects. With soil moisture loss and strong drying winds, sandy soils become easily vulnerable to erosion. Wind-blown dust then becomes a common issue in the catchment during these periods. We sometimes heard about this dry weather phenomena being referred to as "stoor" and "drouthy weather" in the local vernacular. These events were seen as particularly important for the catchment as farmlands were often exposed during spring due to tilling in preparation for summer crops. Participants #3 and #21 tell us more about this:

"*I think what causes it is if you have dry-ish but windy conditions. It has to be quite windy and usually from the west, which is not uncommon round here. Usually around March time when the fields have been worked but the vegetation hasn't really grown up yet so there is a lot of bare soil. Sometimes it can be triggered if they are doing something like running a tractor across to roll it, particularly rolling the ground before things are sown or just after. What that does is send up clouds of dust into the air that blow down the Howe of Fife over the village of Ladybank usually and sometimes getting toward Springfield and down that way. It can be really quite dense .... It has an impact on transport sometimes because I have seen roads blocked by dust that has blown into drifts across the road .... It impacts on people just living down there, I wouldn't be very happy with dust blowing all the time.*" (Conservation volunteer, Participant #3 - INT).

"At certain points in the year, there's quite a light soil in the area, particularly in the area known as the Howe of Fife and it's not unknown to have sandstorms, dust storms, because of the light soil being blown, in high winds, across the fields, into roads, sort of darkening the passage for drivers." (Local resident, Participant #21 – FAS1).

This wind-blown dust phenomenon only impacts some farms and communities based on the soil type in a particular part of the catchment, with light sandy soils in the low-lying basin area of the Howe of Fife, known locally as "the Fife Dustbowl," as mentioned by Participant #3. Here we see a threshold of likelihood of impact differing depending on location and baseline soil conditions, highlighting spatial differences in the drought resilience of soils. There are therefore differences in experience: for some people there is a source of nuisance (e.g., affecting the outdoor drying of laundry), a threat to driving safety, or a risk to health (for persons with a respiratory illness), while for others in a scientific or farming context, there is a threat to agricultural

[5]https://historicdroughts.ceh.ac.uk/content/drought-tools

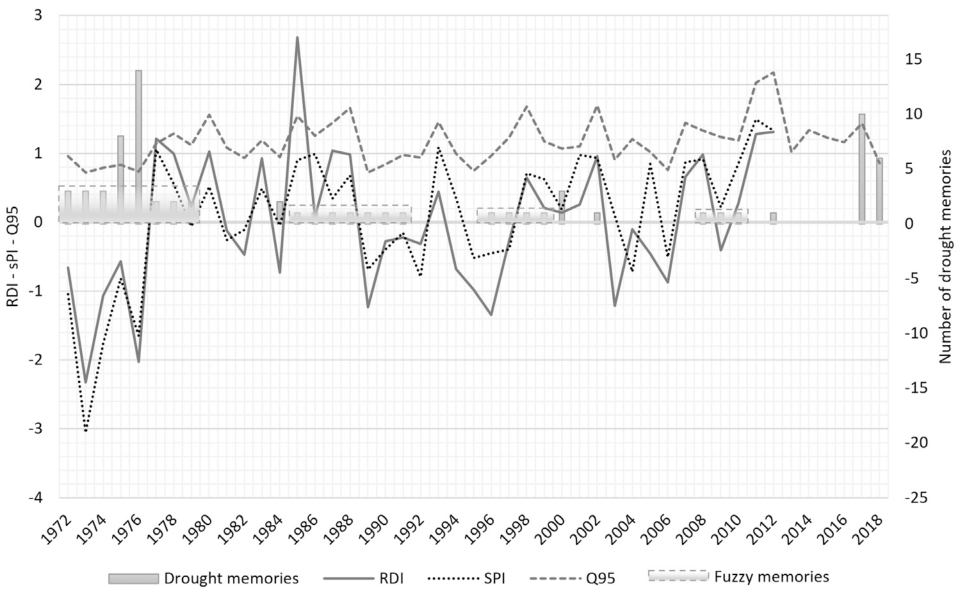

FIGURE 6 | Drought memory timelines overlaid with RDI, SPI and Q_{95} data (1972–2012). Q_{95} data were available up to 2018.

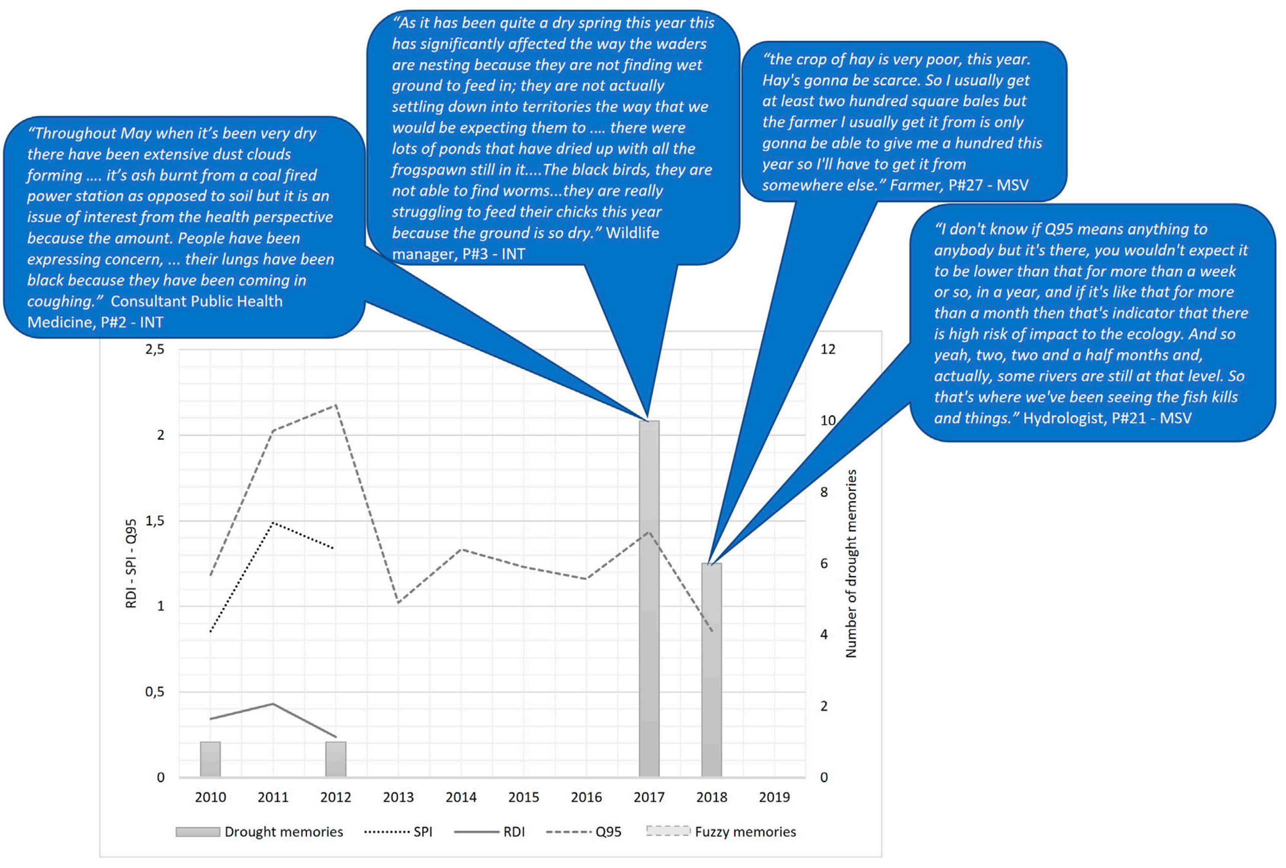

FIGURE 7 | Drought memories overlaid with RDI, SPI and Q_{95} data for the decade 2010 to 2019. RDI and SPI data are only available to 2012. Q_{95} data are used here to provide an indicator of local river levels for comparison with narratives.

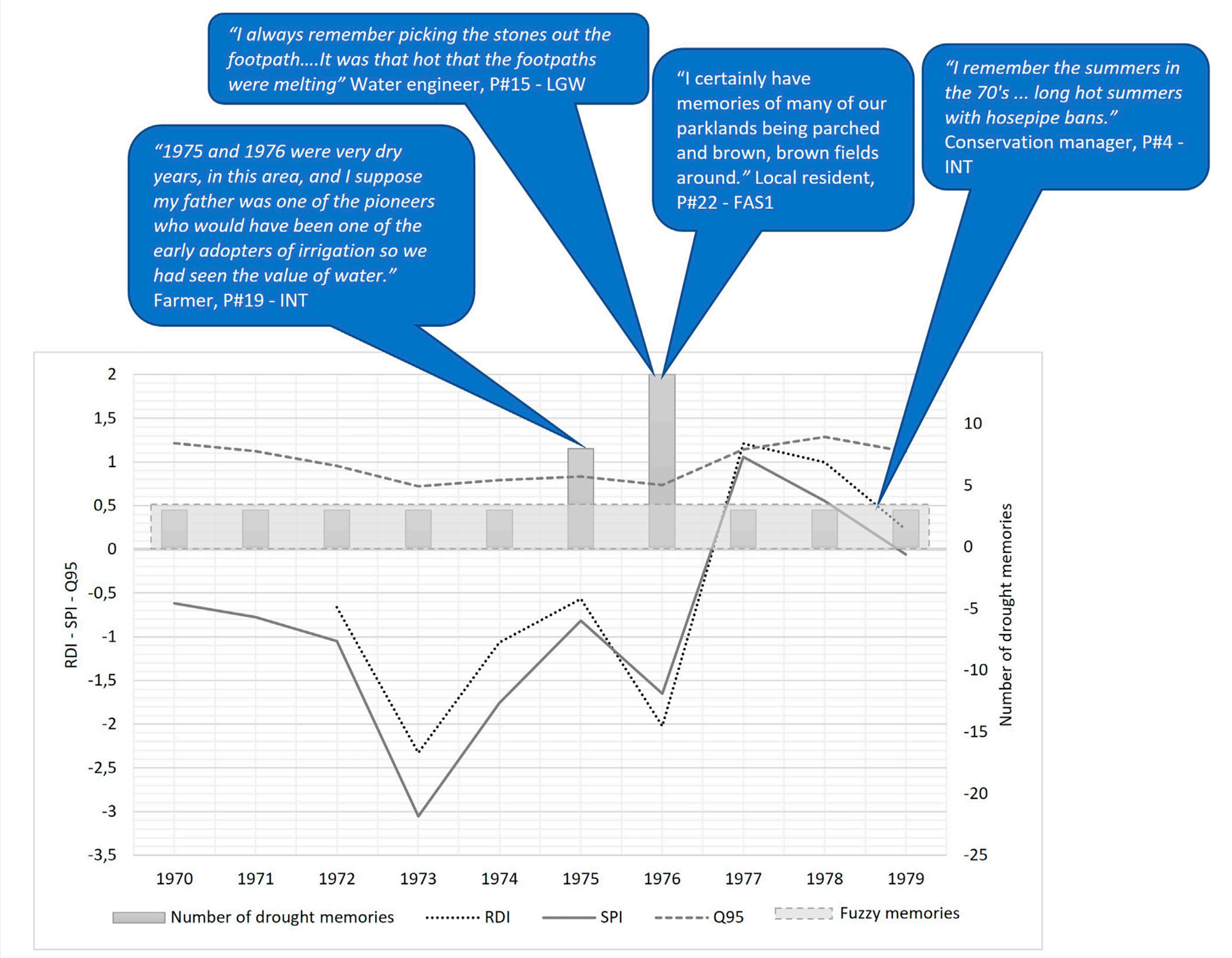

FIGURE 8 | Drought memories overlaid on SPI, RDI and Q_{95} data for the decade 1970 to 1979.

sustainability owing to soil loss. It would be difficult to identify these types of thresholds to impact with only the physical parameters used in SPI or RDI.

Another compelling story of seasonal wind-blown dust thresholds was shared in stories of spring 2017 that led to the "Fife ash clouds." This involved blowing of coal fly-ash from an industrial property ca. 5 km from the Eden catchment – dust that was a major concern for local residents who feared resulting health effects (**Figure 7**). Again, the threshold of impact (to health in this case) may be reflected by prevailing baseline conditions, such as the levels of exposure to the dust clouds (linked to location and activities) or underlying health conditions of an individual, as we heard from Participant #2 below:

"*The impacts are likely to be short term health impacts in terms of causing coughing or eyes watering .... but if you've got pre-existing illness it can make things worse in terms of provoking or worsening cardiovascular or respiratory illness.*" (Health professional, Participant #2 - INT).

Although we did not have SPI and RDI data for the 2010s, this event did not correspond with a low Q_{95} value (<1) (**Figure 7**). This signals that the conditions were probably short term and possibly at the early stages of drought. The presence of wind-blown dust is therefore potentially one of the early indicators of drought onset in this catchment.

Transition: Agricultural and Hydrological Drought

The extreme drought in 1975/1976, and successive dry winters, impacted both agriculture and river/lake environments, not just in the Eden catchment but throughout the United Kingdom (Doornkamp et al., 1980), marking the transition between an agricultural and hydrological drought. This drought has been attributed to lack of replenishment of major water bodies following two or more successive dry winter seasons throughout the United Kingdom where reservoirs and aquifers would normally be replenished. In Scotland, and particularly the Eden catchment, even with the reduced rainfalls, rivers were still flowing, unlike in parts of England where rivers were dry. From

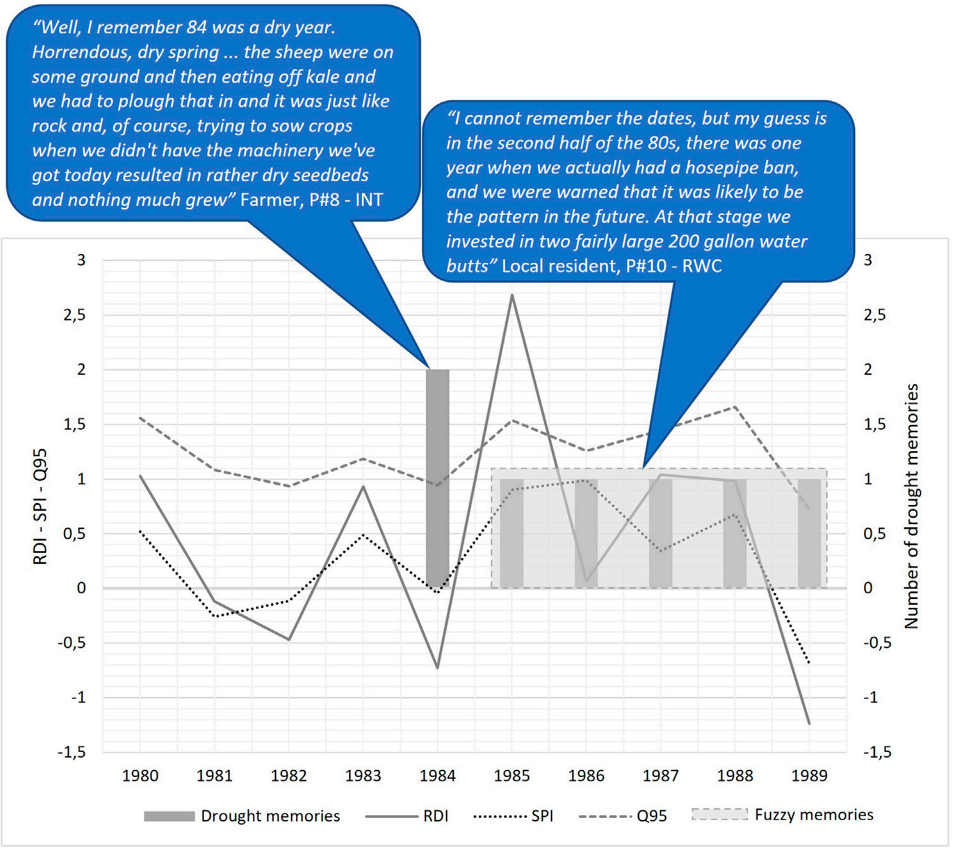

FIGURE 9 | Drought memories overlaid on SPI, RDI and Q_{95} data for the decade 1980 to 1989.

Figure 8, we can see that participants recalled the drought occurring somewhere between 1975 and 1976, corresponding with a period of fluctuating low SPI, RDI (<-0.1) and Q_{95} values (<1). Other participants' memory of the year of the drought is "fuzzy" and approximate (e.g., "*sometime in the 1970s*").

However, central to farmers' memories was the drought's impact on potato yield, quality and price, and its eventual influence on irrigation practices that now define root vegetable farming within the catchment.

The case of potato irrigation was a dominant theme encountered throughout the various narrative settings applied in this and other DRY catchments e.g., in the East and Southwest of England. Due to the low rainfalls experienced during this period, the potato harvest fell far below normal expectations. Only a few potato farmers in the Eden catchment were already using irrigation technologies before the 1976 drought and as a result, were able to produce potatoes at the appropriate standard and quantity in a period of high national demand and shortage. This provided them with great financial gains as the demand-supply balance shifted with the progressing drought. Therefore although rainfall was limited in the catchment, water was still flowing in rivers—beneficial for farmers with irrigation technology. Therefore, unlike farmers elsewhere, with little or no access to water, a few Eden catchment farmers with the appropriate technology were able to make use of the little water available in watercourses to increase productivity. This drought event acted as a tipping point for subsequent expansion in use of irrigation equipment in vegetable farming in the Eden catchment to improve both quality and yield. This situation also triggered a major national market change in potato farming. Although farmers like participant #8 (INT) expected a similar situation in a drought today, the financial thresholds met by farmers then, are not expected in today's market as discussed by participant #19 below.

"*Well I suppose … it's kind of legendary now. Especially 1976. Potato prices were extremely high that year and it was basically because there was a shortage and there wasn't that many people that had the capability to irrigate …. those who had potatoes made a lot of money, in 1976. And that was really because the country was shot. We probably haven't seen anything like that, ever since, to such an extent. We've seen potato prices climb but, when you do the maths on it, you know, today, that price, and they were getting 300 pounds a tonne then, that price, today, would need to be about 1,200 pounds a tonne …. We're nowhere near 1976.*" (Farmer, participant #19 INT).

So a tipping point in the potato market was met; it is not expected that this threshold would be crossed again in current market conditions. However, stories continue on—when potatoes became more expensive after the 1976 drought, that there was a shift to cheaper "faddy foods" such as rice and pasta, with potatoes never returned to similar extent in the British diet.

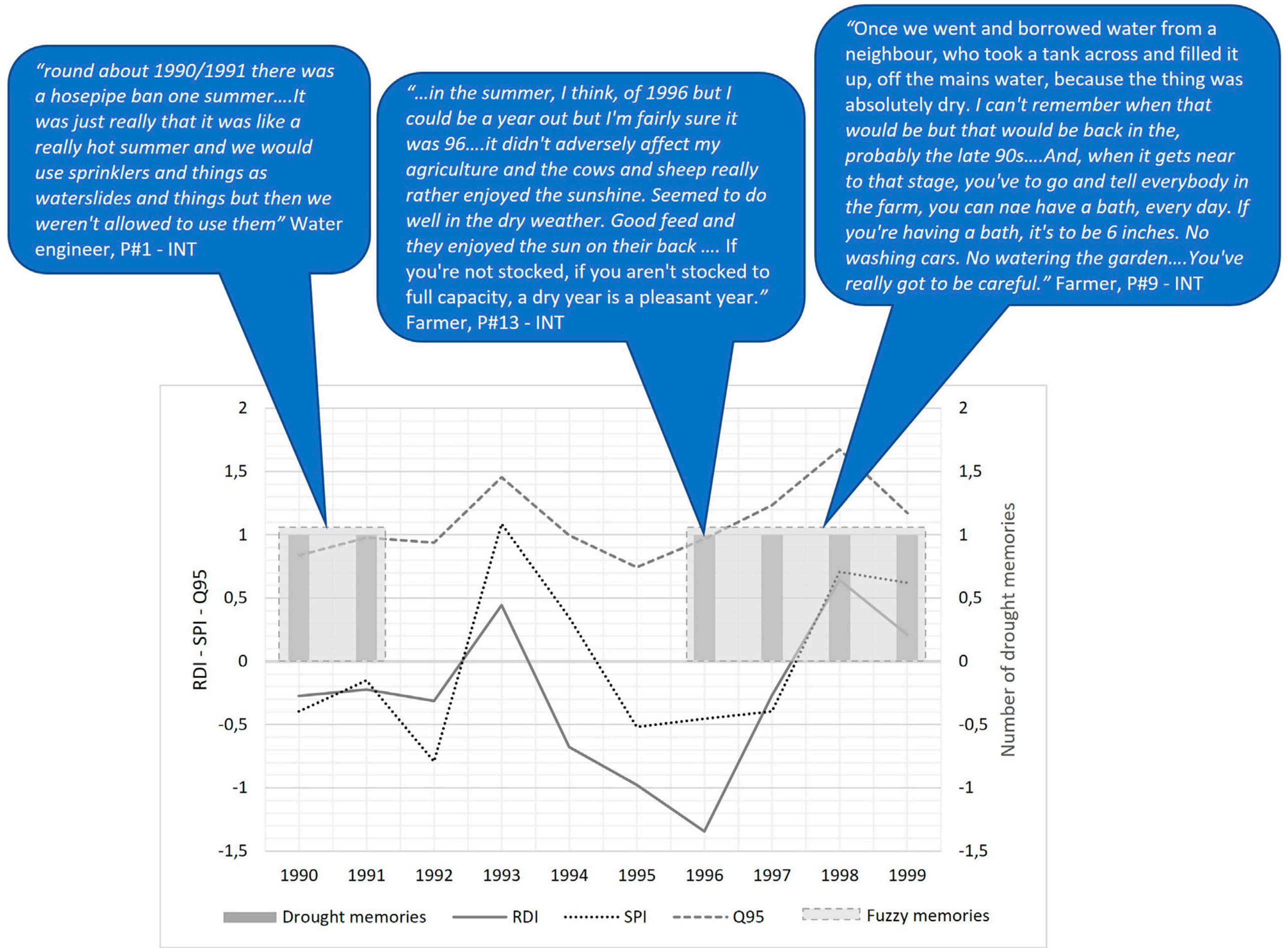

FIGURE 10 | Drought memories overlaid on RDI, SPI and Q_{95} data for the decade 1990 to 1999.

Today, in the Eden catchment, potato crops are commonly irrigated, and irrigation is also widespread in the production of some vegetables and soft fruits (e.g., broccoli, strawberries). Participant #8 (INT) explains how this drought led to the shift in irrigation practices:

"*Well 76 was, I remember . . .. irrigation was relatively new in Scotland, at that time and once you've had an experience where your yields have been dropped, you then tend to think how can I mitigate that and so irrigation equipment was right across Scotland .... So big, high demand on irrigators now . . .. it's one of the biggest improvements, I think, in the potato growing, in Scotland, was that year, 76.*" (Farmer, participant #8 - INT).

This drought hence led to a shift in market standards that now presents a farming environment requiring adequate water supplies to produce the "perfect" crop. The need to irrigate certain crops during specific seasons therefore can be seen as a major indicator of agricultural drought in the catchment, although the threshold for action can be difficult to determine as we see in the account from Participant #26 about the dry spring of 2017:

"*We got the irrigator out. We got it all set up, in the dry spell, in the spring, and they tested it and that was it. We put a new pump into the bore hole, at vast expense, and then the rain came and that was it for the summer.*" (Farmer, Participant#26 – INT)

Some farmers were already using science-based approaches in their decision-making, to determine whether and when irrigation should commence:

"*I would think most people, nowadays, are scheduling their irrigation. Doing what I am. Monitor the rainfall. Monitor the evaporation and work out how much water they need to put on. You know, before you used to go, oh the potatoes are hooking now, they're starting to form small tubers. We'll give them an inch, just for good measure. Some people maybe still do that. I don't know.*" (Farmer, participant #14 - INT).

Nonetheless, while the approach toward deciding when to irrigate may be more systematic and strategic, farmers are not always guided by the measurements and analyses from instrumentation but rather on intuitive judgements, as we heard in some cases. This involved running the soil through their hands or kicking the soil (the "boot method"), and appraising the growth stage of the crop against seasonal expectations, in deciding whether or not they should add "a bit" of water (irrigate). One farmer told us that better soil management practices were needed to improve soil quality (e.g., increased organic matter, moisture holding capacity, etc.) in ways that would improve soil performance and thresholds for disruption both in floods and droughts. Another impediment to the use of these scientific indicators as a guide for irrigation is very much dependent on the farmer's location and geology within the Eden catchment, as noted above. For example, farms that do not adjoin the river or are downstream several large farms are at a disadvantage in accessing irrigation.

"*There's still water going round there but, perhaps, if you count back the river, there's been probably six or seven irrigation reels, pulling out water, before it gets to us and we're probably the last one, before it joins the Eden. So it's come close. Not very often.*" (Farmer, Participant #19 - INT)

Another interesting perceptual drought threshold articulated by farming participants, related to farming under dry versus wet conditions. Some farmers growing arable crops much preferred dry (winter) conditions as they were "*able to work the land*" much better than during wet, muddy winter periods which was much more challenging and sometimes more destructive. So for arable farming, when growing three different crops during summer 2018, "*drought is good*" (participant #8 INT). However, this narrative is specifically around short-term summer drought rather than deficits that extend over more than a few months. **Figure 9** highlights Participant #8's commentary on flooded versus droughted farms, based on his experience with flooding in 1985. This theme seemed to resonate particularly within the Eden catchment as opposed to other DRY catchments in England and Wales. With limited experience of drying rivers and reduced access to irrigation water even during a drought, some farmers could afford to be more optimistic toward drought unlike those in say the South East of England where abstraction may well be restricted during drought.

Livestock farmers had similar differential experiences with drought in the catchment. They generally agreed that animals thrive in dry weather as they are less susceptible to diseases, e.g., diseases of the feet and liver which are common in wet weather. The story of Participant #13 in **Figure 10** is a good example in illustrating how dry weather is mainly perceived as beneficial to livestock farming. However, further on in her story, this participant does highlight the issues with being overstocked during a drought, which is where the benefits become outweighed with limited food supply if the drought prolongs. This is also explained in the story by Participant #9:

"*Well it could have a knock on effect on the amount of animals we could graze because, in a drier summer, they don't produce as much grass. Even though they thrive well enough, you can sometimes find yourself. In the 90s, when there was a few dry summers, our farm looked like the Sahara Desert. It was just brown ... There was one year, we started feeding straw in August 'cause the grass had stopped growing. And, obviously, if it's been a dry summer, you probably haven't got the bulk of silage. You maybe got good quality but you don't have the bulk.*" (Mixed farmer, Participant #9 - MSV).

This very threshold was crossed in the catchment during the 2018 drought where there was a shortage of grass for hay and silage due to the low rainfall and dry weather experienced ($Q_{95} < 1$ – **Figure 7**).

"*The crop of hay is very poor, this year. Hay's gonna be scarce. So I usually get at least two hundred square bales but the farmer I usually get it from is only gonna be able to give me a hundred this year so I'll have to get it from somewhere else . . .. the hay crop, for anyone using hay, is very poor this year.*" (Estate manager, Participant #27 - MSV).

Some farmers, whose stories we garnered, had diversified (whisky distilling, farm shops, holiday accommodation) in ways that could influence their narratives of drought experience, thresholds of disruption and their personal and business resilience.

In terms of impact to the natural environment, narratives highlighted the strong interconnections among drought, nature, and human health and well-being. As discussed in Bryan et al. (2020), drought conditions can present opportunities for people to engage more with the natural environment through various land and water-based activities (e.g., field sports and sailing). These activities are often linked to positive health and well-being outcomes as seen below.

"*Scottish Natural Heritage (SNH) . . .. is becoming increasingly interested in what Scottish government calls the "Preventative Spend Agenda," so getting people out to appreciate the natural heritage so that their mental and physical health is improved and therefore costs the country less to treat them . . .. drought makes it easier to get people out and about in the outdoors and appreciate it before it frizzles up, because then you've not got the problems of mud and drainage issues ... So, when it's dry, it's actually a whole lot easier to get people to go out and appreciate the natural environment.*" (Conservation manager, Participant #4 – LAG2).

However, there are also thresholds involved here; there comes a point when the benefits are outweighed by the costs of engaging in some of these activities during a serious drought, and particularly during summer drought when water shortage may combine with heatwaves. Hot, dry weather can lead to worsening of chronic health conditions and hence potential fatalities for some people (e.g., older people and children), thereby showcasing the dangers associated with drought and outdoor activities. They can also lead to environmental conditions that make it unsafe or impractical for recreational activities. These include low water levels, algal blooms, dried sports fields, increased fire risk to vegetation etc.:

"*If the water gets too short then they can't (water-ski). And, also, because if there's more heat and less water, we get a lot of blue green algae blooms which, actually, prevents access to the water.*" (Local government, Participant #16 - LGW).

"*I guess we used to play football. I play a lot of golf. I guess the golf courses become hard and become when they get hard, they get harder to play . . .. Yeah it's something that you never really notice that you know oh that could happen ok. . . .. Yeah so my recreational play would be actually quite impacted.*" (Water engineer, Participant #1 - INT).

The impact of drought on the natural environment can also lead to direct and indirect effects on the mental health and well-being of humans as they watch the ecosystems, habitats and species they value and enjoy, deteriorate and struggle to survive. Although some participants believed that many more mobile species in the Eden catchment would be able to migrate under severe drought, we did hear of extreme examples of systemic species impacts. These included the deaths of a fragile local community of hedgehogs as feeding habits of certain predators like badgers changed due to dry weather conditions during the spring 2017.

"*A badger had dug its way into my garden and killed all three hedgehogs. Then went into a friend's garden and killed the hedgehogs there, leaving bloody badger footprints and blood all over the patio. Another friend found her hedgehog turned inside out, that had been eaten by a badger and everybody else has lost all their hedgehogs. We reckon that is because of the drought, badgers would normally be eating worms and they are trying desperately to feed young at this time of year. Although badgers are the only thing that can eat hedgehogs, they wouldn't normally do it unless they were desperate. Our hedgehog population has gone back down to zero from what I can tell. There are wildlife effects to drought that I am very conscious of*" (Conservation volunteer, Participant #3 - INT).

The narratives also revealed that some species of birds and frogs were not able to nest and feed during a drought as they normally do, which could ultimately impact their future population growth and possibly longer term diversity. These critical behavioral changes of certain key species could also serve as local indicators of this type of hydrological drought transition in the Eden.

The spawning of migratory fish such as the Atlantic salmon, or lack thereof, also seemed to be another indicator of hydrological drought conditions although this was quite complex as drought (low flows) is one of a combination of factors perceived to be contributing to this problem. Participant #17, a long-time angler in the catchment, explains further:

"*I've fished the river Eden for nearly fifty years now and have watched it gradually decline from a very healthy river to one that doesn't, is not able to support migratory fish, annually. Fish catches have dropped, dramatically, over the whole of Scotland. I know there are other reasons for it ... But, in recent years, particularly in dry weather, the fish have, instead of running up the river in June, July and August, have accumulated in the estuary, due to low water or water conditions or conditions which are not favourable for fish running ... Low water flows have to support higher volumes of effluent. The amount of water which has been drawn out of the river has got a serious effect on it. It affects the gravel beds that the fish spawn in because of the low flows no longer are able to scour the gravel and certain weeds, ranunculus weeds, are drying off which no longer give cover for juvenile fish, leading to higher predation. They will not run up the river in the summer months ... as a fisherman, it's extremely worrying to see this happen*" (Recreational fisherman, Participant #17 - RVK).

Here we see how he perceives that various land use activities interact with meteorological conditions to impact negatively on the spawning and migration of specific fish species in the Eden catchment. Interestingly, the anglers we talked with were not able to give precise figures of what "low water level" was critical, as the interaction of quantity and quality was perceived as more important. This seemed to be based on an intuitive judgment developed through interactions and experiences with the river over several decades. Anglers were concerned that intensive irrigation practices, impacting cumulatively downstream in the catchment, could exacerbate low water flows on the river during dry or drought periods, thereby impeding the conditions required for successful spawning. In addition to affecting spawning, visual evidence of fish kills was observed and recorded during the 2018 summer drought (**Figure 7**), and were said to correspond to extreme low flow levels (<1 Q_{95}). Here the low flows were quantifiable through the Q_{95} index, alongside the intuitive judgment used above. This shows how narrative and science evidence could be combined to better understand the potential impacts in a given sector and guide decision-making in water resource management.

Water Supply Drought

While there is no record of any water supply failure in the Eden catchment within living memory, some narrative participants highlighted themes that were important from a water supply point of view. These included issues around abstraction, water quality and health, private water supplies and recreation. Although there was a general perception that Scotland was a wet country among members of the public, different thresholds of adaptation emerged within the narratives. These were usually shaped by one or a combination of past experiences of drought, and expert guidance that future climate change dictates a need for such behavioral change. For instance, we found people (incomers) with experiences of drought from elsewhere, e.g., from Southeast England, were importing water efficient practices in a catchment where the dominant narrative was that there were abundant water supplies. This was exemplified in the story of one former London resident, who shared how he built a passive house in the Eden catchment to conserve not only money and energy, but also water, based on his experiences of living with periods of water scarcity in England.

"*Our house is close to 'Passive' house . . .. and water is one we want to minimalize . . .. Water meter was one part of it . . .. Toilet with dual flush and extra low, the bath we looked at we did a water saving bath . . .. A++ washing machine. We couldn't have a tumble drier. It had to be a heat pump dryer. Taps were low consumption and I have also fitted them with one litre a minute restriction.*" (Local resident, Participant #18 – FAS1).

However, this drive to implement water saving measures into the house was overshadowed by the challenge of installing a water meter in Scotland. Here, households are not required to install water meters, and as such it was a major difficulty for the householder to embark on this particular adaptation measure.

"*Down south, water is in short supply there is hose pipe bans. So it made some sense to control it a little. In Scotland it doesn't seem to be the same. They say oh it is part of your rates . . .. I can't find out how to do it. I have called the water company and they say they will call me. I can't find any info on what it costs. I just hit a blank wall.*" (Local resident, participant #18).

Participant #10 complained about investing in a large water tank (see **Figure 9**) for gardening needs following a drought in the 1980s in response to expert guidance at the time that "*it was likely to be the pattern in the future.*" He considered that the investment was not warranted, as there had not been any major droughts since the 1980s event. These two examples illustrate how thresholds in adaptive behaviors can sometimes be challenged by various factors in the water sector, as well as the nature and uncertainty of future climate change. This also indicates a potential space for the combined use of scientific and narrative data in decision-making.

DISCUSSION

Our research shows tensions and opportunities in the interplay between the scientific thresholds and perceptual thresholds within different catchment stakeholder groups, as evidenced through the narratives garnered. Here we return to our four aims.

Aim 1: To explore the concept of "*drought thresholds*" *from scientific and narrative perspectives and their comparison, in context of spatial and temporal variations in drought in the catchment.*

Hydrological modeling uses continuous variables such as precipitation, river flow and groundwater levels, against which thresholds can be defined for operational or analytical purposes. Some of these variables can be focused at a point, such as a rain gauge, borehole, flow gauge or abstraction point, while others may be focused on a whole catchment, best illustrated by catchment-averaged rainfall. Data source availability may define which focus is used. Even a catchment-averaged value may fail to capture the variability in conditions present within a catchment as a whole.

While the numbers in a hydrological report may be quite precise, the decision about whether to act, e.g., to issue a drought order/water shortage order, is ultimately a judgment to be exercised by statutory decision-makers. In Scotland, this responsibility rests with government Ministers, suitably informed by Scottish Water and SEPA. So actually, while some might expect that community perceptions and actions may be nuanced and subjective, experience across DRY generally indicates key decisions in the water industry may be too. Decisions to be made by Ministers could be seen to fit within the range of conditions during which there may be scope to regard the need for actions to lie within some range of hydrological uncertainty. In such uncertainty, Beven (2016) encourages hydrologists to communicate more explicitly and openly about it in their modeling, not least while communicating with decision-makers.

Perceptual thresholds for public/community awareness and action will vary subjectively depending on a variety of factors, including the nature and extent of people's connections to signs of emerging drought, with the "most severe drought" determined by their activities and goals at the time of the event. Even within a sector, our Eden case-study indicates that drought experiences can be diverse. For example, farming activity in the Eden catchment is varied, with grain, vegetables, soft fruits (raspberries) and livestock all experiencing drought conditions in different ways, which mean that metrics used need intra-sector attuning.

Local geography and catchment hydrology also play a part in controlling drought risks. Variations in soil type cropped up as a local factor for some impacts, e.g., light sandy soils and increased vulnerability to the "stoor." Farmers' narratives related to potatoes, irrigation and location in the catchment – a lack of water in some lower tributaries due to upstream abstraction – suggests perhaps the need for spatially varying impact thresholds. The spatial and temporal aspects of drought experienced are linked to the impacts of base flow from the sandstone aquifer. Other thresholds emerge from the narrative data e.g., drought-induced potato shortage leading to demand/supply imbalance; the intersection of seasonal factors when dust blows off cultivated fields or when fire risk to vegetation occurs; when technology or experience indicates irrigation need for farmers and gardeners; and the thresholds determined externally by the water companies leading to hosepipe ban or potential water supply failure and stand pipes. It is not just spatial scale that is important. A need exists to better match the seasonal resolution of quantitative hydrological thresholds to particular local activities, resource needs, habitats and species lifecycles etc., e.g., the seasonal and catchment specific nature of salmon runs or seasonal variations in demand for irrigation water.

In the Eden catchment, drought conditions are not as frequent or as long as in the southern United Kingdom (e.g., in chalk catchments like the Berkshire Pang, another DRY case-study catchment). People may have variable and imprecize drought memories, particularly when impacts may be more muted and hidden in their experience and locale. People generally do not remember the date of a drought but they remember the event when they are personally (and emotionally) impacted. Memories that did exist varied significantly in their detail and temporal precision, given also variability in the formality of recording/archiving something that is "not there" (in diaries, photos etc.). Hence local memories may be in conflict. Mismatch also existed between what is displayed on scientists' time-series graphs and what people actually remember which is not easily captured on a hydrological time series. These are the indicators that traditional scientific thresholds do not consider. In addition, in the Eden catchment, perceptual thresholds of particular stakeholders, e.g., the extent of "low water levels" that influence recreational fisheries, are not quite definable in narratives, again illustrating a sort of "fuzzy knowledge."

Aim 2: To evaluate the perceived thresholds for drought impacts by different stakeholders across sectors and their connection, and how this maps against scientific indices and thresholds.

This poses questions as to how scientific definitions of thresholds can be more flexible to incorporate these types of local knowledges and their links to actions, so adding to research and practice on drought severity and drought perception. In the Eden catchment, such local knowledge included farmers' detailed weather journals or diaries with records of rainfall, soil and crop conditions. Farming also provides a good example of perceptual thresholds influencing thresholds for action. Farmers have potential to access technical innovation with soil moisture monitoring devices but do not necessarily use them. Rather some use sensory judgements of thresholds—tactile and visual interpretations – and experience.

Another variable in unraveling the relationship between scientific and perceptual thresholds is the precise nature and severity of the drought actually experienced, given that all droughts are different. Here differences existed between memories, and associated lay knowledge, of short, sharp summer droughts (e.g., 1984) and long-term droughts that build up over several dry winters (e.g., 1973–1976 drought). In the latter, it is the later stages of the drought that are now remembered, linking beyond the local to extreme drought elsewhere in the United Kingdom. In addition, media coverage beyond the local may influence people's perceptions and memories. In contrast, the science for the Eden (RDI data) shows lower rainfall for 1973 versus 1976 while people remember 1976 as being worse than 1973.

In the rural Eden catchment, the potential to link scientific and perceptual thresholds also varies in different aspects of the hydrological cycle. Here, the main impacts are those on agriculture, ecosystems and environment, and so the connection with some scientific drought indices is more direct than with others. For example, the simplest connection might be expected to be between thresholds for minimum river flows and perceptions of fish health. Even in this instance, the identification of quantitative thresholds, in terms of flow or depth, does not include important water quality issues. However, some impacts involve a much wider complex network of connections and threshold exceedance. For example, the seasonal dryness of "the stoor," a complex socio-hydrological system exacerbated by ploughing and exposed soil, is further removed from "direct hydrology" so it becomes harder to pull out hydrological thresholds. Scaling also exists in the operation of thresholds for action (e.g., around supply and demand). For example, drought induced economic thresholds need to be crossed before certain market conditions apply – then farmers who have invested in resilience measures get to reap extraordinary returns while less well-capitalized farmers get less return. Local narratives tell us that the thresholds for the uptake of adaptive practices are not just triggered by drought. Other drivers and externalities exist including the threat of abstraction licences being limited or suspended.

Aim 3: To explore the potential for a framework for science-narrative drought "threshold thinking," as a way of bridging different types of drought knowledge.

This poses questions about how scientific indices of drought severity and their thresholds can be more flexible to incorporate these types of local knowledges, and to help rethink communication strategies and decision-making in drought risk management that are better tailored to the local at a sub-catchment level. There is a need to develop meaningful drought thresholds that local people can relate to in comparison to apparently somewhat abstract thresholds for physical indices like SPI. This includes ensuring that the choice of drought indices used are best suited to the stakeholder's activity and impacts, particularly seasonal aspects. It involves co-working longitudinally with stakeholders to identify thresholds of importance to their particular activities. This highlights the potential value of researching locally relevant, catchment-based drought impact indices (e.g., "potato drought," "salmon drought," "dairy drought") within the Eden catchment. Perhaps potential exists to derive farming related drought impact thresholds from detailed farmers' journals/diaries that could in turn be used to inform scientific thresholds. These different perspectives on thresholds also have particular value–in an emergent risk with impacts that become visible slowly. If we had the data on perceptual thresholds, we could produce a normal distribution curve of where thresholds should be and how this reflects levels of risk aversion. So there is a fuzziness in perceptual thresholds and thresholds of response, and a key question is how to recognize and communicate these uncertainties.

Thus, fuzziness around perceptual thresholds has several facets (including what is remembered, extent of archiving, nature and resilience of activity, emotional connection, physical location in catchment) while hydrological drought indices appear to be more precise. In considering possible frameworks for bringing science and narrative thresholds together, we share two graphical methods of combining scientific and drought thresholds as a basis for dialogue, engagement and to support decision-making, using the Eden catchment as a wider exemplar. The first is by mapping quantitative drought indices against narrative accounts. Such "drought memories" overlaid on the SPI, RDI and Q_{95} plots act as a way for identifying thresholds, although with acknowledged fuzziness. If we take science indices together with drought memories, we can identify more locally resonant drought impact thresholds (rather than just statistically based thresholds in terms of number of deviations from normal). From **Figures 6–10**, it appears that SPI or RDI values < -1.5 to -2.0 are associated with significant drought memories/impacts, while an SPI or RDI values in the range < -0.5 to -1.0 has less significant, but still noticeable impacts/memories. Recommending a range for the thresholds is an appropriate way of reflecting the fuzziness, rather than a single quantitative value threshold that is usually used in practice.

Our aspiration was then to create a table or graphic that showed thresholds and their systems connections/interrelations according to sector, season, severity and duration of deficit. In theory, this could be a good way of bringing together the various messages from this research, however, this was challenging in practice. Instead, we aspired to emphasize some of the greatest contrasts in perspectives and vulnerability. Extreme rainfall deficit could be a problem for gardeners while nearby the farmers who have benefit of the aquifer or (if wealthy) irrigation lagoons, or both, are not worried. Not all members of a single sector are situated in the same way – some farmers are vulnerable while others are not. We propose the idea of mapping local indicators to drought stage and/or physical indicator as a precursor to identifying thresholds and a first order systems synthesis (**Figure 11** linked to **Table 3**) building up in scale and severity. Although presented for the Eden, we suggest this could be used more widely as a drought memory mapping methodology within a wider context of "science-stimulated narratives" and "creative participatory science" (Liguori et al.,

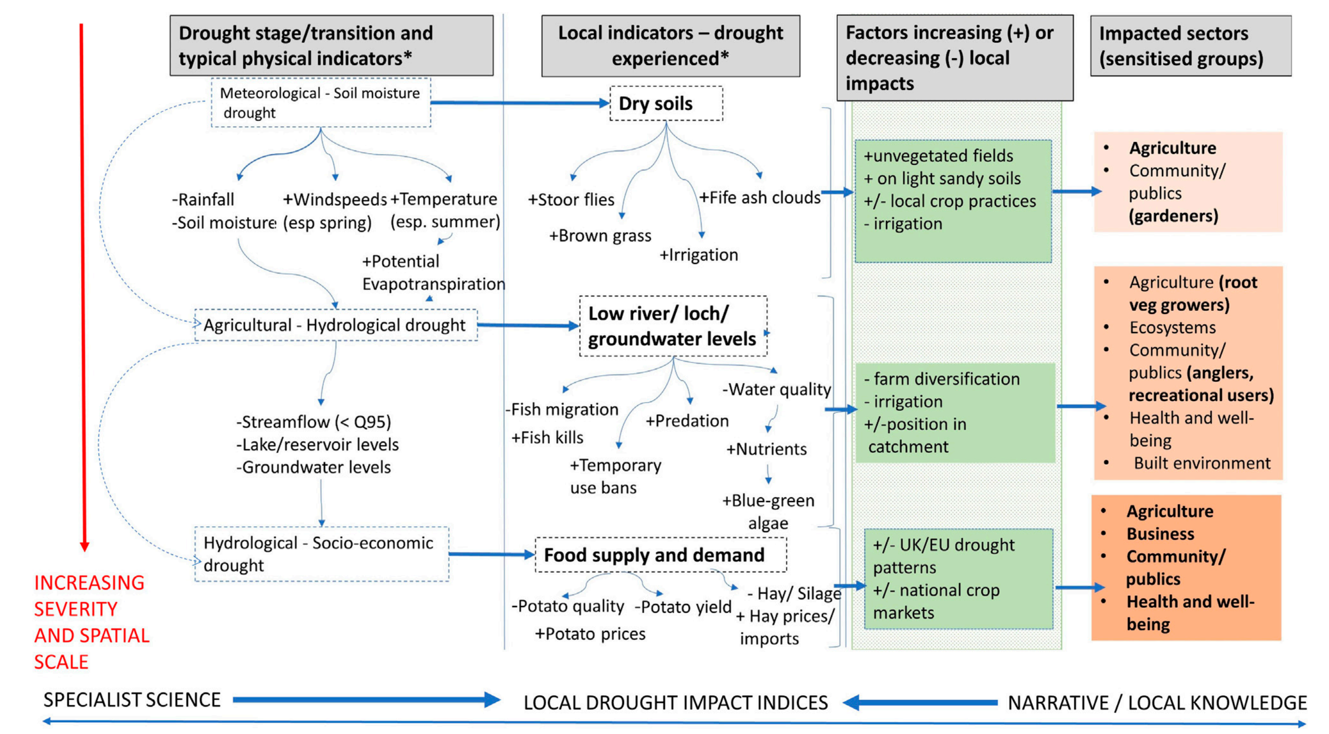

FIGURE 11 | Development of a framework for science-narrative drought "threshold thinking."

2021). The drought stage/transition and the affected sectors are likely to be similar from place to place, but the local indicators will change, so this then becomes a tool for consolidating the various local memories/stories to particular local impact areas to make sure that thresholds developed reflect local interests. These could be integrated within locally-relevant themed drought impact indices as articulated above.

Aim 4: To reflect critically on how this focus on "threshold thinking" might inform the policy and practice of public/ community involvement in local drought risk management, including communication and messaging about drought risk.

Having explored the potential for a framework for science-narrative drought "threshold thinking," some points become apparent. This approach relies on the scientist being prepared to accept the uncertainty associated with defining "fuzzy" impact threshold ranges based on narratives, which contain useful knowledge but are not defined using a traditional numerical framework based on simple threshold exceedances. However, there is a growing awareness of the implicit as well as explicit uncertainties in hydrological data and modeling (e.g., Beven, 2016), and in hydro-social systems (Westerberg et al., 2017), which has been slowly changing hydrological practice. Therefore inclusion of narrative knowledge in the selection of drought indices and threshold development should be encouraged as another facet of improving the exploration of uncertainty as a routine part of hydrological science. It also has implications for practice, in terms of scientists/regulators becoming more comfortable with uncertainty.

For example, it is interesting to compare the fuzzy local thresholds developed above with Scottish Environmental Protection Agency (2020) generic impact thresholds framed in terms of "water scarcity" (see **Table 4**) and based on NPI and NFI. Although these thresholds are not for exactly the same indices used in this study, the indices are broadly comparable. The fuzzy thresholds ("noticeable" memories/impacts at < –0.5 to –1.0 and "significant" at < –1.5 to –2.0) appear to map quite well with SEPA's moderate to significant water scarcity. It is revealing that the fuzzy local thresholds imply that drought might only just be on the local radar in some sectors when a water scarcity alert is issued (0.5), and the early warning (0.25) might be being issued too soon or at least before any apparent impacts.

If the "local thresholds" methodology were applied to other catchments, it would be interesting to appraise any national/ regional variations – which could reflect local drought resilience/ local geography etc. – and hence the need to have local thresholds to ensure relevant drought risk messaging.

The concept of thresholds and the practice of "threshold thinking" provide a creative bridge between different types of knowledge. The policy and practice of public involvement in drought risk management might usefully involve unpicking of how scientific thresholds are perceived and lived locally. Such insights might usefully inform risk communication and messaging so potentially changing the messenger and the nature of the message (Weitkamp et al., 2020), tailoring it to catchment experience and knowledge. We argue that the framework proposed above has the potential to become a key communication tool for messaging with the wider public as it

TABLE 3 | Physical and local indicators of drought in the Fife Eden catchment.

Drought category or stage	Sector impacted	Physical indicators	Local indicators (from narrative)
Meteorological	Agriculture	• No significant rainfall	• "Stoor flies" become iminent following spring tillage • "Fife ash clouds" of 2017
Agricultural	Agriculture (root veg growers) Public/Community (Gardening)	• Lack of rainfall, possibly combined with high temperatures and increased potential evaporation (in summer), results in low soil moisture. • Particular crops may require irrigation to maintain quality and/or yield. Plant growth decreases. Clay soils may crack. Organic soils may oxidize, shrink and become susceptible to wind erosion.	• Severe dry weather of summer 1976 meant that potato fields had to be irrigated as no rainfall available for crops • Brown grass
Hydrological	Agriculture Public/Communities (Gardening/ Recreation) Ecosystems	• Lack of rainfall reduces groundwater recharge from soils (permeable catchments). Decreased groundwater levels reduces flows to water courses (decreased baseflow) and/or decreases in direct surface runoff to water courses. River flows and levels decline (may fall below Q_{95}; ephemeral streams may retreat from headwaters; possible disconnection of river sections). Lake levels fall. Reservoirs start to be drawn down. • Reduced dilution of effluents potentially decreases water quality. • High temperatures (in summer) increase potential evapotranspiration and also increase river/lake water temperature with increased risk of algal blooms. • Very dry soils may become hydrophobic.	• Threat to seasonal fish migration • Badgers prey on hedgehogs as feeding habits change due to dry weather • Birds and frogs nesting habits affected • Fish kills • Blue green algae swarms • Some land and water-based activities become limited or dangerous • Water brought to supply private water users • Temporary use bans (hosepipe bans) • Abstraction restrictions (farming/bulk users) • Brown grass
Socio-economic	Water supply Agriculture Public/Communities	• As above, with increased severity • Low river and lake levels	• Reduced supply of goods such as potatoes in 1976 • Increased price of potatoes in 1976 • Investment in water tanks following 1984 drought • Investment in irrigation lagoons

TABLE 4 | Scottish Environmental Protection Agency's Drought scarcity indices (source: Scottish Environmental Protection Agency 2020).

	Rainfall index (Cumulative rainfall)	River flow index (Average flow)
Condition	3 months	1 month
Normal Conditions	<0.25	<0.25
Water scarcity early warning	0.25	0.25
Water scarcity alert	0.5	0.5
Moderate water scarcity	1.0	1.0
Significant water scarcity	2.0	2.0

reflects local interests, rather than just the typical approach of "save water, we're in a drought."

Similarly local people have strong potential to be the "eyes on the ground" through emerging drought by contributing their geo-referenced, time tagged observations and photographs of impacts through crowdsourcing to build to catchment scale pictures (see #Mapmydrought[6]), working with statutory organisations as citizen observers. This would have the aspiration to make hidden drought more visible both in catchments but also in the public psyche.

Wider Contexts: Drought and Water Management Futures

There is important future context to our drought "threshold thinking" and need to bring together specialist and lay knowledges to support better local drought risk decision-making. Future climate change scenarios for the Eden catchment reveal more frequent "extreme drought events" (defined when RDI below -2) under high emission scenarios, as compared to the medium and low emission scenarios (see Afzal and Ragab, 2020). The "severe drought event" (defined as RDI between -1.5 and -1.99) was observed two times more often under medium emission scenarios, in comparison to under low and high emission scenarios. The occurrence of extreme drought events could significantly affect important sectors, such as agriculture where more irrigation would be required to irrigate crops during future dry seasons. Brown et al. (2012) already predict very significant increases in irrigation water demand in the Eden catchment. Even under medium emissions, drought will be a future challenge for the Eden catchment. This warrants new ways of understanding how drought unfolds in the catchment and emphasizes the need to identify and understand new types of indicators outside of the traditional hydrological ones.

Taking a step back, water resources have long been studied and managed through a systems approach, linking sources, storage, treatment and distribution infrastructure, and "consumers." Goals in these systems are avoidance of supply failures, plus a balance of such statutory requirements and other priorities as deemed locally important, e.g., environmental protection, financial costs, fisheries interests, etc. Forecasting skill as a precursor to management interventions is often tackled as a numerical challenge, e.g., Madrigal et al. (2018). Hewett et al. (2020) argue that a holistic approach to catchments as systems is necessary for effective management, integrating spatial and temporal variability, and both quantity and quality dimensions in water resources management. However, system goals themselves also require periodic review and revision. McLoughlin et al. (2020) argue for reflexive learning in adaptive management of water resource systems, emphasizing challenges of decision-making in contexts of uncertainty and complexity, thereby promoting evolutions in thinking about actual goals and how they may be achieved. Similar thinking can be extended to the setting of thresholds used in local drought management, and construing that task in creative participatory ways. In Europe, introduction of the Water Framework Directive was partly inspired by the necessity for stakeholder engagement (beyond being "consumers"), and recognition of diverse and potentially incompatible needs. These may easily be under maximum strain during drought periods. Bringing together different types of evidence for better determining thresholds to support multi-stakeholder decision-making is arguably a critical part of this process.

[6]https://dryutility.info/mapmydrought

CONCLUSION

There are major advantages of unpicking and interweaving disciplinary understandings of thresholds in developing increased understanding of what "drought is" in a given catchment, with multiple stakeholders. Using "thresholds" as a creative bridging concept in interdisciplinary science-narrative research can bring together how different physical types of drought can be perceived, experienced and remembered locally. This recognizes that local drought can be perceived in diverse ways, depending on prior stakeholder capital and socio-environmental connections. This influences the extent to which the hidden risk becomes cognitively revealed—how gradual or rapid, with what impacts on whom, and with what local thresholds of awareness and action. Our research demonstrates the need for different thinking about how drought is defined locally – in terms of less abrupt fuzzy thresholds, complex systems controlled by local and external factors, and as spatial and temporal in its physical and perceptual construction. This feeds into important research questions about how we can better define combinations of conditions leading to local threshold crossing.

We proffer our deliberations about the character of a framework for integrative science-narrative "threshold thinking," critiquing its strengths and challenges. Such "threshold thinking" has important implications for research and practice: in developing new participatory ways of linking drought severity and perception, and in locally tailored drought risk communication to promote adaptation and transformation to future drought. This is particularly important in maritime catchments where public narratives of wetness dominate, with large variations in drought experience and diverse thresholds for impact within and across sectors.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because some data are already in the public domain (dryutility.info); anonymised interviews will be lodged in the ESRC data portal after project completion (Dec 2020). Requests to access the datasets should be directed to dry@uwe.ac.uk.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of the West of England Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LM, AB, and JB contributed to conception and design of the DRY study. KB organized the narrative database and performed the science-narrative graphical analysis with LM. MA performed the scientific modeling and visualization. LM, KB and AB wrote the first draft of the manuscript, with JB and MA writing sections. JB contributed to science-narrative thinking, with KB, LM and JB contributing to the "Framework." All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.589980/full#supplementary-material.

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Climate Change Impacts on the Future of Forests in Great Britain

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Forests provide important ecosystem services but are being affected by climate change, not only changes in temperature and precipitation but potentially also directly through the plant-physiological effects of increases in atmospheric CO_2. We applied a tree-species-based dynamic model (LPJ-GUESS) at a high 5-km spatial resolution to project climate and CO_2 impacts on tree species and thus forests in Great Britain. Climatic inputs consisted of a novel large climate scenario ensemble derived from a regional climate model (RCM) under an RCP 8.5 emission scenario. The climate change impacts were assessed using leaf area index (LAI) and net primary productivity (NPP) for the 2030s and the 2080s compared to baseline (1975–2004). The potential CO_2 effects, which are highly uncertain, were examined using a constant CO_2 level scenario for comparison. Also, a climate vulnerability index was developed to assess the potential drought impact on modeled tree species. In spite of substantial future reductions in rainfall, the mean projected LAI and NPP generally showed an increase over Britain, with a larger increment in Scotland, northwest England, and west Wales. The CO_2 increase led to higher projected LAI and NPP, especially in northern Britain, but with little effect on overall geographical patterns. However, without accounting for plant-physiological effects of elevated CO_2, NPP in Southern and Central Britain and easternmost parts of Wales showed a decrease relative to 2011, implying less ecosystem service provisioning, e.g., in terms of timber yields and carbon storage. The projected change of LAI and NPP varied from 5 to 100% of the mean change, due to the uncertainty arising from natural weather-induced variability, with Southeast England being most sensitive to this. It was also the most susceptible to climate change and drought, with reduced suitability for broad-leaved trees such as beech, small-leaved lime, and hornbeam. These could lead to important changes in woodland composition across Great Britain.

Keywords: LPJ-GUESS, drought, vulnerability, leaf area index, net primary productivity, CO_2

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INTRODUCTION

Forest ecosystems play a critical role in global carbon cycling and ecosystem service provision (Seddon et al., 2019). There is evidence of changes in the composition, structure, and functioning of forests in response to contemporary climate change and associated drought and heat stress (Ciais et al., 2005; Allen et al., 2010; Choat et al., 2018), as well as increases in CO_2 (Peñuelas et al., 2017; Haverd et al., 2020; Walker et al., 2020). The projected shift of precipitation and temperature patterns in the twenty-first century (Seneviratne et al., 2012; Dai, 2013), along with increased CO_2, therefore, is likely to have profound impacts on forest ecosystems (Hickler et al., 2012; Anderegg et al., 2013; Senf et al., 2018; Baumbach et al., 2019). Hence, understanding the potential impacts of climate change, especially of associated drought and CO_2 on forests and their functioning, is important for policymakers and stakeholders to effectively plan appropriate adaptation measures for coping with the future.

Exploratory data analysis is one of the common approaches to studying the ecological response of plant species to recent mean climate change. Extreme events are of particular interest as they can help improve the understanding of phenological and physiological responses of tree species for better planning of management options. These studies are based on the observed stress signs of plant species, such as canopy dieback (Carnicer et al., 2011), growth condition (Van der Werf et al., 2007; Hogg et al., 2008; Pasho et al., 2011; Eilmann and Rigling, 2012), leaf coloring and decline (Leuzinger et al., 2005), and mortality (Bigler et al., 2006, 2007; Senf et al., 2018). However, the lack of agreed indicators of particular stress signs as a function of climate limits their use for climate change impact studies. In the United Kingdom, there are some observations of climate change impacts and especially drought on forests and tree species (e.g., Peterken and Mountford, 1996; Mountford et al., 1999; Green et al., 2008; Cavin et al., 2013), while a few studies have investigated impacts on tree growth, but they have been limited to a few species (Petr et al., 2014).

Bioclimatic envelope models, or others based on similar statistical approaches, are popular tools for the assessment of climate change impacts on the distribution of climate suitability for individual species (Fordham et al., 2013; Watson et al., 2013; Pacifici et al., 2015; Baumbach et al., 2019). However, when modeling forests, the fundamental mechanisms of tree species interactions and carbon and water cycling are not taken into account. Therefore, it is difficult to tackle the response of tree species and forest to changes over time, especially with respect to climate extremes like drought.

Process-based ecosystem or forest models, with their capability of simulating the ecophysiological and biogeochemical processes dynamically, are alternatives for studying terrestrial ecosystems and forest functioning under climate change. Such models have been used by many studies to investigate ecosystem properties, like net primary productivity (NPP) and net ecosystem exchange (NEE) of carbon, in order to understand the carbon uptake and release of terrestrial ecosystems in global carbon cycling; such models have been used (e.g., Morales et al., 2005; Chang et al., 2017; Fernández-Martínez et al., 2019). They have also been used to investigate transitional changes in vegetation composition (Hickler et al., 2004, 2012; Tang et al., 2012) and the physiological aspects of model outputs like drought-induced forest mortality (Steinkamp and Hickler, 2015). However, many similar models only represent broadly defined plant functional types (PFTs) instead of tree species. So, the model outputs are too coarse to be applied for regional studies and cannot be used for the ecological interpretation of individual tree species. Hickler et al. (2012) developed a tree species-based European version of the dynamic global vegetation model (DGVM) LPJ-GUESS and applied it to simulate future climate-driven changes in the potential natural vegetation. In this model version, ecophysiological process representations are adopted from the DGVM, but parameters are defined for the main tree species instead of PFTs and additional processes are included to distinguish tree species, in particular a drought limit for establishment. Note also that the LPJ-GUESS DGVM represents tree species population dynamics at a greater level of detail than most DGVMs, which is a prerequisite to define tree species. The model includes different cohorts of trees and related characteristics of canopy structure (Hickler et al., 2012). A version adopting the "average PFT" approach without cohorts (in the code referred to as "population mode") from the LPJ DGVM (Sitch et al., 2003) within LPJ-GUESS is not used anymore.

The aim of this study was to use the tree species parameterization of LPJ-GUESS by Hickler et al. (2012) with an updated version of LPJ-GUESS to explore further the ecological responses of individual tree species to climate change and in particular to drought in Great Britain, as well as the potential effects of increasing CO_2. Elevated CO_2 generally increases photosynthesis and reduces stomatal conductance, at least for non-conifers (Körner et al., 2007; Hickler et al., 2015; Klein et al., 2016), but experimental effects on plant growth have shown contrasting results and are therefore highly uncertain (Hickler et al., 2015; Klein et al., 2016; Terrer et al., 2019; Jiang et al., 2020). Also, we investigated a source of uncertainty that has seldom been quantified in the context of ecological modeling: natural weather-induced variability, defined here as the internal variability of the atmosphere due to its highly nonlinear and chaotic behavior (Lorenz, 1965). Other sources of natural weather-induced variability that cannot be addressed with the climate-driving data we used include externally forced natural variability (for example due to variability in solar radiation input or volcanoes) and internally induced variability in the oceans.

The model was driven by the ensembles of climate model outputs from the MaRIUS project (Managing the Risks, Impacts and Uncertainties of drought and water Scarcity)[1] with projections to the end of the twenty-first century. To our knowledge, this study is the first to apply a tree-species based dynamic ecosystem model at a regional level, driven by a potential large set of hydro-meteorological time series with unprecedented high spatial resolution. The novelty of this study lies in (i) assessment of the climate change impacts on forests using a large, high-resolution, plausible climate scenario ensemble for Great Britain; (ii) understanding the uncertainty arising from the natural weather-induced variability and the plant-physiological effects of increasing CO_2 in ecosystem model projections (Hickler et al., 2015); and

[1] http://www.mariusdroughtproject.org

(iii) the assessment of the climate vulnerability of typical British tree species.

MATERIALS AND METHODS

Dynamic Ecosystem Model and Modeling Protocol

The Lund–Potsdam–Jena General Ecosystem Simulator (LPJ-GUESS) is a dynamic vegetation model that simulates vegetation dynamics and ecosystem processes in terrestrial ecosystems (Smith et al., 2001, 2014; Hickler et al., 2012). The model combines physiological, biophysical, and hydrological processes (Gerten et al., 2004) with detailed representation of plant growth, competition for resources (e.g., light, space, and water), disturbances, and canopy structure. Vegetation dynamics (establishment and mortality of individual trees) are simulated using a forest gap model approach (Bugmann, 2001; Hickler et al., 2012). The establishment, growth, and death of individual trees are simulated in a number of replicate patches for a given grid cell (defined by the spatial resolution of the model input data), also accounting for stochastic processes that influence the stand dynamics at a scale of 1,000 m^2. The results are then averaged to characterize the mean vegetation and ecosystem variables (e.g., soil and total carbon storage) for a grid cell. Model input consists of daily values of temperature, rainfall and radiation, annual atmospheric CO_2 concentration, and soil texture.

Model results have been evaluated against a wide range of test datasets (see publications on www.nateko.lu.se/lpj-guess), including vegetation structure and LAI, the potential natural vegetation across Europe (Hickler et al., 2012), and observed results for free-air CO_2 enrichment (FACE) experiments (e.g., Hickler et al., 2015; Medlyn et al., 2015 and references therein). The framework of LPJ-GUESS is flexible and allows adoptions or parameterization for different regions and research questions. In most applications[2], the model has been run based on plant functional types (PFTs) and oak and lime species, for example, being represented by a temperate broad-leaved tree. In temperate and boreal regions, however, the model structure makes it possible to parameterize main tree species, which is more relevant for foresters and stakeholders than PFTs (e.g., Hickler et al., 2004, 2012; Koca et al., 2006). In this study, we adopt version 3.1 (Smith et al., 2014) with the European parameterization of major tree species and shrub PFTs by Hickler et al. (2012) to simulate the dynamics of forests across Great Britain and to assess the potential effects of climate change. The nitrogen cycle (Smith et al., 2014) has not been enabled here because the parameters governing the population dynamics of trees (Hickler et al., 2012) would need to be re-parameterized first.

The LPJ-GUESS model was run at a 5-km spatial resolution across Great Britain, with each grid cell represented by 25 replicate patches in order to average the effect of stochastic disturbance, tree establishment and mortality, and, hence, stand development. The soil texture was determined according to the dominant soil texture class (based on a United Kingdom classification of soil texture) by aggregating the Soil Parent Material 1-km database (Lawley, 2012). The simulation was spun up for 1,000 years from bare ground forced by the annual global CO_2 taken from McGuire et al. (2001) and the first 30 years of detrended climate input for 1961–1990 to reach a vegetation state in equilibrium with the climate (Sitch et al., 2003). The model was driven by historical observation data (i.e., monthly temperature, precipitation, and sunshine interpolated to get daily input) from 1961 to 2011 as a reference.

Driving Climate Data

To model the carbon dynamics and vegetation patterns for the twenty-first century, the model was driven by 100 time series that represent potential climate change projections for 1961–2099 (for more details, see Guillod et al., 2018). These climate scenarios were generated using weather@home2 (Guillod et al., 2017) under the RCP 8.5 emission scenario. Weather@home consists of an atmospheric global climate model (HadAM3P) which is dynamically downscaled over Europe by the regional climate model (RCM) HadRM3P. The CO_2 concentration used in LPJ-GUESS for the future was consistent with the emission level in RCM 8.5 (van Vuuren et al., 2011). The future time series, unlike some other RCM outputs, were found to represent mean climate and extreme hydro-meteorological events, like drought and flooding, relatively well (Guillod et al., 2018). The MaRIUS climate dataset (from which monthly mean temperature, bias-corrected precipitation, and solar radiation were used) covered three time slices from 1961 to 2004 (baseline), 2020 to 2049 (2030s), and 2070 to 2099 (2080s) at a spatial resolution of 25 km. We compare the two future time slices (2030s and 2080s) to a 30-year baseline period of 1975–2004 in order to capture both short-term and long-term ecological responses in LAI and NPP.

The dataset was disaggregated to a 5-km grid in order to match the LPJ-GUESS modeling grid using the following procedures: (i) multiplication of the ratio of Standard Average Annual Rainfall (SAAR) at a 25-km grid to the SAAR value at 5 km by the 25-km grid rainfall (Bell et al., 2007); (ii) application of a lapse rate to the temperature of the 25-km grid according to the elevation differences; and (iii) assigning the value of solar radiation to the 5-km grid equivalent to the 25-km grid encompassing it. Thus, the climate data input was based on a large ensemble, rather than several projections, and was at a high spatial resolution compared to many equivalent modeling studies.

LPJ-GUESS also required the continuous simulation of the ecosystem from 1961 to 2099. The gaps in the MaRIUS output for the periods 2005–2019 and 2050–2069 were filled in using the procedures proposed by Morales et al. (2007). This not only retained the interannual variability patterns associated with the existing climate data but also enabled a smooth transition of the temporal means and variances of the climate variables between two periods. **Table 1** summarizes the LPJ-GUESS simulations used in this paper. In order to understand the CO_2 effects, the simulations of all projection scenarios also were run with a constant CO_2 level for 2011 for comparison.

[2]http://www.nateko.lu.se/lpj-guess

Tree Mortality as an Indicator of Climate Vulnerability

The tree mortality function was adapted from forest gap models (e.g., FORSKA). It affected plant successional dynamics and community structures (Keane et al., 2001). The tree's death was a complex process commonly caused by interactions of different biotic and abiotic factors, such as age, drought, poor growing conditions exhausting carbon reserves, wind storms, insect outbreak, fire, and anthropogenic harvest. Here, we only considered the growth-dependent mortality, which was strongly driven by climatic variations and characterized the quality of growing conditions for a given tree species or PFT. The mortality was modeled as a stochastic function at a stand level (Steinkamp and Hickler, 2015):

$$mortality = \frac{0.3}{1+\left(\frac{greff_{mean}}{greff_{min}}\right)^5} \quad (1)$$

$$greff_{mean} = \frac{NPP\ \left(\mathrm{kg\,(C)\,m^{-2}}\right)}{LA\ (\mathrm{m^2})} \quad (2)$$

where $greff_{mean}$ was the growth efficiency, defined as annual NPP divided by LA based on a 5-year running average. $greff_{min}$ was set to 0.04, 0.06, and 0.08, respectively, according to whether the tree species or PFT was classified as shade-tolerant, intermediate-shade-tolerant, or shade-intolerant (Hickler et al., 2012). Water stress was modeled as the difference between water demand for optimal non-water-limited photosynthesis and water supply from root-distribution-weighted soil water content. It would result in reduced CO_2 uptake, photosynthesis, and eventually slowed growth for several years leading to tree death. Hence, higher growth-dependent tree mortality partially reflected the degree of drought impact. For the water supply function, we used a species-specific formulation (Schurgers et al., 2011; Appendix B), which better reflected species-specific drought responses than the more general model applied in Hickler et al. (2012).

We developed the climate vulnerability index (CVI) which related future climate-induced mortality to a baseline period (1975–2004). Firstly, based on the simulated mortality in baseline, the zero-mean normalization was applied separately to the 2030s and the 2080s to obtain the time series of z-score in each period. This transformation provided a standard measure (i.e., z-score) allowing for comparison of the degree of climate impact on tree species at different time periods ignoring the temporal trend and spatial variability of the background mortality. Secondly, a threshold needed to be determined to identify the mortality of concern. The CVI was obtained by the summation of simulated mortality above the threshold (S) in the future divided by that of baseline, represented as:

$$S = \sum_{i=1}^{n} z_i d_i \quad if\ z_i \geq z_t\ \ d_i = 1\ else\ d_i = 0 \quad (3)$$

$$CVI = \frac{S_{future}}{S_{baseline}} \quad (4)$$

where n is the number of years of the simulated mortality time series; z_i is the z-score of the ith year in the simulation period; z_t is the specified threshold; d is equal to 1 to indicate a concerned drought impact and set to 0 otherwise; and S is the summation of the mortality of concern indicating the severity of the potential climate impact during the corresponding simulation period. Although the CVI was not an indicator for assessing tree mortality in reality and the threshold was usually determined subjectively, a higher CVI would indicate a higher degree of climate change and drought vulnerability. It could be used to compare the differences in potential climate impacts between the

TABLE 1 | Overview of the LPJ-GUESS simulations.

Name	Interpretation time period	Driving data	Modeling settings	Number of realizations
Historical	1975–2004	UKCP09 gridded observation	1000-year spin-up and starting from 1961 to 2011	1 (observed)
Baseline	1975–2004	MaRIUS dataset	1000-year spin-up and starting with MaRIUS climate from 1961 to 2099. Climate dataset from 2005 to 2019 and from 2050 to 2069 is interpolated using Morales et al.'s (2007) methodology	100 (sampling natural variability)
2030s	2020–2049			
2080s	2070–2099			

geographical regions and species. A CVI of <1 meant that the potential impact was lower in the future compared to the baseline.

Projected Future Climate Changes

The MaRIUS 100 RCM outputs show that the projected mean annual temperature change over Britain increased from between 0.8 and 1.4°C in the 2030s and between 2 and 3.8°C in the 2080s (**Figures 1A,C**). **Figures 1B,D** show the range of projected mean annual temperature change varying from 0.15 to 0.4°C in both the 2030s and the 2080s. Greater warming appeared in southern Britain and in summer, with an increase of 4 to 4.5°C in the 2080s. This greater warming is consistent with other recent climate scenario outputs for the United Kingdom, such as UKCP18 (Lowe et al., 2018). Annual precipitation was projected to decrease across Britain except for the northwest coast of Scotland. The greatest reduction of precipitation was projected to occur in Wales, southwest and northwest England, and west Scotland, with an annual decrease of 50–100 mm in the 2030s and 100–150 mm in the 2080s (**Figures 1E,G**). The precipitation reduction in southeast England was around 0–50 mm in the 2030s rising to 50–100 mm in the 2080s. The range of the projected annual precipitation change showed a similar pattern for both the 2030s and the 2080s, with more than 300 mm on the northwest coast; 100–200 mm in Scotland, Wales, and northwest and southwest England; and 0–100 mm in southeast England (**Figures 1F,H**). Thus, the MaRIUS climate datasets could be considered as an appropriate test bed for dry conditions, although it may overestimate the dryness in southeast England.

RESULTS

The potential impacts of climate change were analyzed by comparing the modeled average LAI (i.e., representing vegetation structure) and NPP in the 2030s and the 2080s to the baseline (i.e., 1975–2004). With 100 modeling runs available, mean changes in modeled ecosystem properties are shown, complemented by the range of the 10–90th percentiles to indicate the uncertainty arising from natural weather-induced variability. The climate vulnerability of selected tree species was assessed using the CVI based on comparing the simulated growth-dependent mortality in the future to that of the baseline.

LAI Change

The projected mean change in LAI summed across all tree species and PFTs over Britain ranged from 0.25 to 2.24 in the 2030s and from 0.9 to 4.2 in the 2080s (**Figures 2A,B**). Without a change in CO_2, the mean LAI change was slightly less with ranges from 0.2 to 2.2 in the 2030s and from 0.6 to 3.7 in the 2080s (**Figures 2C,D**). As expected, the CO_2 level only affects the degree of modeled LAI change but has no impact on the geographical patterns. In both CO_2 settings, the simulated areas of greatest LAI change occur in Scotland and northern England, as conditions

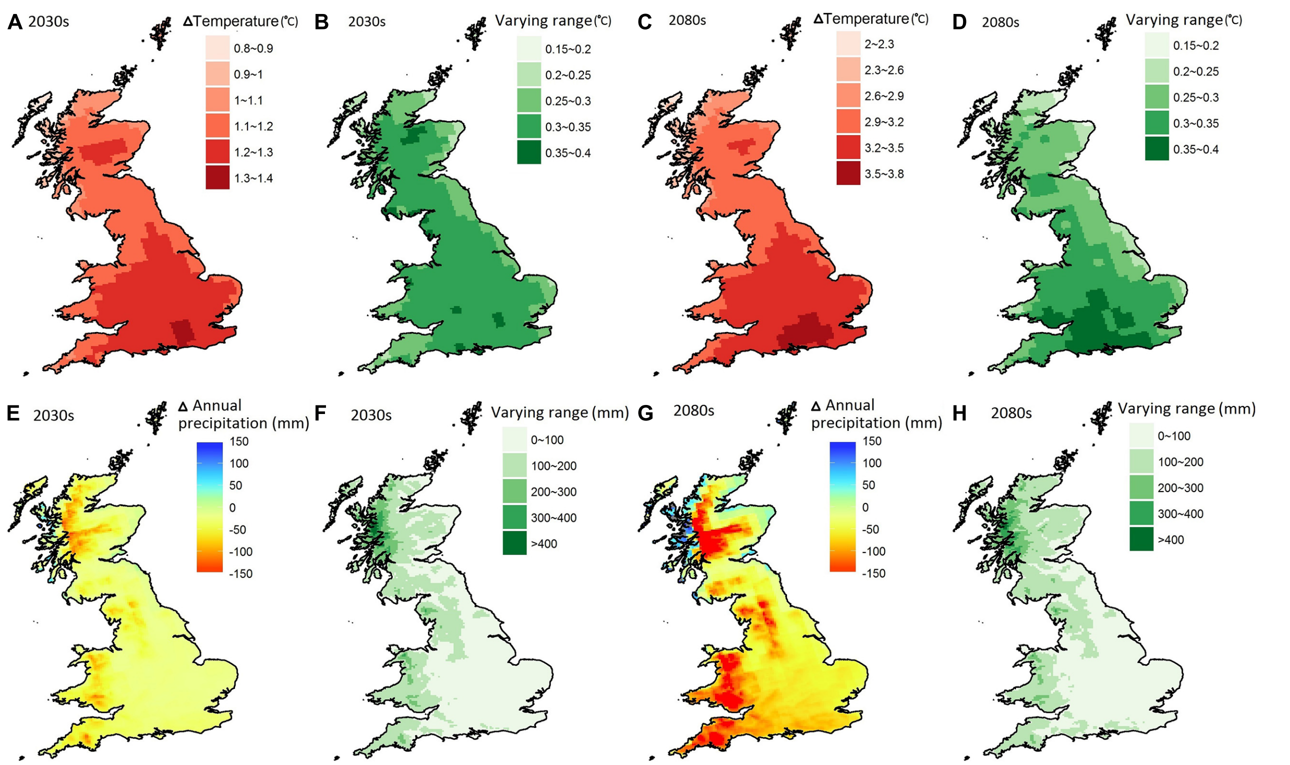

FIGURE 1 | The mean change of the projected annual temperature **(A,C)** and precipitation **(E,G)** averaged over the 2030s and the 2080s relative to the baseline (1975–2004); the range of the projected change of temperature **(B,D)** and precipitation **(F,H)** between the 10 and 90th percentiles in the 2030s and the 2080s.

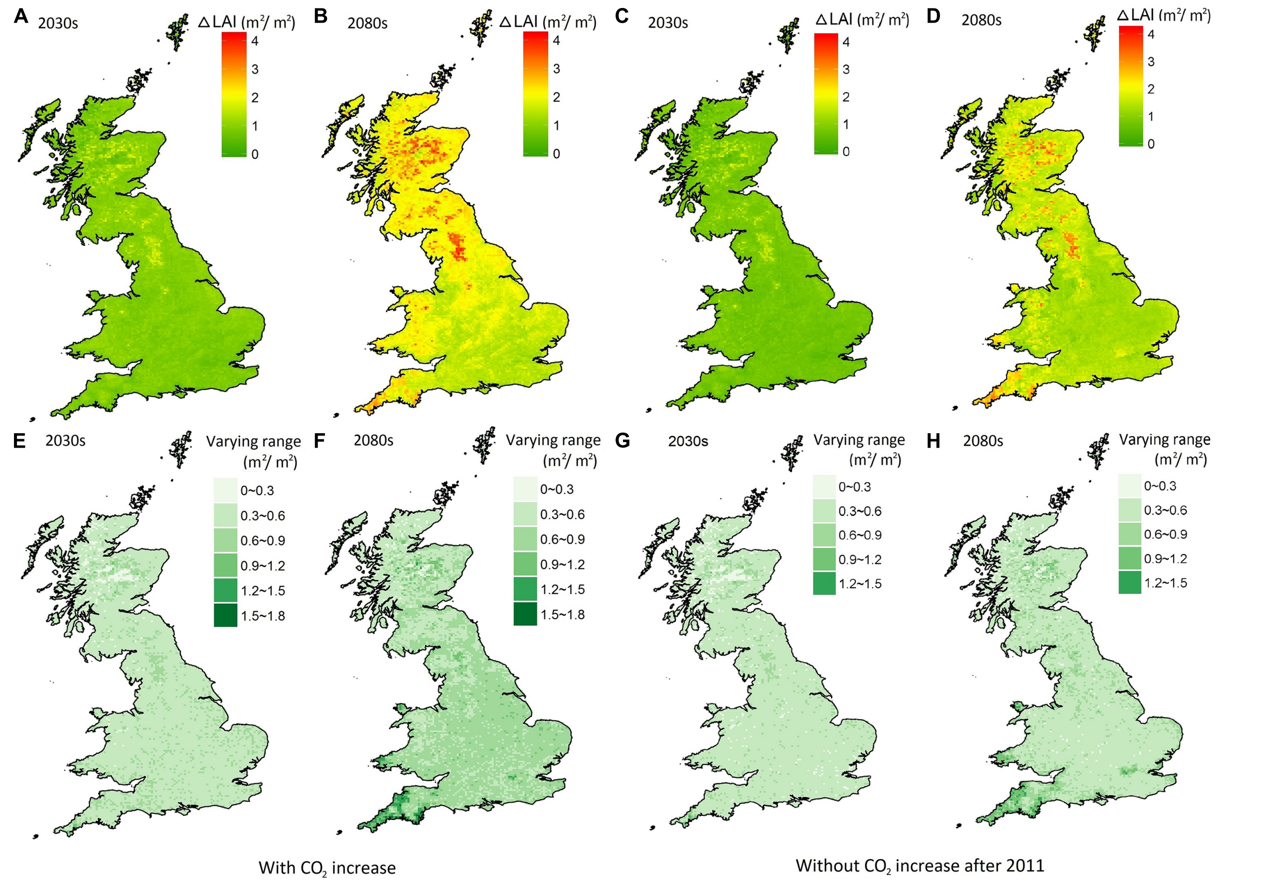

FIGURE 2 | The projected mean change of LAI in the 2030s **(A,C)** and the 2080s **(B,D)** relative to the baseline from 1975 to 2004; the range of the LAI change between the 10 and 90th percentiles in the 2030s **(E,G)** and the 2080s **(F,H)**.

become more suitable for deciduous tree species to grow under the warming climate. This also implies that a greater change in tree composition may occur in these regions.

The range of projected LAI change due to the natural weather-induced variability is slightly lower (0.1–1.3) in the 2030s (**Figure 2E**), than the 2080s range of 0.1–1.8 (**Figure 2F**). According to the ratio of the projected range of LAI change to the mean value, the degree of uncertainty (in terms of model results with different climate ensembles members) was slightly larger in the 2030s (with the ratio from 0.14 to 1.1) compared to that in the 2080s (from 0.08 to 0.92). Geographically, the climate-related uncertainty is slightly larger in southern Britain. A similar pattern, but with a slightly lower degree of natural weather-induced uncertainty, can be found in the modeling results without CO_2 increase (**Figures 2G,H**), with a range of 0–1.5 for both the 2030s and the 2080s. The results revealed that the CO_2 increase has limited impact on the degree of uncertainty caused by climate variability.

The simulated net LAI change was in a range of −0.2–0.98 and −0.95–1.93 in the 2030s and the 2080s, respectively, under the stable CO_2 scenarios (**Figures 3A,B**). In the 2080s, the net LAI change increased from 0 to 1.93 in Britain, except for SE and SW England, where the net LAI change decreased by 0–0.95. The difference of projected net LAI change between stable and increased CO_2 showed that the increase of CO_2 led to an increase of net LAI change of 0–0.3 in the 2030s with the same climate conditions (**Figure 3C**). In the 2080s especially, the increase in CO_2 had a greater effect on the increase of net LAI in England and Wales with an increase of 0.8–1.2, compared to most areas in Scotland with an increase of less than 0.8 (**Figure 3D**). This indicated that the CO_2 increase had a relatively greater effect on tree species composition in these regions (**Figure 3D**) in comparison to temperature and precipitation.

The time series of simulated net LAI (**Figures 3E,F**) showed that for the 50th percentiles, the LAI across Britain was projected to increase gradually by around 30% for the uplands and 100% for lowlands from 1975 to the late twenty-first century. The associated uncertainty remains stable for all the years, with the range between 5 and 10% of the 50th percentiles. Compared to the modeling results for 1975–2004, simulated by the observation climate dataset (black dots), the dynamic ecosystem model driven by the ensemble RCM scenarios tended to overestimate the LAI of the 50th percentiles in the uplands. Therefore, it should be noted that the future physiological response of trees in reality is most probably in the lower range of the MaRIUS scenarios in the uplands.

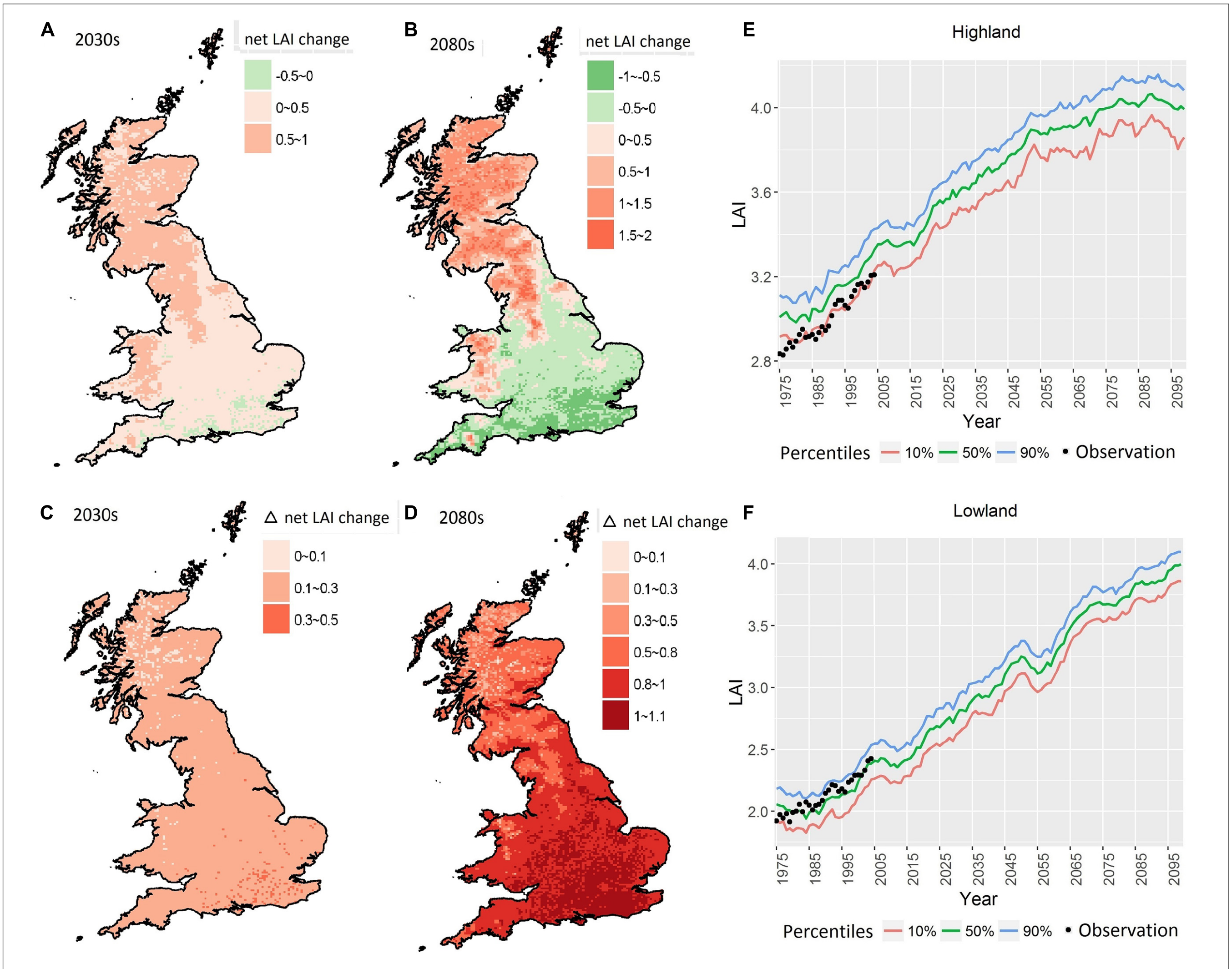

FIGURE 3 | The projected net LAI change in the 2030s **(A)** and 2080s **(B)**; the difference of projected net LAI change when CO_2 increase was enabled compared to its absence in 2030s **(C)** and 2080s **(D)** relative to **(A,B)**; the time series of net LAI in highland **(E)** and lowland **(F)** simulated using observations and MaRIUS climate.

Plotting the ratio of LAI change of individual tree species relative to baseline for the 19 river basin regions used in UKCP09 (Murphy et al., 2009) helped understand more regional potential tree species composition change (**Figure 4**). The LAI generally increased for all the tree species in the 2030s. Despite the overall LAI increment in the 2080s, downy birch (*Betula pubescens*), hornbeam (*Carpinus betulus*), beech (*Fagus sylvatica*), and small-leaved lime (*Tilia cordata*) showed lower increments in England and Wales. The LAI increase for hazel (*Corylus avellana*), silver birch (*Betula pendula*), ash (*Fraxinus excelsior*), aspen (*Populus tremula*), oak (*Quercus* spp.), and elm (*Ulmus glabra*) in southern Britain (i.e., Anglian, Thames, SE England, SW England, Severn, and W Wales basins) remained at a similar level to that in the 2030s. The magnitude of LAI increment for these species increased gradually from southern to northern Britain. This indicated the increased future suitability of conditions in northern Britain for most deciduous tree species. Without an increase of CO_2 (**Figure 5**), the degree of relative LAI change for each species mostly decreased, especially in southern Britain river basins. A decrease of LAI can have mixed effects, decreasing water and nutrient use but also NPP and carbon uptake. In terms of relative LAI change, the nondominant species (i.e., silver birch, hornbeam, hazel, aspen, and small-leaved lime) had larger uncertainty than other species, especially in the 2080s and in southern Britain.

Carbon Fluxes

The geographical distribution of NPP averaged over 1975–2004, simulated by using the observation climate dataset varied from around 0.1 to 0.5 kgC/m^2/year over Britain, with an average of 0.36 kgC/m^2/year (**Figure 6A**). The dynamic global vegetation model, JULES, which has been applied to Britain and is based on five plant functional types, only two of which are woodland, had baseline (1998–2008) NPP values of 0.2 to 1.0 kgC/m^2/year (Ritchie et al., 2019). However, it is acknowledged that it possibly overpredicts productivity and it has a shorter, more recent

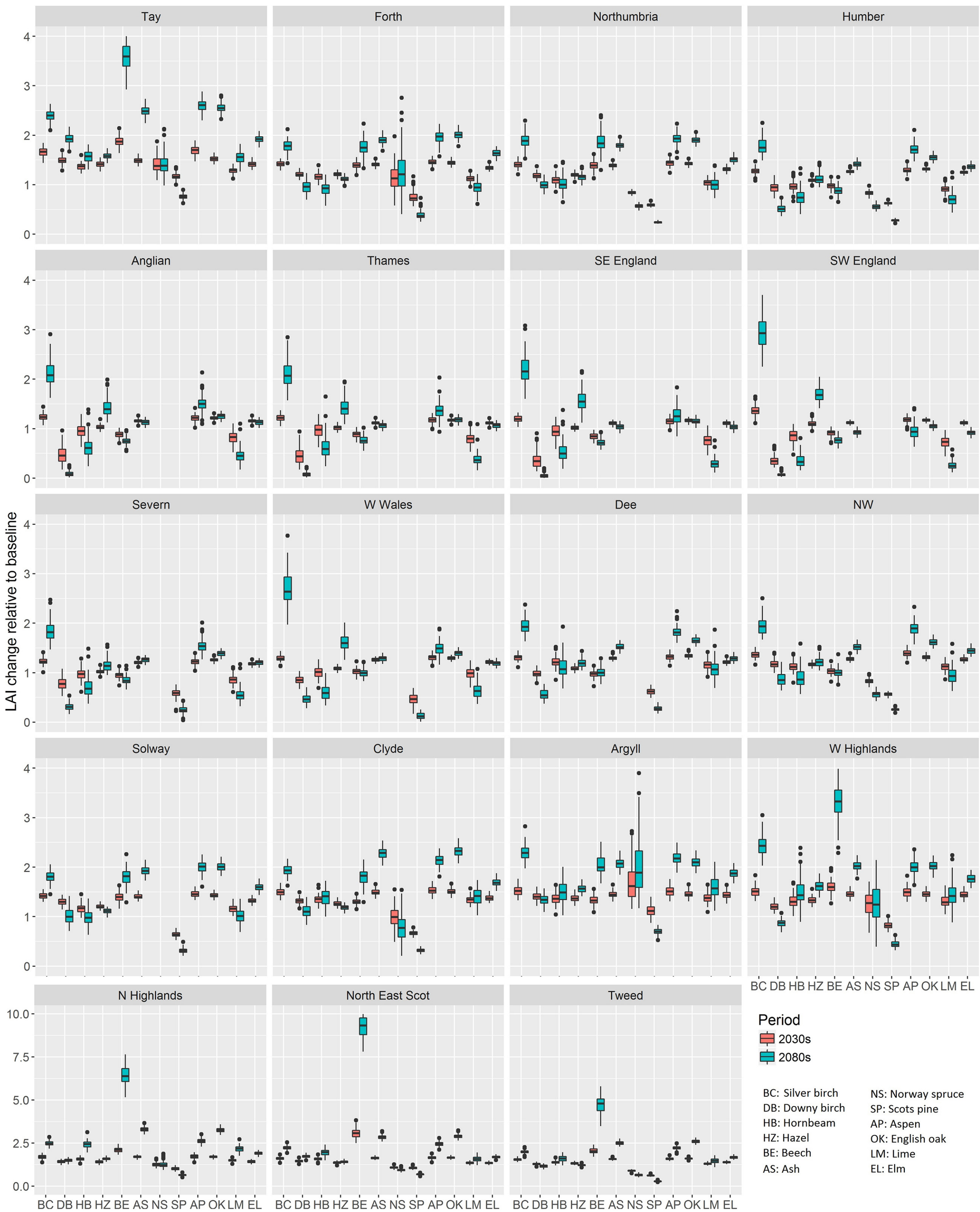

FIGURE 4 | The boxplot of simulated LAI change with CO_2 increase enabled in the 2030s and the 2080s relative to baseline (1975–2004) for 12 modeled tree species and 19 river basin regions.

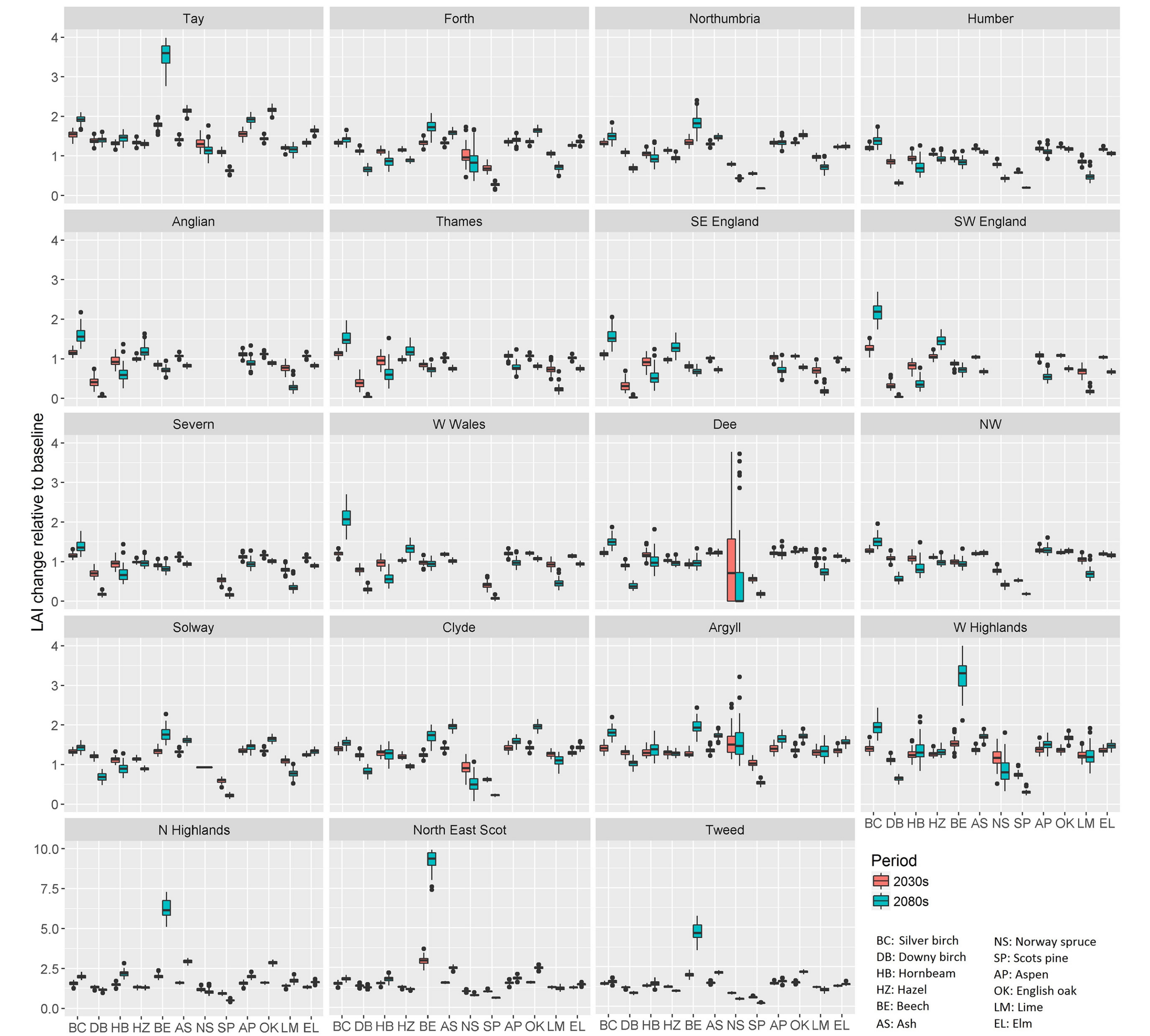

FIGURE 5 | The boxplot of simulated LAI change without CO_2 increase in the 2030s and the 2080s relative to baseline (1975–2004) for 12 modeled tree species and 19 river basin regions.

baseline. It showed a good agreement, not surprisingly, with the average estimate for Europe (i.e., 0.38 kgC/m^2/year) from an earlier version of LPJ-GUESS based on PFTs, driven with results from a range of RCMs at 0.5° resolution (about 50 km) from CORDEX (Morales et al., 2007). It also was within the range of measurements of NPP at a seminatural woodland, Wytham Woods, Oxfordshire, United Kingdom, which recorded NPP as 0.13 kg/m^2/annum over a 2-year period (Thomas et al., 2011), while an earlier study, including soil productivity, recorded 0.7 kg/m^2/annum (Fenn et al., 2010).

NPP was projected to increase by 0.03–0.18 kgC/m^2/year in the 2030s and 0.05–0.39 kgC/m^2/year in the 2080s (**Figures 6B,D**). Without a CO_2 increase, a relative smaller NPP increase, and even a very slight decline, was projected of −0.02–0.15 kgC/m^2/year in the 2030s, and −0.12–0.28 kgC/m^2/year in the 2080s (**Figures 6F,H**). These figures are lower than Ritchie et al. (2019), who modeled changes for 2,100 without CO_2 ranging from −0.5 kgC/m^2/year in southern Britain to +0.5 kgC/m^2/year in the north and from 0.1 to 0.5 kgC/m^2/year with CO_2.

The CO_2 effect had greater impacts on southern Britain with a modeled decrease of NPP change without CO_2 increase. The geographical patterns of the NPP change projections in the 2080s were similar to those of Ritchie et al. (2019). Morales et al. (2007) also showed larger increases in the northern half of Britain and west Wales. According to the LPJ-GUESS

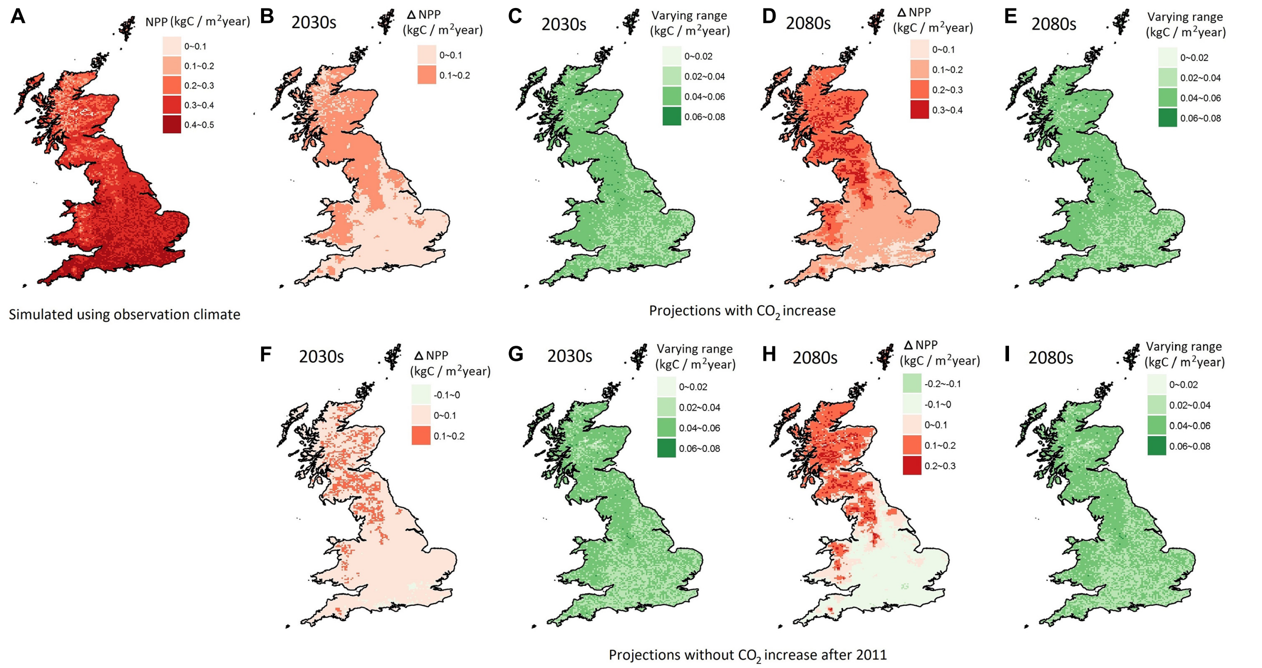

FIGURE 6 | The modeled present-day NPP **(A)** averaged over the period from 1975 to 2004 driven by observation climate dataset; the mean **(B,D,F,H)** and range **(C,E,G,I)** of the NPP change in the 2030s and the 2080s with and without a CO_2 increase, respectively.

model, the higher temperatures are likely to increase the suitable conditions for most deciduous trees growing in northern Britain, with the potential to replace the non-woody vegetation and coniferous species. The relatively lower increment of NPP in south and southeast Britain might be due to the offset effects of increased evapotranspiration and soil water depletion caused by the increased temperature. These results are consistent with the conclusions of Broadmeadow et al. (2005), based on the Ecological Site Classification model (which does not include potential plant-physiological effects of increasing atmospheric CO_2), that water limitation in southern England is likely to lead to an overall reduction in growth for the majority of native broadleaf species. Thus, this paper, using a process-based model, demonstrates the vulnerability of woodlands in southern Britain to climate change, especially without further increases in CO_2.

The range of the projected NPP change across Britain (**Figures 6C,E**) was from 0.01 to 0.067 in the 2030s, which is greater in the 2080s (0.01–0.076). It showed a similar level to the modeled range under scenarios without CO_2 increase (**Figures 6G,I**). Relative to the mean change of NPP, the degree of uncertainty in NPP change was slightly larger in the 2030s. The absence of the CO_2 increase added to the degree of uncertainty originating from natural weather-induced variability.

Climate Vulnerability of Tree Species

Figure 7 shows the statistical distribution of the mortality z-values simulated using the observation climate dataset. We selected the z-value of 1.18 as the threshold to derive the CVI because the temporal pattern (i.e., inset figure in **Figure 7**) of the climate-induced mortality above this threshold showed the peaks of climate impacts in 1977/79, 1985–87, 1996, 2002, and 2004. These are consistent (with slight lags in some) with the reported historical drought events in 1975/76, 1984, 1989/90, 1991/92, 1995–97, 2003, and 2004–06 in the United Kingdom. The time lags were expected because mortality is often increased some years after drought events (e.g., Peterken and Mountford, 1996) and also the model formulations are based on a 5-year running average growth efficiency. With 100 ensemble projections available, we interpreted the CVI at the 50th percentiles under the scenarios with CO_2 increase enabled. The choice of percentile and CO_2 modeling scenario will lead to variations in the CVI value; however, it will not affect the geographical patterns of climate vulnerability among the tree species and across river basin regions. Hence, it could guide the government or stakeholders in investing resources strategically to more vulnerable species and regions. Overall, climate-driven mortality was projected to decrease in the future (**Figure 7**), but with large spatial and species-specific variation (**Figure 8**) as discussed below.

Figure 8 shows the geographical patterns of climate vulnerability for the 12 modeled tree species in the 19 river basin regions. The degree of climate vulnerability of all the tree species increased slightly in most regions in the 2080s compared to the 2030s. This suggests that the temperature increase and precipitation reduction are likely to lead to more potential drought stress for tree growth. However, the LAI and NPP were still projected to increase in the longer term, which is likely to be due to the ecological recovery capability of tree species, together with increased ecosystem productivity in the non-drought period due to warmer climate and rising CO_2. Downy birch, ash, oak,

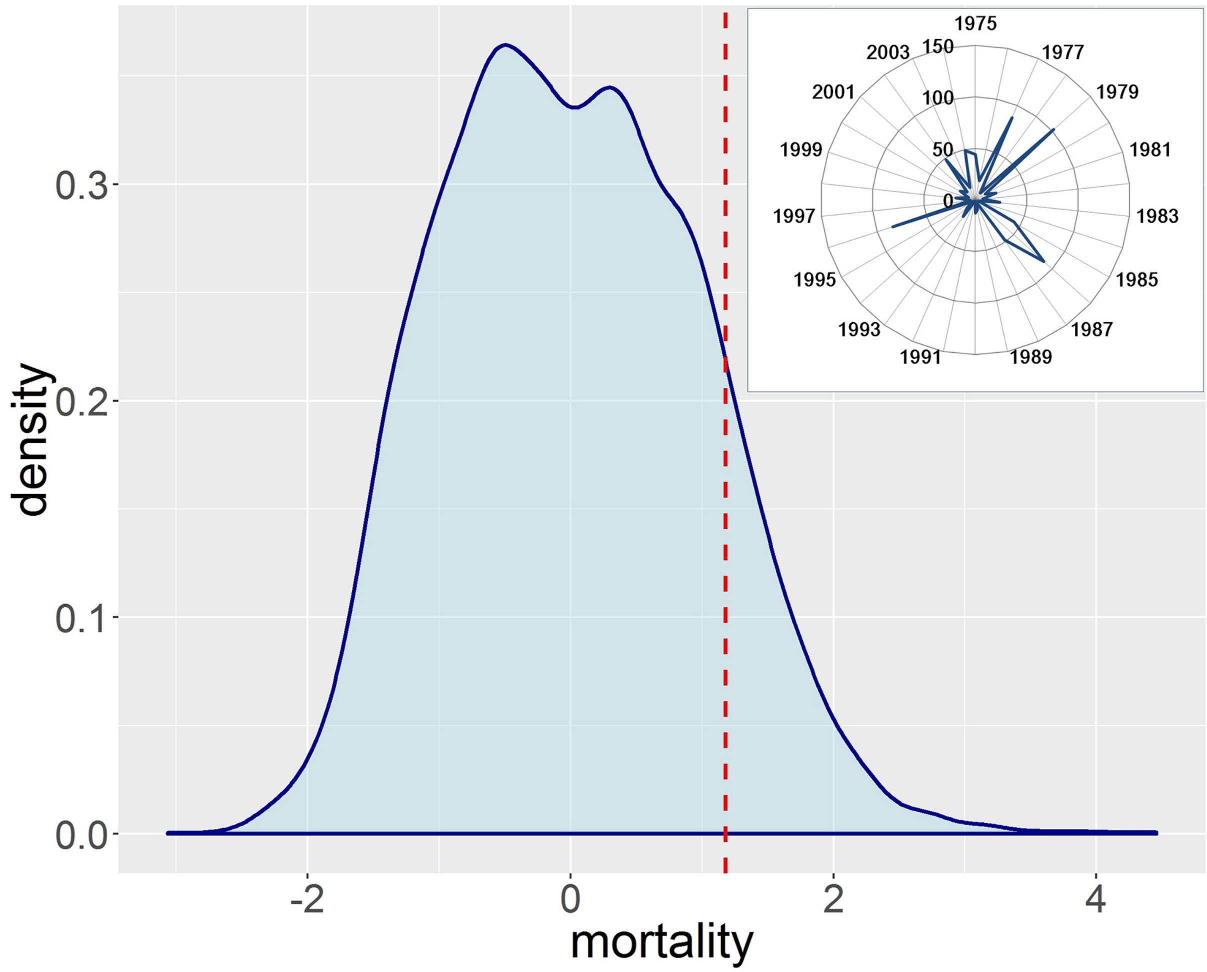

FIGURE 7 | Statistical distribution of simulated mortality *z*-values using observation climate dataset and temporal pattern (i.e., percentiles) of mortality *z*-values above the threshold for different years (inset figure).

and elm were projected to be more vulnerable in southeast England (i.e., Anglian, Thames, and SE England) in the 2030s, with vulnerable regions spreading across Britain in the 2080s. The climate vulnerable regions for silver birch and hazel were the Thames and Severn basins, and northern Scotland, respectively. Those for hornbeam, aspen, and lime were more in the northern England and southern Scotland. Beech showed stress across almost the whole Britain in the 2030s, the most vulnerable regions being the Forth, Clyde, Tweed, and Solway basins in the 2080s. In addition, the increment of the threshold to consider more severe climate-induced mortality generally resulted in a reduced CVI in the 2030s and in northern Britain. In the 2080s, southeast Britain (i.e., Anglian, Thames, SE England, Severn, Humber, etc.) was the stress region for most of the deciduous tree species. Several actions are possible to reduce these impacts making forests more resilient to these stresses, including planting more drought-tolerant provenances and species and planting a greater variety of species (Broadmeadow et al., 2005).

The projected climate-vulnerable regions for Norway spruce and Scots pine were in W Highland and Clyde, but the degree of vulnerability for Scots pine was lower under the higher threshold. This is consistent with the pattern of drought impact in terms of stand yield projected in these regions by Petr et al. (2014). In addition, they projected their decline in south and southeast Britain, which should also be considered. Overall, taking both the degree of vulnerability and the number of affected tree species into consideration, the river basin regions of Anglian, Thames, and SE England were most vulnerable to climate change and drought impacts. The vulnerability could affect the whole England and Wales (in the 2080s) if the severe climate-induced mortality is considered.

DISCUSSION

The application of a tree-species based dynamic ecosystem model driven by a novel large, fine spatial resolution hydro-meteorological time series for the United Kingdom enabled the assessment of the potential ecological responses of forests and trees in Britain to both climate change (including drought) and

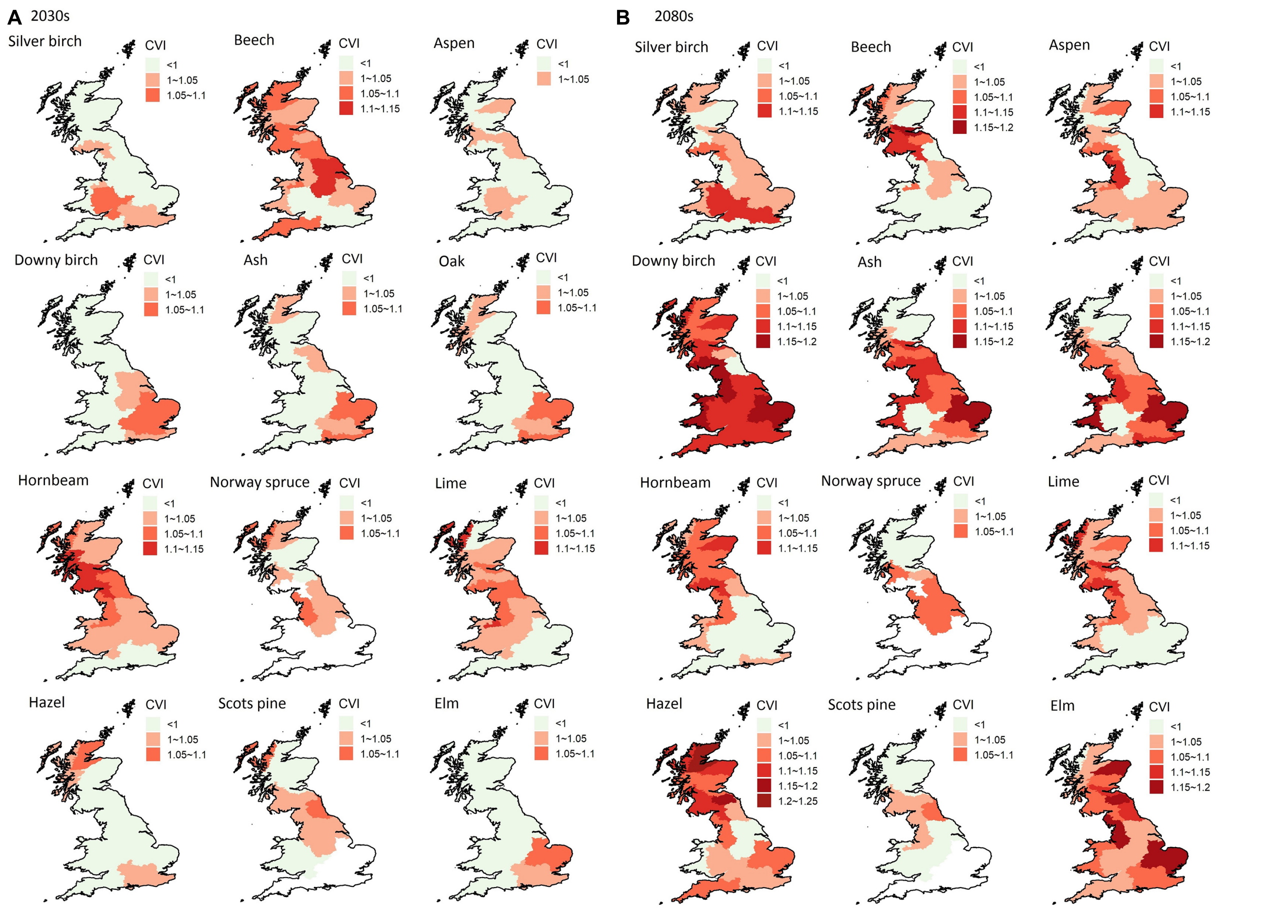

FIGURE 8 | The climate vulnerability of 12 tree species in the 19 river basin regions in the 2030s **(A)** and the 2080s **(B)**, with the threshold set at the median level.

potential physiological CO_2 effects. While the dynamic global vegetation model, JULES, has been applied at a finer resolution to Britain, it is based on only five plant functional types and does not include specific tree parameterization, although outputs include changes in NPP in broad-leaved woodland, both with and without CO_2 (Ritchie et al., 2019).

In our work, the projected spatial pattern of ecological responses showed an increase of LAI across Britain both with and without CO_2, with larger increments when CO_2 effects were included. There were also regional differences, with greater increases in Scotland, northwest England, and west Wales. Stronger increases in more temperature-limited areas are expected, and positive effects of temperature increases have also been observed in central European and northern ecosystems (Lucht et al., 2002; Pretzsch et al., 2014; Zhu et al., 2016) and other modeling studies (e.g., Mankin et al., 2017; Ritchie et al., 2019). The reduction in NPP in southern Britain under the no CO_2 increase scenario, especially in the 2080s, supports the proposed role of CO_2 in alleviating drought stress (Swann et al., 2016; Ault, 2020). Also, less carbon could be sequestered in southern and central England and easternmost parts of Wales in 2080s with the no CO_2 increase scenario, as NPP decreased in these regions relative to the baseline.

Precipitation reduction was a secondary factor influencing the NPP. The NPP increase in southeast Britain was insignificant when including CO_2 effects, most likely through a balance of negative impacts of more drought stress and positive impacts of elevated CO_2 on photosynthesis and water use efficiency. Thus, this paper, using a process-based model, endorsed the vulnerability of woodlands in southern Britain to climate change, especially without further increases in CO_2. Also, it demonstrated the potential increases in productivity, especially in the 2080s, in the higher parts of England and throughout Scotland both with and without changes in CO_2, as a consequence of the improving climate.

Secondly, it could be expected that the climate scenarios were the major uncertainty sources in climate impact studies leading to different spatial patterns of ecosystem responses (Morales et al., 2007). However, the natural weather-induced variability was shown to influence the projected changes of LAI and NPP (at a level of 5–100% of the projected mean change), but not their geographical patterns. According to the model, southeast England is most sensitive to climate variability; in particular, the nondominant species (e.g., silver birch, hornbeam, hazel, and aspen) were strongly affected and potentially this could lead to changes in woodland composition. Therefore, the effectiveness of adaptation measures adopted in southeast England might be inappropriate in other regions in Britain. Finally, this region was also the most susceptible to climate change and drought, which is consistent with previous studies (Broadmeadow et al., 2005; Petr et al., 2014) and western Britain was projected to be more resilient to drought and climate change.

Some current key woodland-forming species, such as oak, elm, beech, and ash, showed little change or a slight decrease in LAI in the SE and SW England, Anglia, and Thames basins, and three (ash, oak and elm) were projected to be particularly more vulnerable in the 2080s in the SE England, Anglia, and Thames basins. In these areas, current and future species planting plans will need to be reevaluated to ensure they are robust, not just to mean climate change, but also, as shown by this paper, to natural weather variability and drought. In contrast to these canopy-forming species, some characteristic understorey or earlier successional tree species, such as hazel, aspen, and silver birch, could be less vulnerable to climate change.

However, in the West and North Highland and NE Scotland basins, ash, oak, and elm showed not only an increase in LAI but also a decreased vulnerability. Currently, however, they form a small percentage of the composition of native broad-leaved woodland, with birch (silver and downy) being the most important species depending on region (Price and Macdonald, 2012). While silver birch had increased LAI in the future, this was not true for downy birch and although both showed lower vulnerability in the 2030s, downy birch is vulnerable almost throughout Britain in the 2080s. These two contrasting examples demonstrate the potential for significant future changes in the species composition of broad-leaved woodland in Britain.

The main limitations of this study were that the tree species had been parameterized for Europe and their values for Britain might be more constrained. Also, we only modeled a selection of the tree species that were widely distributed in Britain without considering the human derived land use patterns (i.e., agricultural and urban areas) and we excluded waterlogged vegetation classes that are topographically affected. Hence, the projected ecological responses (i.e., LAI and NPP) were interpreted as the potential change determined by climate and soil conditions alone. Human management could modify the outcomes, thus introducing a new source of uncertainty, as could changes in atmospheric composition. Decreases in the deposition of nitrogen and sulfur may also affect NPP, although a study of their impact on temperate forests in Europe and United States (1995–2011) suggested that their effects may cancel each other out (Fernández-Martínez et al., 2017) and that CO_2 is the dominant influence on net ecosystem productivity and gross primary productivity increases.

Related to this, the model only projected the presence of coniferous species (i.e., Norway spruce and Scots pine) in northern Britain (i.e., W Highland, N Highland, North East Scot, Argyll, Tay, etc.), as it was considering the potential vegetation, whereas in reality conifers are widely planted for forestry purposes across Britain. Norway spruce is not considered a natural species and has only been cultivated in low densities, partly as Sitka spruce performs much better in Britain (Savill, 2002; Caudullo et al., 2016). Thus, the parameterization of the model could be refined for further applications to the study area and other modeling tools (e.g., species distribution models and ecological site classification model) would be needed to assess their response to climate change. However, such models do not incorporate the dynamic ecological processes and thus are not so appropriate for informing climate adaptation for woodland conservation.

Heat- and drought-stressed-related tree mortality has become increasingly important in Europe, in particular since the dry summer of 2018 (Schuldt et al., 2020). Therefore, it is important that the model appears to capture mortality events related to main drought events in the past, but it is difficult to evaluate these results quantitatively. Furthermore, trees often die because of secondary stressors such as insect pests, which were not explicitly included here (but see Jönsson et al., 2012 for a version of LPJ-GUESS with bark beetles for Sweden). Nevertheless, evaluating simulated drought impacts should be a research priority for the future (Steinkamp and Hickler, 2015).

Given the various commitments to tree planting to address the United Kingdom's legally binding target of net zero emissions by 2050, many have argued that the planting needs to be the right tree in the right place (e.g., Natural Capital Committee, 2020; Seddon et al., 2020), including ensuring that they are resilient to climate change. Thus, understanding the future impacts of climate change, natural variability, and CO_2 on forests and the growth of different species is important. This study has shown that climate change could particularly affect the carbon storage potential of forests and the appropriate choice of tree in southern Britain, with many current woodland-forming species potentially being unsuitable in the future. However, in the north a wider range of tree species could be suitable, thus increasing options. In both regions, there could be significant changes in woodland composition.

This study has provided an indication of which species may be appropriate when tree planting for climate mitigation and adaptation. However, one should keep in mind that the vegetation model does not cover all aspects of the ecology of the tree species (Hickler et al., 2012). For example, specific responses to water logging and soil pH are not covered. These shortcomings and the uncertainties related to the climatic inputs and potential CO_2 effects, therefore, call for risk spreading as an important component of any climate adaptation strategy, i.e., promoting species-rich mixed stands or mosaic with stands dominated by different species.

Therefore, this study was the first to apply a fine-scale process-based ecosystem model to the issue of the potential impacts of climate change, natural weather-induced variability, including drought, and direct CO_2 effects on trees in Great Britain. The modeling showed that the net change in LAI and NPP could increase with CO_2 and more so in the 2080s than the 2030s. However, there were smaller changes projected for southern Britain, where NPP could decrease without the effects of increasing CO_2. Also, its potential for future carbon sequestration is less. The greater apparent vulnerability of southern England was reflected in the potential responses of many of the tree species, for example, downy birch, ash, oak, and elm. Southeast England was the most sensitive to climate change, natural weather-induced climate variability, and drought, so in this region particular consideration needs to be given to adaptation measures for existing forests and to future plantings. In contrast, there were greater increases in LAI and NPP in parts of northern England, west Wales, and Scotland, with trees such as ash, oak, and elm becoming less vulnerable. As these are not currently an abundant component of forests, this would require different adaptation strategies. Therefore, this study has shown how climate change could differentially affect the future of forests in Great Britain in terms of their vulnerability, composition and need for adaptive management.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. The climate data used as model input are freely available from https://catalogue.ceda.ac.uk/uuid/0cea8d7aca57427fae92241348ae9b03. LPJ-GUESS is available from http://web.nateko.lu.se/lpj-guess/.

AUTHOR CONTRIBUTIONS

TH supplied the LPJ-GUESS model. BG supplied the Marius climate data set and commented on scenario outputs. JY downscaled the climate scenarios and ran the LPJ-GUESS model. PB directed the research, helped in the ecological interpretation of the results. All authors have contributed to writing the manuscript, but JY led the draft of the manuscript, and PB its revision.

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BRIEF RESEARCH REPORT
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Achieving Water Efficiency in the Public Sector Through Social Norms

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Water efficiency campaigns in England and Wales currently focus on private domestic customers and private businesses and usually focus on either the implementation of technological devices, financial incentives or educational programs for school children. This brief research report focuses on the public sector (schools, hospital, universities, local government), an underexplored area for investigating the role of social norms in facilitating water saving. It takes the approach that the public sector provides so far untapped potential for water savings and asks how water saving behavior can be changed. Based on a review of academic, grey literature, documents and a workshop with stakeholders from water companies, regulators and public sector organizations, nine key themes are presented and discussed. The themes, which can also be understood as recommendations, emphasize that water saving behavior is influenced not just by individual decisions, but social and psychological drivers such as social norms, values or group behavior. For example, water saving competitions among different departments, embedding water into the bigger environmental story or the question of who delivers the water saving message may contribute to changing water saving behavior at the workplace[1]. The public sector is well placed to implement water efficiency programs involving social norms and could act as role model for other sectors.

Keywords: water scarcity, drought, water efficiency, social norms, public sector, United Kingdom

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INTRODUCTION

Water efficiency is a cornerstone of water resources management and public water supply. Yet, typical water efficiency campaigns are aimed at private domestic customers and private businesses. In addition, existing water efficiency campaigns focus on two key drivers of water saving behavior: technological devices such as water meters and financial incentives but leave unexplored the potential of social norms to create behavioral commitments to water saving. This brief research report focusses on the role of social norms for encouraging water saving behavior in the English and Welsh public sector. As yet there have been few studies on water efficiency in the public sector (schools, hospitals, universities, local government). For example, Fidar et al. (2016), Hassell and Thornton (2014) or Bremner and Jordan (2012). Cotton et al. (2016) focus on energy saving but the study included questions on water saving as well. It is the purpose of this article to provide concrete recommendations for water efficiency campaigns in the public sector. Public sector organizations provide significant untapped potential for water saving by virtue of their size and/

[1]I use the term "workplace" very loosely. Hence, I consider school children and university students attending school or lectures, seminars etc. as being at their "workplace."

or their nature as public organizations, thereby contributing to overall water savings. It was not possible within this research to estimate the scope of potential water savings by the whole public sector (see also under *Current State of Water Efficiency and the Public Sector in the UK*). However, one English water supplier, Essex and Suffolk Water, could show how beneficial water efficiency could be to borough, district and county councils, not just in terms of water savings, but also monetary savings. A water saving initiative carried out across five councils in their supply area 10 years ago saved 34,000 L of water per day (Essex and Suffolk Water, 2014, 230). Given that there are 333 councils in England alone, this points to the potential water savings. Furthermore, the total water consumption of the English health and social care sector in 2017, 2.3 million cubic meters, was similar to that of a country such as Estonia (Public Health England and NHS, 2018, 12), which again emphasizes the importance of the public sector in terms of water consumption but also potential savings.

This research is placed in the wider context of drought and water scarcity in the UK and the need to make substantial water savings in the future. “Drought is a recurring feature of the UK climate.” (Marsh et al., 2007, p. 88) The UK experienced a dry spell in summer of 2018 and recent drought events were between 2010 and 2012, 2004–2006 and 2003 (Met Office, 2012, 2013, 2016). The UK Climate Change Risk Assessment 2017 attributes a “medium magnitude now” but a “high magnitude in future” for the “risk of water shortages in the public water supply, and for agriculture, energy generation and industry, with impacts on freshwater ecology” (Committee on Climate Change Risk Assessment, 2016). The overall assessment is that more action is needed in this area.

The research presented here has its limitations and is based on a brief 6 months research project. In the following sections the main concepts of water efficiency and social norms are briefly introduced and discussed. Next, the Methods section outlines the research that was based on a literature and document review plus the input of key stakeholders during a workshop. Based on this, nine key themes and recommendations for successful water efficiency campaigns in the public sector are presented and discussed. Nonetheless, this research contributes to the discussion about water efficiency, which usually focusses on private households. Hence, the research presented here is preliminary and should be the start of further empirical research on the issue, which for example could go into more detail about how water is used in group contexts and the experiences and results of water saving campaigns in universities, schools, hospitals or other public buildings. This way, it could also help starting a discussion about the simplistic and reductionist relationship English and Welsh water companies have with their “customers” (Grecksch, 2021).

Current State of Water Efficiency and the Public Sector in the UK

Water efficiency in the English and Welsh public sector is an underexplored gap. Current approaches to water efficiency focus on private domestic customers, i.e., either single or multiple occupancy households, or private businesses (Grecksch, 2018). This relates for example to building design standards in the UK, which require newly built homes to include water efficient appliances such as low flow taps, waterless urinals etc. to achieve the required 125 L per person per day maximum consumption (HM Government, 2015). Given that public water supply to private customers makes up the largest share of public water supply use, this focus is justified (Lawson et al., 2018, 9). However, more than five million people are employed in the UK’s public sector (UK Office for National Statistics Public Sector Employment, 2018, 38). This includes government departments at central level, local government, the National Health Service (NHS), state schools and universities. For instance, a recent report on both virtual and actual water use in the Health and Social Care sector in England suggests that food production, preparation and consumption is with 28.7% the single largest area of water use by the sector (Public Health England and NHS, 2018). Apart from that, exact numbers for public sector water use are hard to establish since water companies use different methodologies to present data about non-household water consumption. Estimates range from 6 to 29 per cent of the total water use recorded by individual water companies (Grecksch and Lange, 2019, 12).

Organizational Learning, Social Norms and Behavior Change

Understanding and changing behavior in relation to water use can be part of wider organizational learning processes that may be of significant benefit to organizations beyond the specific context of being resource efficient. Organizational learning is discussed in particular by two academic disciplines, business management and social psychology. Business management literature defines social learning as more than the sum of individual learning, as a collective process. Organizational learning is about collective learning processes and is based on knowledge exchange among its members (Argyris and Schön, 1978). Social psychology emphasizes behavior change as a result of knowledge change through learning. Here, social learning can be understood a process of change on a society level that is based on newly acquired knowledge, a change in predominant value structures, or of social norms which results in practical outcomes (Luks and Siebenhüner, 2007).

Three types of organizational learning can be distinguished (Argyris and Schön, 1978; Pahl-Wostl, 2009): *Single-loop learning*, where people, organizations or groups modify their actions according to the difference between expected and reached outcomes (“re-moving symptoms”). *Double-loop learning*: in addition to single-loop learning, double-loop learning corrects or changes the underlying causes behind the problematic action. And *Triple-loop learning* reflects on how we learn in the first place: “learning how to learn.” In practical terms, a single-loop learning process with regard to water efficiency would involve installing water saving devices, without user patterns changing. A double-loop learning process would trigger a behavioral change, i.e., altered user patterns (for example: turning off the tap while washing the dishes in the office kitchen). Triple-loop learning would then reflect upon the learning process, i.e., why people were open to particular learning opportunities in the previous steps thereby improving the internal organizational learning process.

For the purposes of water efficiency campaigns and strategies with public sector organizations, double-loop learning seems the more interesting type of learning as it could lead to incremental or radical changes. Hence, an emphasis of the themes and recommendation discussed in the results section will be on the role of social norms–value commitments that shape water use behavior. The inclusion of a social norm in a message can be a way to encourage citizens, or in this case employees, to carry out a wide range of socially desirable acts. An example for a social norm is the message one can find in almost every hotel room about the re-use of towels. This research considers social norms as the missing link between technical and economical drivers of water behavior and actual water behavior change.

According to Lede and Meleady (2019) social norms serve as cues that help people make sense of social situations in terms of how people are expected to behave. They motivate action by providing information about what is likely to be effective and adaptive. Posner (2002, 34) describes social norms as "the behavioral regularities that occur in equilibrium when people use signals to show that they belong to the good type." It is important to note the distinction between two types of social norms. First, descriptive social norms represent beliefs about what people do, or in other words, the typical patterns of social activities and choices (Larson and Brumand, 2014) For example, a water bill may contain a comparative number, i.e., how a customer's water use compares to the average water use in the postcode area. Second, injunctive social norms, which convey a more prescriptive message. This is less frequently used, but can feature in interventions or an account of environmental outcomes and involve judging the un/desirability of specific actions.

The embedding into organizational learning, social norms and behavior change was chosen based on the author's background and familiarity with the literature. There are of course other approaches that go beyond behavior change, oriented around social or socio-technical practices rather than psychological concepts of social norms. For example, Strengers et al. (2015, 2) emphasize that by focusing on social practices, "the result is a perspective that focuses on the practices that sustain and implicate people in environmentally damaging and inequitable ways of life."

METHODS

The results presented in this article rest on two main pillars. First, an extensive academic and grey literature review that included topics such as water efficiency, water use behavior, the use of behavior change methods, social norms and resource efficiency strategies in the public and private sector, for instance energy saving initiatives. The latter was included in the search, since a scoping exercise of the literature revealed a number of journal articles dealing with energy efficiency and behavior change. The aim was to get vital insights from this discussion. The academic literature review was non-systematic and based on searches using Web of Science, a meta-search engine for peer reviewed academic journal articles that allows detailed keyword search. The following search terms, reflecting the key research interests, were used: "water efficiency AND public sector," "water AND social norms" and "energy saving AND public sector." The first two search terms were oriented toward the focus of this research, the third search term was selected to reflect that more research has been carried out on energy savings in the public sector as identified by the scoping exercise described above. The initial search period were the years 2008–2018 but cross-referencing from identified studies lead to the inclusion of earlier studies on the issue as well. In total, 30 academic publications, 32 documents or reports and 23 Water Resources Management Plans (WRMPs) were analyzed and an overview can be found in the **Supplementary Material**. The grey literature, i.e., studies, or reports from policy-makers and environmental management professionals, included documents from key actors in the UK drought and water scarcity governance space (Lange and Cook, 2015). This included: Waterwise–a UK non-governmental organization concerned with water efficiency, Ofwat–the economic regulator of the privatized water supply system in England and Wales, the UK Department for the Environment, Food and Rural Affairs (Defra), the English Environment Agency (EA) and other regulatory bodies, for example Natural Resources Wales (NRW), as well as English and Welsh water companies' Water Resources Management Plans (WRMP) for the years 2014–2019 and some draft WRMPs for the next planning period. WRMPs, updated every 5 years, outline how English and Welsh water companies meet supply and demand over a period of 25 years and include information about water efficiency measures. The grey literature and documents were identified from the different organizations' websites or previous research carried out by the author in the English and Welsh water sector (Grecksch, 2021). In order to gather ideas and data about water efficiency and the public sector from sources as widely as possible a scoping exercise was undertaken to look at water efficiency campaigns in California, Australia and South Africa, countries which are more experienced with drought and water scarcity. A full account is available in Grecksch and Lange (2019), however, since the results, as in the UK, showed that little is done in direct relation to the public sector, it is not further discussed here.

This research was part of the "Engaging diverse stakeholders and publics with the outputs from the UK Drought and Water Scarcity Programme" project (www.aboutdrought.info). Hence, it was an aim of the research presented here to actively engage with stakeholders and co-develop knowledge. Based on the results of academic and grey literature review, a so-called primer document was drafted (see **Supplementary Material**). The idea behind a primer is to provide an accessible document for stakeholders and the public, i.e., concepts and results are presented in a light manner, avoiding terminology and making use of visuals. To add the aforementioned element of co-development, a small workshop was organized with participants from a regulatory body (EA), a water company and a public sector organization (university) in January 2019.[2] Two further stakeholders, one from a regulatory body, the other an environmental public health specialist, who could not make it to the workshop, provided written comments. The workshop intensively discussed all aspects of the primer document, confirmed the findings from the literature and document review, and delivered useful recommendations from the participants that also influenced the formulation of the nine recommendations below. Hence, the workshop fulfilled the intention to get detailed comments and insights from the different stakeholders and to subsequently include the feedback into the final version of the primer (Grecksch and Lange, 2019). This, it was hypothesized, also helps to increase the legitimacy of the document.

The analysis of the academic and grey literature and the discussion during the workshop produced an understanding of water efficiency in the public sector and it included the identification of key themes that emerged from reading the literature, documents, WRMPs and the workshop discussions. Themes are recurring ideas, issues or statements expressed in the data, however, often not directly. Hence, identifying themes can help to uncover further dimensions and facets of in this case water efficiency in the public sector. The identified themes have in the next step been 'translated' into the nine themes or recommendations as discussed in the next section.

RESULTS

This section presents the results of the academic and grey literature review and the stakeholder workshop. It starts with a brief outline of current water efficiency and behavior change activities by English and Welsh water companies. The main part of this section then introduces and discusses the key themes, as identified by the literature, documents and the workshop. As mentioned before these key themes can also be read as recommendations for water efficiency campaigns with the public sector.

Water Efficiency and the UK's Public Sector

So far only a few of the approximately 25 water companies explicitly aim water efficiency campaigns at the public sector. Examples of water companies that mention these activities in their 2014/2015 Water Resources Management Plans are Thames Water (2014), Dee Valley Water (2013), Essex and Suffolk Water (2014), Welsh Water (2014) and Severn Trent Water (2014). Sutton & East Surrey Water concludes that a large part of its non-household consumption is associated with the general population and includes schools, healthcare etc. (SES Water, 2018, 50). The UK Department for Environment, Food and Rural Affairs (Defra)'s 25 Year Environment Plan only sets household water reductions as a goal without specifying an actual target (HM Government, 2018, 70). The UK National Infrastructure Commission (2018) also focusses on technological fixes and metering to increase water efficiency. For government owned and occupied buildings, the Greening Government Commitments (Defra, 2014) encourages all government units to embed sustainability, which includes water saving, without further specifying how this could be done. The Water Resources Management Plan (WRMP) Guideline (Environment Agency and Natural Resources Wales, 2016) prescribes what water companies have to include in their WRMPs, which are strategic documents outlining how a water company will meet supply and demand (see also Method section). Regarding water efficiency, however, the text is very general and only includes for example increased customer metering as a measure to promote water efficiency. Ofwat, the economic regulator for the water companies in England and Wales published a report in 2007 encouraging schools and hospitals to carry out self-audits and to involve key stakeholders in spreading the water efficiency message e.g. local Members of Parliament, trade bodies, and local authorities (Ofwat, 2007). An environmental public health specialist who commented on the draft primer document mentioned that there is an appetite for public sector interventions especially if they encourage employees or tenants to adopt services at home too (email communication with the author).

Behavior Change and English and Welsh Water Companies

Lewis (2017) discusses four barriers to behavior change with reference to English and Welsh water companies: first, entrenched attitudes within organizations. Second, water companies are traditionally focused on changing infrastructure not customer behavior, also in light of the fact that revenue is generated by selling water to customers. Third, some water companies do not see it as their responsibility to educate people about water consumption; and fourth, there may be limited knowledge and skills about behavior change and its success. Waterwise (2017) sees a water-saving culture as the goal in order to accomplish wide scale water efficiency. This includes the need for water efficiency to become the norm across all activities throughout everybody's lives. The Year one report on their water efficiency strategy (Waterwise, 2018) highlights "the importance of people and communities for water efficiency as behavior change and greater customer engagement and participation are linked to water efficiency."

The approximately 25 English and Welsh water companies refer to the potential of social norms to change behavior, however, the number of water companies actively engaging in it is low. Essex and Suffolk Water (2014) are engaged in using social norms theory and behavior change. At least three of their water efficiency initiatives apply it, but the focus is not on the public sector (ibid.). Other water companies are more cautious, saying that "we cannot accurately quantify behavioral change activity although we acknowledge that this is possibly the single most important driver of water efficiency." (sembcorp Bournemouth Water, 2015) The Environment Agency (2018) stated that "the water industry must innovate

[2]The workshop adhered to the required ethical standards and approvals as set out by the author's institution. Workshop participants were informed about their rights, data protection measures and were asked to provide written consent

and change behaviors in order to reduce demand and cut down on wastage." An Ofwat report (Lawson et al., 2018, 34) also suggests that prioritizing research into behavior change for influencing consumer choice of products and changing water use practices in one of the first steps to deliver deep reductions in household demand.

A recent assessment by Defra (Orr et al., 2018) generated evidence about what approaches to water efficiency and behavior change have been used so far in the UK, however, the focus was on private households. The authors note only one study (Ross, 2015) that examined water saving and behavior change. Accordingly, customers who received behavior change information coupled with a water saving device increased their water saving to 7 L per property per day. This was a water saving that was by 38% higher than the water savings achieved by those household customers who did not receive the behavior change information, and only received the water saving device.

Nine Themes and Recommendations for Water Efficiency Campaigns With the Public Sector

This section outlines and discusses nine themes and recommendations for conceptualising water efficiency campaigns with the public sector. The development of the nine recommendations and the discussion are based on the results of the literature and document review and taken into account are also the discussions during the stakeholder workshop, which confirmed most of the findings from the literature review. The general view among the stakeholders was that water efficiency campaigns with the public sector are a viable and necessary option. These nine recommendations are hopefully the basis for the discussion about widening the scope of water efficiency campaigns in England and Wales and beyond.

Understanding Why and How Water is Valued

It is important to explore what values water users hold towards water and why or why not they engage in water efficient behavior. Sharma and Jha (2017) highlight that the value systems of people in different cultures are influenced by society, religion and wider belief systems, which determine the reasons why people engage in sustainable consumption behavior. Apart from values a range of other factors can influence consumer decisions in relation to water too, for example, whether people perceive water as a scarce resource (Sofoulis, 2005; Hoolohan and Browne, 2016). For example, Simpkins (2018) discusses how an event such as the 2018 Cape Town "Day Zero" threat can increase the value of water. According to Corral-Verdugo et al. (2008), motivation plays an important role for conserving a resource such as water. Sofoulis (2005) emphasizes that changing consumption patterns mean changing habits and routines. More efficient water use may thus first require the de-routinising of habits and learning new ones. Ajia (2020, 212) points out that there needs to be more granularity in the understanding of the public with regard to water efficiency.

Narratives and Stories

The ancient philosopher Plato said that those who tell the stories rule the world. Hence, telling a story or shaping a narrative matter. It is therefore important to tell the bigger story, i.e., water efficiency should be linked to the wider environmental story that includes, for example, the management of a river catchment, or includes the water-energy-food nexus (Foden et al., 2019). The story must also resonate with existing audiences' values and could be built around a local community or organizational communities, such as a school. The idea here is to put water efficiency into context–and to make an explicit case for why it is necessary. One such important individual and social context is the energy-water saving nexus. Waterwise UK, for instance, notes that hot water use in the home accounts for around 5% of UK carbon emissions, which represents a key opportunity for promoting water efficiency as well as reducing fuel poverty (Waterwise, 2018, 7).

Framing

How social norms and behavior change are framed and communicated is an important factor for successful strategies (Byerly et al., 2018). Framing can be understood in two ways. First, it refers to how information is shaped and contextualized within a familiar frame of reference and meaning. Second, it concerns the effect of framing on members of the public. Audiences may adopt the frames of reference offered by journalists or a messenger and see the world in a similar way (McQuail, 2005, 555). Hence, the context in which decisions are made and who conveys the message or who suggests the behavior change, i.e. water companies, regulators or intermediaries, is important (Byerly et al., 2018; Whiting et al., 2019). Also, water use is of a very personal nature and people may or may not want to talk about it (Browne, 2016). Everyone has different attitudes and values when it comes to washing, showering, toilet use etc. Hence, communication in relation to this must be adapted so as not to be felt as too personal and intrusive.

Setting Realistic Targets

There is a limit to water conservation as we need, for example water to wash or to wash clothes. People may need water for religious reasons and some people simply do not care about efficient water use. There may also be unintended rebound effects, i.e., a water-saving shower head may lead to longer showers. Steg (2008) and Mills and Schleich (2012) report that only campaigns focusing on direct and specific targets, such as actual consumption data are likely to promote conservation behaviors. Similarly, Ek and Söderholm (2010) show that campaigns that provide specific information tend to outperform those that provide generic information. Siero et al. (1996) suggest that the higher the performance goal, and the more precise the goal has been formulated, the better the performance will be.

Competition

Competitions can leverage the power of social norms. Perceptions and beliefs about how members of a group think and behave relative to others have been found to be a significant incentive to participate in a competition. In other words, people like to know where they stand compared to others and they like to be told that they are good. Siero et al. (1996) focus on comparative feedback, which involves receiving information about the performance of other groups, i.e., another department within the same company with regard to saving resources. Drawing attention to the existence of another group with whom a group can compare itself makes the behavior of one's own group more salient and receiving information about the performance of other groups can lead to competitive feelings and an improved performance (ibid., p. 236).

Petersen et al. (2015) conducted a large study about electricity and water saving on US college and university campuses. They found that the impact of financial and other incentives and knowledge is often overestimated, while people's perceptions of what other people are doing, i.e., social norms, is underestimated: "The emphasis on achieving behavioral change in colleges and universities also recognizes the undergraduate experience as a seminal and transformative period during which future decision-makers develop knowledge and habits that inform the personal, professional and political choices that they make throughout the rest of their lives." Vine and Jones (2016) refer to structured competitions, one form of social comparison, as a potentially powerful mechanism for leveraging the power of social norms.

Useful to consider might also be the opposite, cooperation or collaboration to achieve a common goal and save or conserve water. Likewise, social media and apps could support both competition and cooperation by providing for example up to date information on water use.

Reference Groups

Reference groups are people close to us, e.g., work colleagues or friends and family. Our behavior orientates itself to the behavior of reference groups, also through group think. In other words, we tend to adapt our behavior according to what is the norm within a reference group. Herein lies a significant potential for water efficiency campaigns in the public sector. Work teams or units are important reference groups and could help to influence water-saving behavior.

Goldstein et al. (2008, 476) use social norms in their study about the reuse of hotel towels and conclude that another well-established factor affecting norm adherence is the extent to which individuals identify with the reference group: "In experiment 2, we examined whether the towel reuse norm of hotel guests' immediate surroundings (i.e. the provincial norm for their particular room) motivates participation in the conservation program to a greater extent than the norm of guests' less immediate surroundings (i.e., the global norm for the whole hotel)." In other words, if the message was "other people who used this room, reused their towels" people were more likely to reuse towels than in the case of the more general message of "other hotel guests reused their towels."

Align Structural and Behavioral Change Measures

Installing water saving devices or new plumbing and harnessing social norms to change behavior can go together. The studies by Goldstein et al. (2008), Ek and Söderholm (2010), Steg (2008) and Mills and Schleich (2012) suggest this to be a successful strategy. Fidar et al. (2016, 823) analysis showed that low flow taps have greater mean water consumption per use than conventional taps, however, more interesting, they also conclude that water consumption is more influenced by user behavior rather than the technology: "(. . .), this study confirmed the less predictable and rather complex use behaviour is the most significant variable in forecasting the water use of the taps, particularly in commercial (non-residential) buildings." Rocarro et al. (2011) present a study where the objective was to verify and compare water conservation in residential and public (schools and sport centers) buildings located in Sicily (Italy) by implementing high-efficiency plumbing fixtures (structural measures) and educational programs (non-structural measures). The results show that structural measures led to relevant water savings, while non-structural measures only added a negligible effect. Other potential structural constraints may need to be taken into account as well (Mondejar-Jimenez et al., 2011). For example, water saving behavior may be guided by the fact whether a property is rented or owned (Russell and Fielding, 2010). Homeowners have direct control over their homes and are in a better position to undertake retrofitting of efficient devices. Private tenants on the other hand have less control over the installation of water efficient devices (ibid.).

Building Water Saving Messages on Energy Saving Campaigns

A big factor discouraging people from water-saving behavior is the fact that they have less control over water infrastructure as, for example, compared to energy. Switching off a light is easy but most of the water infrastructure is actually hidden. The study by Petersen et al. (2015) revealed that changing the water behavior of others was seen as more personal and intrusive, i.e. suggesting to someone to switch off a light or turn down the heating was seen as less intrusive by study respondents compared to telling others to close the tap while brushing teeth or taking a shorter shower. One solution is to use a strategy that sends messages with different levels of appeal to self- and collective self-efficacy. For example, a message that targets shorter showers could primarily appeal to the fact that it saves energy instead of focusing on the water-saving aspect that comes with it. Hassel and Thornton (2014, 115), in their study on rainwater harvesting in UK schools, highlight that there are likely more cost-effective ways to save water than the installation of rainwater harvesting. According to the authors an easily achievable measure would be to curtail hot water use behavior.

Data and Evaluation

Having a good data basis and regularly evaluating the effects of water efficiency campaigns that involve social norms are a precondition for successful water efficiency strategies and campaigns. Limited data or general statements in WRMPs make it difficult to assess the current situation regarding water efficiency strategies and campaigns, especially with regard to social norms and the public sector. Water companies could elicit information about the value customers attribute to water from their customer focus groups and regularly undertake evaluation studies about the effectiveness of water efficiency campaigns and strategies (Orr et al., 2018, 7). In addition, data from using water at workplaces is required to get a more detailed picture of water uses within organizations.

DISCUSSION

Current water efficiency campaigns and strategies in England and Wales focus on individual households and private businesses. The main tools currently used in England and Wales by water companies are water saving devices and messages to reduce bills. But water saving behaviour is influenced not just by individual decisions, but social and psychological drivers such as social norms, values, group behaviour and external factors (culture, family behaviour, infrastructure and regulations).

This research suggests that there is an opportunity for the public sector to act as a role model for other (private) sectors. A large majority of the workforce, students and school pupils spend their days at workplaces where they use water after using the toilet, for washing hands, in the office kitchen, water is used in the canteen, and for showering, the latter in particular if there is an increase in cycling to work. The study by Goldstein et al. (2008) about the use of hotels towels (see *Reference Groups*) can easily be transferred to the public sector since the identification with reference groups (same class, course etc.) plays an important role in schools and universities. Second, there is an opportunity for the public sector to carry out a multiplier function. If water saving behaviour is implemented at workplaces, this behaviour may also be applied at home, but also vice versa (Darnton and Horne, 2013, 6). People who engage privately in water saving behaviour may have an influence upon their peers in larger organisations in which they may work. Public sector organisations are well placed to start water saving behaviour initiatives themselves, with or without the support of water companies, and, for example as a competition among departments, year groups in schools, halls of residence in universities (Petersen et al., 2015) or in the context of staff engagement weeks, or by including water efficient appliances in their procurement activities. And there is scope for water companies and the public sector to increase their cooperation on this issue.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

KG conceptualised and wrote the article.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.575583/full#supplementary-material

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Impact of Reduced Rainfall on Above Ground Dry Matter Production of Semi-natural Grassland in South Gloucestershire, UK: A Rainfall Manipulation Study

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In the United Kingdom, agricultural grasslands cover 40% of the land area, make up 89% of the total agricultural area and are an important land use for ecosystem services and food security. Climate change predictions suggest that the United Kingdom will experience more frequent and severe periods of drought that may impact these grasslands. As part of the Drought Risk and You (DRY) project, a field experiment in which rain shelters reduced precipitation reaching the vegetation by approximately 50%, was set up in the South West of England. The experiment ran for 3 years, from October 2015 to October 2018. The study was carried out at two locations in the catchment of the Bristol River Frome. Both sites were species-rich semi-natural pastures that had received no inputs of fertilizer or herbicide for many years. Automatic weather stations recorded environmental conditions, especially rainfall, within the experimental area. The existing agricultural management regimes were approximated by cutting the vegetation in the plots, by hand, at the appropriate times of year. The effect of rainfall reduction on plant growth was assessed by biomass sampling. At both sites, the rainfall reduction treatment had only small effects on total above ground dry matter production (biomass). These effects were much smaller than the year-to-year variation in total biomass. Our results suggested that well-established permanent pastures in the South West of England were able to tolerate a 3-year period of reduced water supply. The observed year-to-year variation in biomass demonstrated how important the timing of dry weather is for biomass production, and this will be reflected in effects on yield and quality of hay.

Keywords: grassland, climate change, productivity, resilience, reduced rainfall

1 INTRODUCTION

The Earth is experiencing a period of rapid climate change that is likely to impact human activities (National Aeronautics and Space Administration, 2020). International organizations and national governments have raised concerns about how agricultural production, cropping systems, and food security will be affected by climate change (Rivington and Koo, 2010; Elliott et al., 2014). A particular concern is how changes in the distribution of rainfall amounts and events (Met Office, 2018a), particularly periods of drought, will affect agriculture and crop growing conditions.

Droughts and periods of water scarcity are a natural part of all climates. Droughts can be defined in many different ways: meteorological based on lack of rainfall, hydrological reflecting reduced run off or aquifer recharge and agricultural when the availability of soil water for crops is reduced (Marsh et al., 2007). Drought and water scarcity can have wide-ranging impacts: on crop growth (affecting both yield and quality); wildlife (for example, low river flows and associated decreases in water quality can increase mortality in aquatic life, dry conditions can cause newly planted vegetation to die and hasten the death of old or diseased plants); human health (for example, food shortages can lead to malnutrition, worry about food and water supplies can lead to mental health problems); and the economy (the cost of damage due to subsidence associated with the 1976 United Kingdom drought is estimated at £100 million) (Rodda and Marsh, 2011; Staniak and Kocoń, 2015; Edwards et al., 2018).

The United Kingdom has historically experienced periods of drought, for example in 1976, 1990–1992, 1995–1997, 2004–2006, and 2010–2012 (Marsh et al., 2007; Kendon et al., 2013; Met Office, 2013; Environment Agency, 2017). Although droughts can occur at any time of year, in United Kingdom periods of high pressure during the summer are often associated with high temperatures and low rainfall (Met Office, 2021a). The United Kingdom Climate Projections 2018 (UKCP18) (Met Office, 2018a) suggest that by 2050s, hot dry summers, such as the United Kingdom experienced in 2018, could become very common, happening around 50% of the time. Increased summer temperatures will increase rates of evaporation and demand for water. Met Office models show that there is now about a 12% chance of summer average temperatures being as high as the United Kingdom experienced in summer 2018 (Met Office, 2018b); these changes will make droughts and periods of water scarcity more frequent and more severe.

There have been many investigations of the effects of reduced rainfall and drought on grasslands (see for examples Knapp and Smith, 2001; Beier et al., 2012; Wilcox et al., 2017). This reflects the global importance of grasslands, the most widespread vegetation type in the World, covering 52.5 million km^2 (FAO, 2005). Many of these studies are from semi-arid environments, where rainfall is likely to be a factor limiting productivity. There have been relatively few investigations in regions where annual rainfall is unlikely to limit productivity (Matos et al., 2020), and these have produced a range of results. Studies of United Kingdom grasslands have tended to be either on unproductive, but ecologically important, grasslands (Grime et al., 2008; Cole et al., 2019) or on recently established pastures (Grime et al., 2000; Fry et al., 2014). There is little published empirical information about the impact of reduced rainfall on well-established agriculturally productive grasslands.

Agricultural grasslands cover almost 40% of the United Kingdom (Office of National Statistics (ONS), 2018). Grasses are the most important agricultural crop in the country (by area); 89% of all United Kingdom agricultural lands are grasslands (including cereals) (Office of National Statistics (ONS), 2017; Office of National Statistics (ONS), 2018). In 2017 there were 5.363×10^6 ha of pastures (22%), and 4.157×10^6 ha (17%) of semi-natural grasslands (Office of National Statistics (ONS), 2018). This proportion has changed little over the last 60 years; in 1960, around 90% of farmland was under grass of some sort (Moore, 1966). These grasslands support around 10 million cattle and calves and 34 million sheep and lambs. In 2013/14, forage crops contributed £265 million to farm income and the livestock industry £8,889 million (Office of National Statistics (ONS), 2014).

Permanent pastures are agricultural grasslands that have not been ploughed for at least 5 years (Office of National Statistics (ONS), 2020). These pastures may support a wide range of plant and animal species (Bunce et al., 1999; Natural England, 2001; Johansen et al., 2019), and can include semi-natural grasslands with less intensive farming practices. Grassland soils, particularly those under grasslands with a high diversity of different species, can also be an important carbon store (Alonoso et al., 2012; Natural England 2012; Moxley et al., 2014; Moxley and Malcolm, 2014). Permanent pastures often have high water infiltration rates. Infiltration rates from 60 to 600 mm water per hour have been reported depending on the soil type, management and method used; rates are usually higher on permanent pastures than on arable fields and increase with biodiversity (Holtan and Kirkpatrick, 1950; Emmerling et al., 2015; Leimer et al., 2021). This suggests permanent pastures can be important to catchment flood management. In the United Kingdom, winters are predicted to become warmer and wetter, with more frequent episodes of heavy rain (Met Office, 2018a). Thus permanent pastures are important not only economically, but have potential to mitigate some of the impacts of climate change. The importance of permanent pastures is recognized within the United Kingdom Government Basic Payment Scheme for farmers. Farmers may not plough grassland that has been established for more than 15 years without an inspection and approval from Natural England (Rural Payments Agency, 2020). Permanent pastures are not uniformly distributed across the United Kingdom, and are more widespread in the South West of England where they make up 48% of the agricultural area than in the East of England where they are only 11% of the agricultural area (Defra, 2021).

We investigated the potential impact of changing climate on the productivity of pastures in the South West of England by studying the effects of reduced rainfall on two permanent pastures in the catchment of the Bristol River Frome, South Gloucestershire, United Kingdom. Summer rainfall in the Frome catchment is predicted to fall by 29% by the 2080s (based on the UKCP09 high emissions scenario; Afzal and Ragab, 2019). We selected a rainfall reduction of 50% to test of the resilience of productivity in permanent pastures to reductions in rainfall.

We set out to answer whether a 50% reduction in incident rainfall would reduce above ground dry matter (biomass) production; alter the biomass proportions from different plant functional types; and reduce regrowth of vegetation after a summer hay cut.

The rainfall manipulation experiment was set up as part of the Drought Risk and You project (DRY). This interdisciplinary project aimed to improve the evidence-base to support better catchment-based, drought risk decision-making in the United Kingdom. A part of DRY's transdisciplinary research

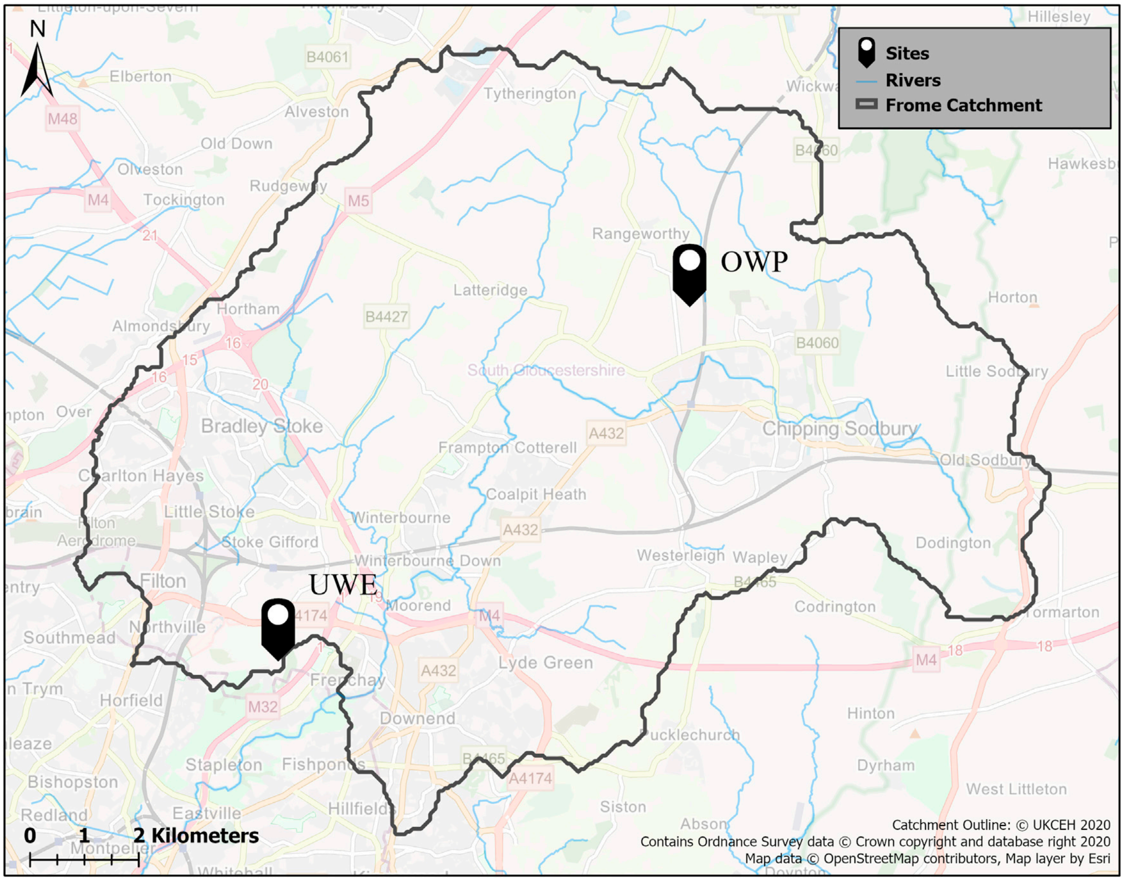


FIGURE 1 | Location of DRY project field sites in the Bristol River Frome Catchment. Image courtesy of H. West (University of the West of England).

process was the engagement of citizen scientists in monitoring the experiment, and bringing professional stakeholders to the experiment to discuss drought impacts on grassland. For further information on the DRY project, see Bryan et al. (2020); Liguori et al. (2021) and McEwen et al. (2021).

2 METHODS

A field experiment was set up at two sites, in the catchment of the Bristol Frome (South Gloucestershire, United Kingdom), approximately 12 km apart. The two sites, University of the West of England (UWE) and Oldwood Pit (OWP) (**Figure 1**), were species-rich semi-natural grasslands, chosen to reflect the typical permanent pastures of the catchment.

2.1 The River Frome Catchment

The Bristol Frome catchment covers approximately 149 km^2, above the Frenchay flow gauging station, lying between 20 m and 194 m above ordnance datum (AOD). Mean annual rainfall (1961–2017 average, based on year 1 October to 30 September) is 816 mm [National River Flow Archive, 2021 (https://nrfa.ceh.ac.uk/)]. Average maximum and minimum air temperatures, for the nearest United Kingdom Met Office station at Filton, South Gloucestershire, (1981–2010 average) are 14.2°C and 7°C (Met Office, 2021b). Grassland is the largest land use in the catchment, covering around 48% of the catchment (Blake and Ragab, 2014); this high proportion of grassland is typical of the South West of England (Defra, 2021). The catchment has experienced numerous drought episodes over the last 60 years, most notably in 1976, 1990, 1995, 2005, and 2011 (Blake and Ragab, 2014). Evapotranspiration and soil moisture deficits within the catchment are predicted to increase in the future because of increased temperatures and reduced summer rainfall, and these changes will outweigh projected increases in winter rainfall (Afzal and Ragab, 2019).

2.2 Field Sites

2.2.1 University of the West of England

The UWE site is located between the University of West of England Frenchay campus and the M32 motorway (Grid ref ST629778). The site is about 135 m AOD and slopes gently (<1.5°) towards the northeast and the river Frome. The soil is a Worcester series gleyed brown earth (Chromic vertic luvisol) (Cranfield University, 2021) developed over Mercia mudstone (Findlay, 1976). The A horizon (0–20 cm) is clay loam above a reddish brown silty clay B horizon (20–50 cm), that has an angular blocky structure and shows some gleying. Below this is a BC horizon (50–100 cm) of silty clay, with a

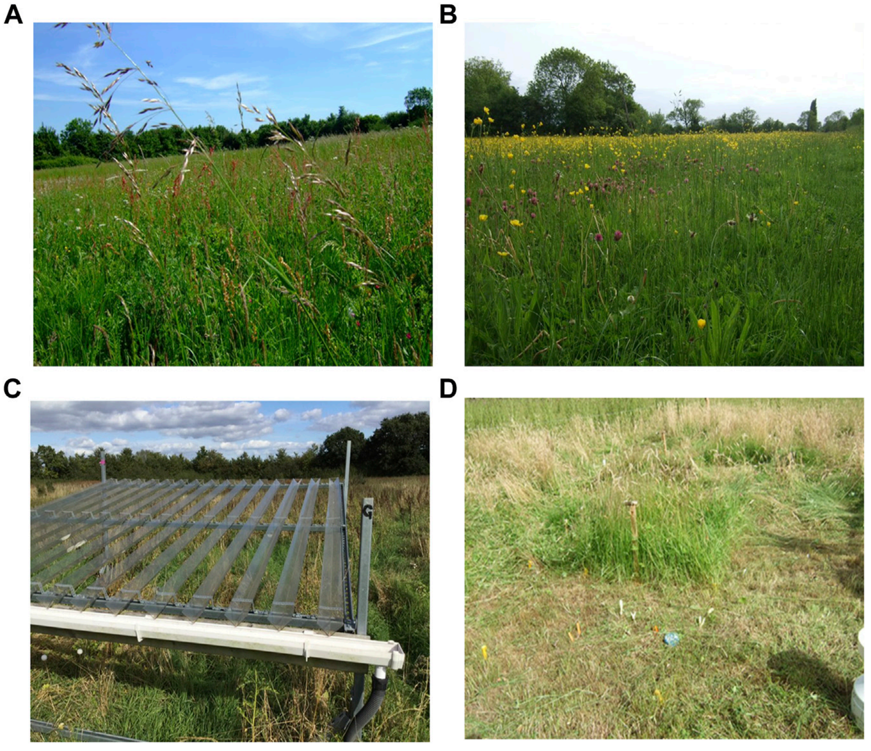


FIGURE 2 | (A) Vegetation at UWE, **(B)** Vegetation at OWP, **(C)** One of the Reduced Rainfall plots at UWE, note metal frame, transparent "V" shaped gutters and pipe to carry intercepted water away from the plot, **(D)** A partly cut Control plot at OWP, note rain gauge in bottom right corner. The coloured markers indicate where samples have been taken. Blue circle is top of Adcon soil moisture sensor. Photographs © S. Ayling.

coarse prismatic structure, and at 100 cm mudstone is the C horizon (Findlay, 1976). Most land within the Worcester series is permanent grassland (Findlay et al., 1984). The field lies within United Kingdom soil scape 8 (Cranfield University, 2021) and is in an area of grade 1 and 2 soils. The field, at one time, was used for arable crops but has been grassland, grazed by sheep or cattle, with minimal artificial inputs for at least 30 years. In the 4 years preceding the start of this work, the field had been cut for hay in late September.

The vegetation at UWE (**Figure 2A**) is dominated by *Arrhenatherum elatius* (L.) (false oat grass), *Holcus lanatus* (L.) (Yorkshire fog) and *Dactylis glomerata* (L.) (cocksfoot) with *Circium arvense* (L.) (creeping thistle), and *Heraculeum sphondylium* (L.) (hogweed), *Chrysanthemum leucanthemum* (L.) (ox-eye daisy), *and Rumex* (L.) *spp.* (docks). There are also less common species such as *Lathyrus nissolia* (L.) (grass vetchling), and the orchids (*Dactylorhiza fuchsii* ((Druce) Vermeul.), *Dactylorhiza praetermissa* ((Druce) Vermeul.), and *Ophrys apifera* (Huds.)). Plant nomenclature follows Stace (2014).

2.2.2 Oldwood Pit

The OWP site is a few miles outside Yate (Grid ref ST699853). The site is at 65 m AOD and level (slope <0.5°). The site lies within the North Bristol coalfield geological area. The soil is a Dale series surface water gley (Findlay, 1976), (Clayic eutric stagnosol (Cranfield University, 2021)). The A horizon (0–20 cm) is a clay loam; the B horizon (20–100 cm) is divided into two zones, both of clay with a coarse prismatic structure. At 20–50 cm, the soil is brown and mottled and 50–100 cm, the soil is grey with ochreous mottles. The BC horizon (100–120 cm) is grey clay with a coarse platy structure. All horizons show signs of gleying (Findlay, 1976). Dale series soils are mainly used for leys or permanent pasture (Findlay et al., 1984). The site lies within United Kingdom soil scape 17 (Cranfield University, 2021). The site is species-rich permanent pasture that is managed either by grazing during spring and summer with sheep, or for hay cut in early July, followed by late summer/autumn sheep grazing. The site has received no artificial fertilizer or herbicide since at least 1960, and probably not since before the Second World War.

The pasture (**Figure 2B**) contains *Holcus lanatus* (L.) (Yorkshire fog), *Agrostis capillaris* (common bent), *Festuca rubra* (L.) (red fescue) and *Lolium perenne* (L.) (rye), as well as numerous nitrogen fixing plants such as *Trifolium repens* (L.) and *T. pratense* (L.) (clover) and *Lotus corniculatus* (L.) (birdsfoot trefoil). The site has some uncommon plants, including *Ophioglossum vulgatum* (L.) (adder's tongue fern) and *Dactylorhiza fuchsii* ((Druce) Vermeul.) (common spotted orchid).

2.3 Vegetation Management

Within the experimental plots at each site, we approximated the existing vegetation management regime by cutting the vegetation, with hand shears, to 1–2 cm above ground level and removing the cut vegetation (**Figure 2D**). In October 2015, when the experiment started, all plots were cut to ensure that samples collected in subsequent years only represented the current year of growth. At UWE, plots were cut each year in late September/early October to simulate autumn mowing. At OWP, plots were cut each year in late June/early July to simulate a hay cut, and again in late September/early October to simulate early autumn grazing. Plots were cut block by block (see Experimental design) to ensure any differences due to date of cutting were distributed across all treatments.

2.4 Experimental Design

At each site, twelve 3 m × 3 m plots, arranged in three replicate blocks were set out. Within each block, there were two reduced rainfall (RR) plots, consisting of metal frames (3 m × 3 m square, 1 m from the ground at the front and 1.5 m from the ground at the back). The frames supported V-shaped transparent gutters (**Figure 2C**), made from PEGT, that intercepted approximately 50% of the rainfall. The design was a variation of Yahdjian and Sala (2002). PEGT is Polyethylene Terephthalate (PET) with the addition of ethylene glycol. PEGT is transparent, flexible and can easily be moulded into V-shapes that are less likely to fracture than V-shapes made from acrylic. Intercepted rainfall flowed into PVC house roof gutters, and plastic pipes carried intercepted rainfall away from the plots. Two plots in each block were Control plots with ambient conditions, no metal frame or roof. The plots and frames were at least 3 m apart. The frames were put in place during April 2015 and the roofs installed on 19–20 October, 2015 at OWP and 21–22 October, 2015 at UWE. The experiment ran until October 2018.

In each (3 m × 3 m) plot, a 2 m × 2 m vegetation plot was marked out. A 0.5 m buffer strip surrounded this vegetation plot. The 2 m × 2 m plot was divided into four 1 m × 1 m subplots. One 1 m × 1 m subplot in each plot was randomly assigned for biomass sampling, and another was used to locate the rain gauge and for access to the other subplots.

The plots were not hydrologically isolated; lateral movement of water within the soil would have been possible. Experimental plots can be isolated, from the surrounding soil, by trenching but this can cause damage to the adjoining vegetation and influence hydrology within the trenched area (Beier et al., 2012). We needed to return the fields to the landowners in the same or better condition after the experiment had finished, this precluded use of trenching. The 3 m space between each plot represented a balance between having the plots far enough apart to minimize interactions in soil water between adjacent plots, need for electrical cables to connect environmental monitoring equipment to data loggers (see below), minimizing the likelihood of changes in soil type and conditions across the site, and the time needed to manage the experimental area by hand.

We collected data over three complete growing seasons and three hydrological years (1 October to September 30, 2015/2016, 2016/2017, and 2017/2018), to assess the impact of reduced rainfall on total grassland biomass production, and biomass of species representing different vegetation functional groups. At both sites, the growing season started from the time that the plots were cut in late September/early October, thus the growing season and hydrological year are the same.

2.5 Environmental Monitoring

At both sites, automatic weather stations recorded data about environmental conditions, including rainfall and soil moisture, every 30 min throughout the experiment. The weather stations were connected to Campbell data loggers (CR-1000, Campbell Scientific, Loughborough, United Kingdom) with mobile telephone data uplift. **Supplementary Table S1** gives details of environmental monitoring instruments at the field sites.

There were six rain gauges at both UWE and OWP. There was one rain gauge in each of the three Control plots at UWE; one in each of two Control plots at OWP (one rain gauge at OWP failed); and one in each of three RR plots at both sites. Replicate gauges allowed us to calculate average rainfall at each site. The under roof rain gauges allowed an estimate of the rainfall reduction by the roofs.

Soil moisture tension and soil temperature were measured using Decagon MP6 ceramic sensors (**Supplementary Table S1**) installed horizontally at 10 cm depth near the centre of the 2 m × 2 m plots, with the sensor head towards the vegetation monitoring sub-plot. In pastures in the United Kingdom, and elsewhere, most roots (65–90%) occur in the top 10 cm of soil (Macklon et al., 1994; Dawson et al., 2000; Brown et al., 2010). Soil moisture content (%) was measured at 10 cm, 50 and 90 cm using Adcon SM1 Soil Moisture Sensors (**Supplementary Table S1**), installed close to the centre of the 2 m × 2 m vegetation plots. Although the majority of plant roots occur in the top 10 cm of soil, those of perennial plants often extend to, and take up water from, 50 cm depth or below (Dawson et al., 2000; Grieu et al., 2001). The soils at UWE and OWP have a C horizon at 1 m (Findlay et al., 1984) that would be difficult to penetrate without risking damage to the surrounding area and we did not anticipate root development and water uptake below this depth.

Photosynthetically active radiation (PAR) was measured using Licor PAR sensors (**Supplementary Table S1**). At each site, one sensor was mounted above and one sensor was mounted underneath the roof on one RR shelter.

2.6 Biomass Sampling

Above-ground dry matter production was assessed by biomass sampling. A randomly selected strip of vegetation (50 cm × 10 cm) was cut, as close to the ground surface as possible, within the subplot that had been assigned for biomass sampling. On each occasion, one sample was taken from each biomass sample subplot. The samples were collected block by block, to ensure any differences due to day of sampling were distributed across all treatments. Cut vegetation was immediately placed in a large plastic bag in a cool box. Samples were stored in a refrigerator at 4°C for not more than 2 days before processing. All samples were collected while kneeling on wooden boards outside the plots to minimize compaction of the soil.

The cut vegetation was sorted into all dead plant material, and live vegetation of different functional types: graminoid (grasses, rushes, and sedges), broadleaved plants, pteridophytes, bryophytes and woody material. After sorting, the different types of vegetation were dried at 60–80°C for at least 4 days and then again for 24 h before weighing.

Biomass samples were collected shortly before vegetation in the plots was cut. The sampling regime reflected the management regime in place at each site. At UWE, biomass samples were collected in autumn (late September/early October) of 2015, 2016, 2017, and 2018 and in summer (early July) 2018. At OWP, biomass samples were collected twice each year; in autumn (late September/early October) of 2015, 2016, 2017, and 2018 to simulate early autumn grazing and in summer (late June/early July) of 2016, 2017, and 2018 to simulate a summer hay cut. **Supplementary Table S2** gives full details of site management and biomass sampling dates.

The weight of samples collected in September 2015 is included in the results because it gives an indication of the initial variability between plots, and the productivity of the fields. However, to be confident that we were making valid comparisons we have excluded data from samples collected in October 2015 (at the start of the experiment, before attaching the roofs) from the main statistical analysis. At UWE, mechanical cutting of the vegetation by the farmer in 2014 (before the experiment was set up in 2015) may not have cut to the same height as our hand cutting and collecting in 2015, 2016, 2017, and 2018. At OWP in 2015, while the experiment was being set up, sheep were kept in the field and no summer hay crop was taken; we then cut the plots in late September/early October.

To investigate the relationship between rainfall and total biomass, we compared the amount of biomass produced in Control or RR plots with rainfall over selected periods. These periods included: 1) Annual; 2) January to March, when rainfall is important for the recharge of groundwater reserves (Afzal and Ragab, 2019); 3) April to June, when grassland plants are growing quickly, flowers are developing, and plant growth may be partly dependent on incident rainfall as surface layers of soil contain less moisture; 4) December to April, when most incident rainfall moves into the soil (Afzal and Ragab, 2019); and 5) March to May, when grassland plants are susceptible to water stress (Grove and Monaghan, 2018). For OWP only, we compared July to September rainfall with the amount of biomass collected in the autumn.

2.7 Data Preparation and Statistical Analysis

Data on environmental variables and biomass from each field site, UWE and OWP, in the Frome catchment were analysed separately, because the vegetation management and sampling regime at the two sites was different.

2.7.1 Environmental data Processing and Analysis

Environmental data [rainfall, soil moisture (tension and content), air temperature, soil temperature and photosynthetically active radiation] were collated and summarized using Excel 2016 (Microsoft Corp., Redmond, United States). Data for days with incomplete records, resulting from equipment failure, were excluded. Comparisons between instruments in the plots, within each treatment, were used to identify any anomalous values; the data and field notes for that day were carefully examined, before making a decision whether or not to exclude those data. Comparisons between environmental variables for each treatment were made using t-tests performed in the statistical package SPSS26 (IBM, Armonk, United States).

2.7.1.1 Rainfall

At each site (OWP and UWE), the rain gauges recorded incident rainfall from July 2015 to October 2018. The average rainfall for each day during this period was calculated, for each site, and the rainfall recorded by each individual rain gauge was compared to the average to check the calibration and function of the rain gauges. The slope of the fitted line between daily rainfall recorded by each individual rain gauge and average daily rainfall was between 0.96 and 1.04 with a correlation (R^2) of 0.99. This meant that if, for technical reasons, one rain gauge was not working we could extrapolate, with confidence, from the neighbouring gauge (within the same treatment) to fill in the missing data. Values of daily rainfall were calculated, for Control and RR plots at each site, by averaging the amount of rainfall recorded, each day, by each rain gauge.

2.7.1.2 Soil Moisture

Soil moisture tension gives an indication of the amount of work that a plant needs to do to acquire water. Water in a soil can be freely available, available, slightly available or unavailable to plants; these amounts depend on the water holding properties (texture and structure) of the soil. Freely available water can be defined as that when the soil moisture tension is less (more positive) than −59 kPa (Berglund, 2020). We calculated, for each plot, the number of days per month when average soil moisture tension was between 0 and −59 kPa (Ayling et al., 2020), and soil water was freely available for uptake by plants. We used these values to calculate an average across Control or RR plots at each site.

2.7.1.3 Soil Moisture Content (%)

Soil moisture content (%) recorded by each sensor was averaged for each day. These daily average values were used for within site quality control and to estimate monthly average soil moisture content for Control and RR plots at each site.

Data about soil moisture tension (kPa) and soil moisture content (%) were used to construct soil moisture characteristic curves for each site.

2.7.1.4 Air and Soil Temperature

For each day, average air temperature was calculated from the daily maximum and daily minimum air temperature (Kendon et al., 2019). Daily average soil temperature at 10 cm was calculated from the daily maximum and daily minimum soil temperature. These daily values were used to calculate monthly averages.

2.7.1.5 Photosynthetically Active Radiation

PAR changes throughout the day and is lower in winter when, in United Kingdom, daylight hours are shorter and the angle of the Sun's rays lower. We calculated the average midday PAR value, between 11:00 and 13:30 for each day.

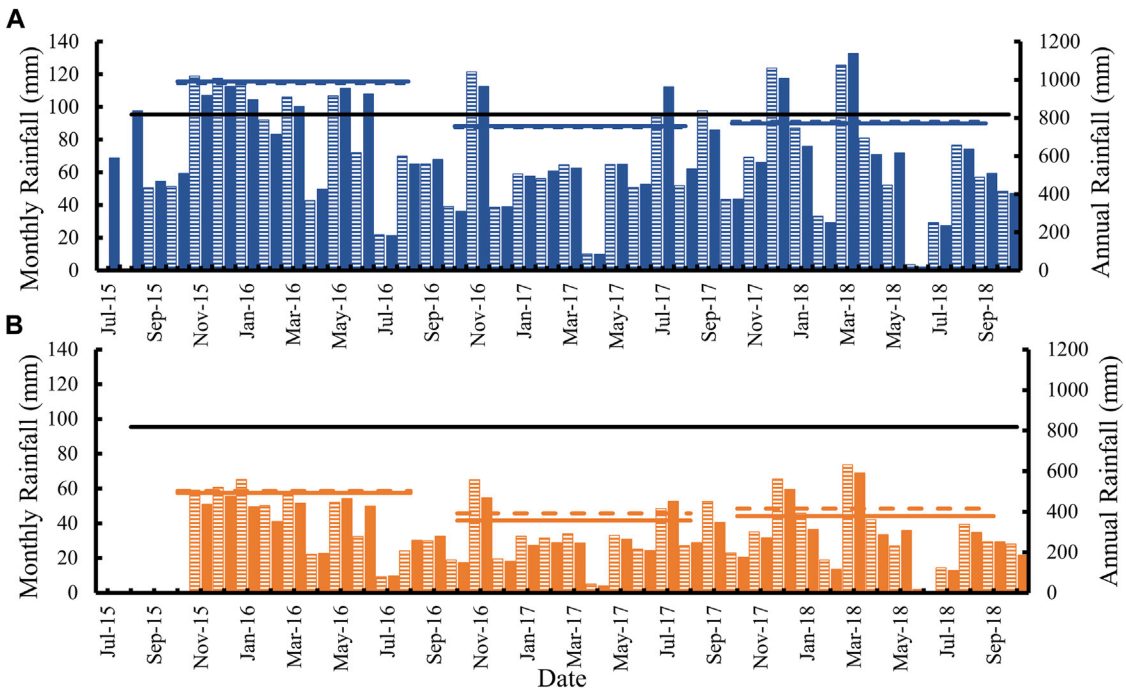


FIGURE 3 | Monthly and annual total rainfall (mm) for **(A)** Control plots at University of the West of England (UWE) and Oldwood Pit (OWP) and **(B)** for reduced rainfall (RR) plots at UWE and OWP. Long-term total annual rainfall for the Frome catchment (1961–2017) is shown for comparison. In this study, the year was defined as 1 October to 30 September.

Monthly rainfall Control OWP	Monthly rainfall Control UWE
Annual rainfall Control plots OWP	Annual rainfall Control plots UWE
Monthly rainfall RR plots OWP	Monthly rainfall RR plots UWE
Annual rainfall RR plots OWP	Annual rainfall RR plots UWE
1961 – 2017 average annual rainfall	

2.7.2 Vegetation Biomass Data

Vegetation biomass data (total biomass and biomass of different functional types) were analysed using a univariate general linear model in the statistical package SPSS26 (IBM, Armonk, United States): treatment and time of year were fixed factors; year was a random factor. Pearson correlation between rainfall and biomass was calculated using SPSS26.

3 RESULTS

3.1 Environmental Data

3.1.1 Rainfall

At UWE, total rainfall for the year (1 October–30 September), in Control plots, in 2015/2016 was 979.1 mm, in 2016/2017 749.0 mm and in 2017/2018 782.4 mm. At OWP, equivalent totals were 990.5, 756.6, and 771.2 mm. There was no statistically significant difference between monthly total rainfall recorded in Control plots at OWP and UWE (p = 0.95, t-test) (**Figure 3**). Total rainfall recorded in Control plots between November 2015 and October 2018 was 2,508 mm at UWE and 2,506 mm at OWP. Over the 3 years of this study rainfall recorded in the RR plots at UWE was 52% of that in the Control plots and at OWP 48% (**Figure 3**).

The 1961–2017 average rainfall for the Frome catchment, for year 1 October–30 September, is 816 mm (National River Flow Archive, 2021) (**Figure 3**). When compared to the long-term average, rainfall recorded in the experimental plots ranged from 44% in the RR treatment at OWP in 2016/2017 to 120% for the Control plots at UWE in 2015/2016 (**Table 1**).

3.1.2 Soil Moisture

At both sites, the soil moisture tension in all plots was between 0 and −59 kPa (soil water deemed freely available to plants; Berglund, 2020) on every day of the month between

TABLE 1 | Total rainfall in each year (1 October–30 September) for RR treatment and Control at UWE and OWP as percentage of catchment 1961–2017 average.

Rainfall year	Control rainfall OWP %	Control rainfall UWE %	Reduced rainfall OWP %	Reduced rainfall UWE %
2015–2016	121	120	61	62
2016–2017	93	92	44	48
2017–2018	95	96	46	51

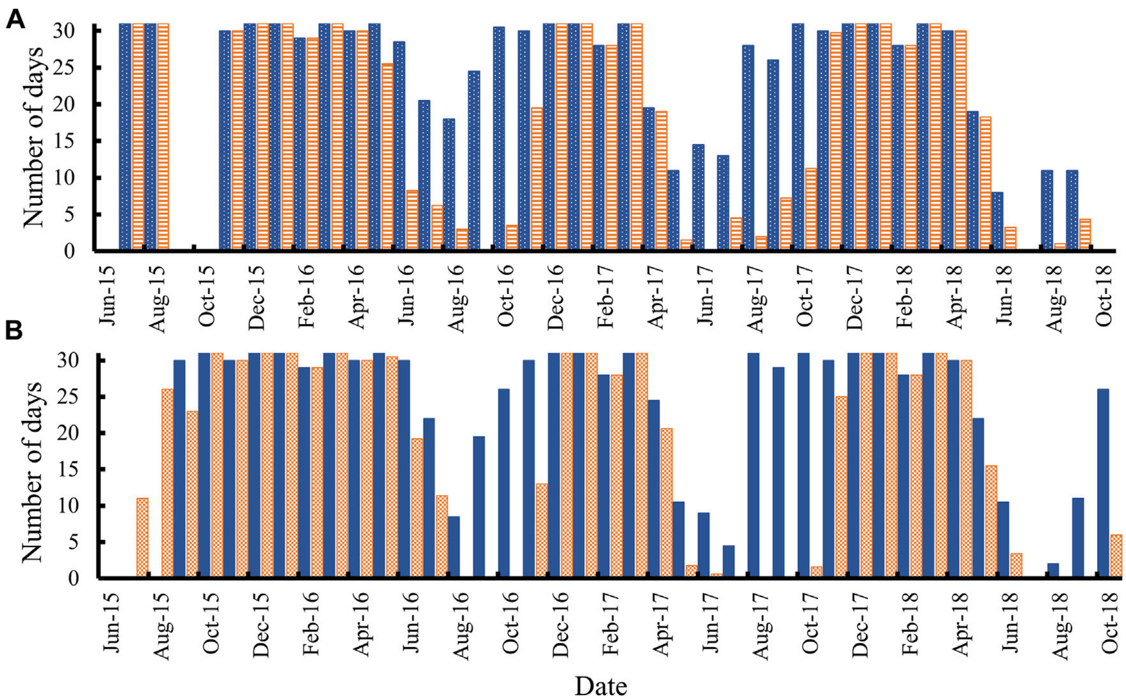
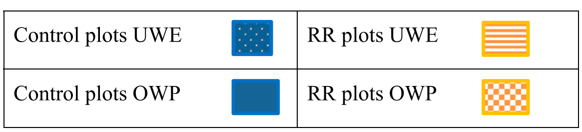


FIGURE 4 | Number of days each month when soil moisture tension at 10 cm depth was between 0 and −59 KPa in Control or reduced rainfall (RR) plots at **(A)** UWE and **(B)** OWP.



December and March of each year (**Figure 4**). Soil moisture tension in the RR plots in each year (2015/2016, 2016/2017 and 2017/2018) was between 0 and −59 kPa for fewer days of each month during the peak growing season (April–September), than in Control plots (**Figure 4**).

Soil moisture content (%) at 10 cm showed large season variations; at UWE from 37 to ~60%, and at OWP from below 30 to ~60% (**Figure 5**). Changes in soil moisture content at 50 and 90 cm were smaller, for example at UWE moisture content at 50 cm ranged from 54–58%, and at 90 cm from 58–60%. Changes in soil moisture content (%) at 50 cm were greater at OWP than at UWE (**Figure 5**) particularly in the RR plots. The changes at 50 and 90 cm generally lagged, in time, behind the changes at 10 cm (**Figure 5**). At both sites, average soil moisture content at 10 cm was usually higher in Control plots than in RR plots. The soil in Control plots returned to field capacity (maximum water content after any excess water has drained away under the influence of gravity) more quickly than soil in the RR plots (**Figure 5**).

Seasonal patterns of changes in soil moisture tension and soil moisture content were similar at both sites. Soil moisture content (%) decreased and soil moisture tension (kPa) increased during the peak growing season (April to September). During the autumn and winter months (October–March), when incident rainfall exceeded the amount of water taken up by the grassland plants, soil moisture content increased and soil moisture tension decreased (**Figures 4**, **5**).

Soil moisture characteristic curves (soil moisture tension vs soil moisture content) (**Supplementary Figure S1**) indicate that at -59 kPa the UWE soil contains ~44%

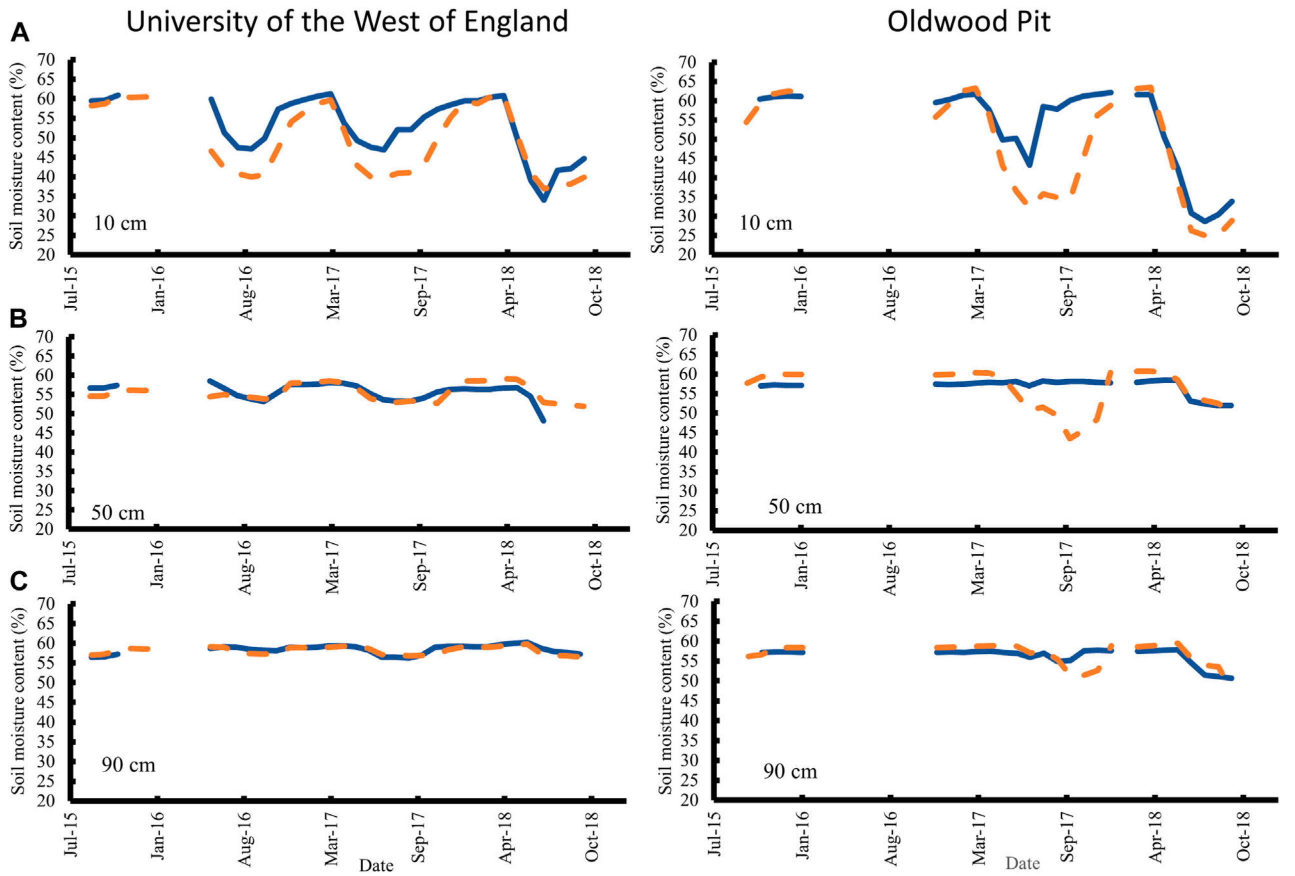


FIGURE 5 | Monthly average soil moisture content (%) at **(A)** 10 cm, **(B)** 50 cm, and **(C)** 90 cm for Control and RR plots at UWE and OWP.

Control plots	RR plots

moisture, and the OWP soil ~50% moisture. At −491 kPa, the UWE soil contained ~36% moisture and the OWP soil ~34% moisture (**Supplementary Figure S1**). Thus, the amount of soil water available to plants between −59 and −491 kPa is ~8% at UWE and ~16% at OWP.

3.1.3 Air Temperature

Over the course of the experiment air temperatures at UWE ranged from −6.4°C to 32°C, and at OWP from −7.9°C to 31.7°C. Average air temperatures were 11.5°C at UWE and 10.9°C at OWP (**Supplementary Table S3**). Average maximum air temperature was 15.5°C at UWE and 15.1°C at OWP. Average minimum air temperature was 7.5°C at UWE and 6.0°C at OWP (**Supplementary Table S3**).

Air temperatures were similar inside (measured below the roof) and outside the rainfall shelters and differences are within the accuracy of the readings [±0.1°C (Gill Instruments, Lymington, United Kingdom)] (**Supplementary Table S3**). **Figure 6A** shows monthly average temperatures inside and outside one rainfall shelter at OWP; the two plots are almost coincident. At both sites, the average maximum temperature inside the shelters was slightly higher, and the average minimum temperature was slightly lower, than outside (**Supplementary Table S3**).

3.1.4 Soil Temperature

At both sites, soil temperature at 10 cm was 0.6–1.6°C higher in reduced rainfall (RR) plots than in Control plots, during the cooler months (December to March), and 0.3–0.7°C lower during the warmer months (June–September) (**Figure 6C,D**). This agrees with field observations that frost always cleared more quickly from the RR plots.

3.1.5 Photosynthetically Active Radiation

The sensors recorded incident PAR, from July 2015 until the roofs were put on in October 2015 and as can be seen in the example set of data from OWP (**Figure 6B**) recorded similar values. After roof installation the PAR was lower (77–95%, average 85%) under the roofs than outside (**Figure 6B**). PAR was reduced by the roof material (PEGT), and short-term condensation and frost on the roof elements.

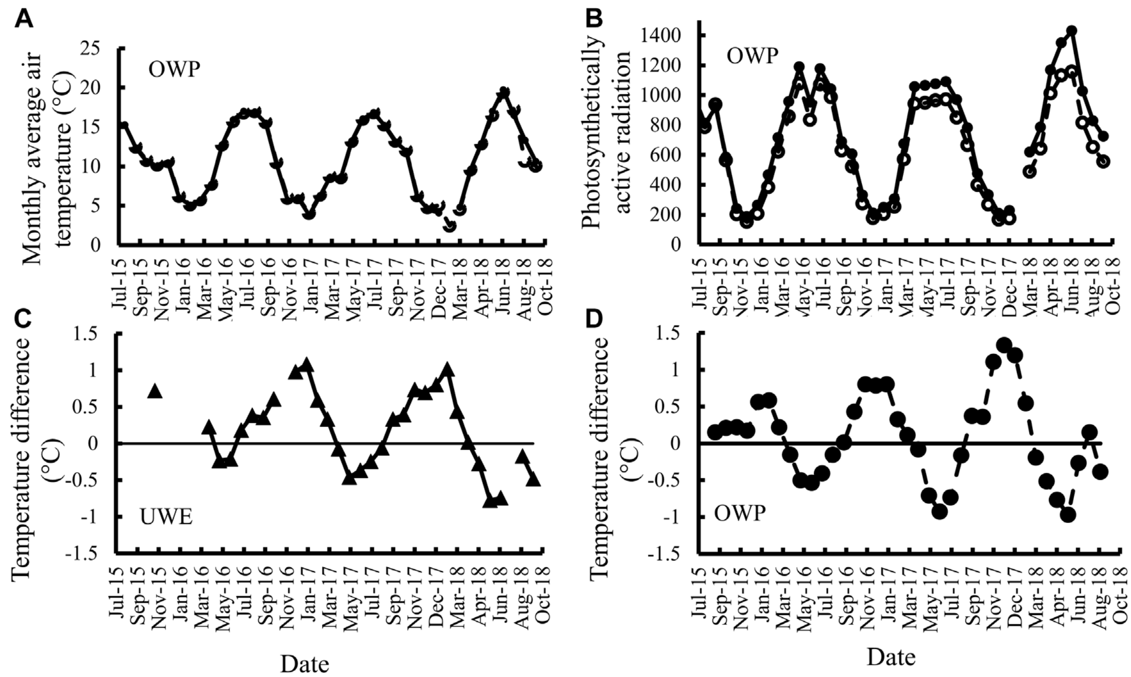


FIGURE 6 | (A) Monthly average air temperature (°C), recorded by weather station, at Oldwood Pit inside and outside the rainfall shelters; **(B)** Monthly average of midday photosynthetically active radiation (PAR) in µmol of photons m^{-2} s^{-1} at Oldwood Pit (OWP), measured and under the roof and outside the rainfall shelters; **(C,D)** Difference in monthly average soil temp (°C), from Degagon MPS6 sensor, at 10 cm between Reduced Rainfall and Control plots at **(C)** UWE and **(D)** OWP. Average temperatures were calculated from daily maximum and daily minimum temperature.

Outside	●——●	Inside	○– – –○
UWE	▲——▲	OWP	●– – –●

3.2 Biomass

3.2.1 Total Amount of Dry Matter

At both UWE and OWP there was considerable plot-to-plot variation in the mass of above ground dry matter (biomass) produced. Total biomass, across both sites, ranged from 392–1,134 g m^{-2} for Control plots, and 328–1,144 g m^{-2} for RR plots. These values are equivalent to 3.9–7.8 t ha^{-1} at UWE and 8.7–11.3 t ha^{-1} at OWP. The coefficient of variation, for weight of biomass samples collected in 2016, 2017, and 2018, averaged across both sites was 29%.

3.2.2 Biomass at University of the West of England

At UWE, overall there was no statistically significant difference between the amount of biomass produced in Control or RR plots (p = 0.12) (**Figure 7**). Year had a large effect on amount of biomass recorded (p < 0.0001), and explained 92% of the variation. There was no statistically significant interaction between treatment and year (p = 0.22).

2017 was the only year in which less biomass was produced in the RR plots (327.6 g m^{-2}) than in the Control plots (391.6 g m^{-2}) (**Figure 7** and **Supplementary Table S4**). In 2016 and 2018, the RR plots produced slightly more biomass than the Control plots, but these differences were not statistically significant (**Figure 7** and **Supplementary Table S4**).

In 2017, less biomass was produced, in both Control and RR plots, compared with 2016 (p < 0.0001) or 2018 (p = 0.001). In 2018, less biomass was produced than in 2016 (p = 0.022) (**Figure 7** and **Supplementary Table S4**).

In late June 2018, slightly more biomass was collected from the RR plots than from the Control plots (**Figure 7**), but the difference was not statistically significant (p = 0.086).

3.2.3 Biomass at Oldwood Pits

3.2.3.1 Annual Biomass Production at Oldwood Pits

At OWP, overall the reduced rainfall (RR) treatment had no statistically significant effect on the total annual biomass (summer and autumn samples combined) produced by the plots (p = 0.478) (**Supplementary Table S5**). There were small differences between years in the annual total amount of biomass produced (p = 0.065), and year accounted for 94% of the variation in annual total biomass. More total biomass was produced in 2016 in both Control and RR plots, than in 2017 or 2018 (2016 vs. 2017 p = 0.021, 2016 vs. 2018 p = 0.032) (**Figure 7** and **Supplementary Table S5**). There was no statistically significant interaction between year and treatment (p = 0.78).

At OWP, there was a strong seasonal effect (p = 0.000); more biomass was collected each year in July (615 ± 48.6 g m^{-2}, mean ±

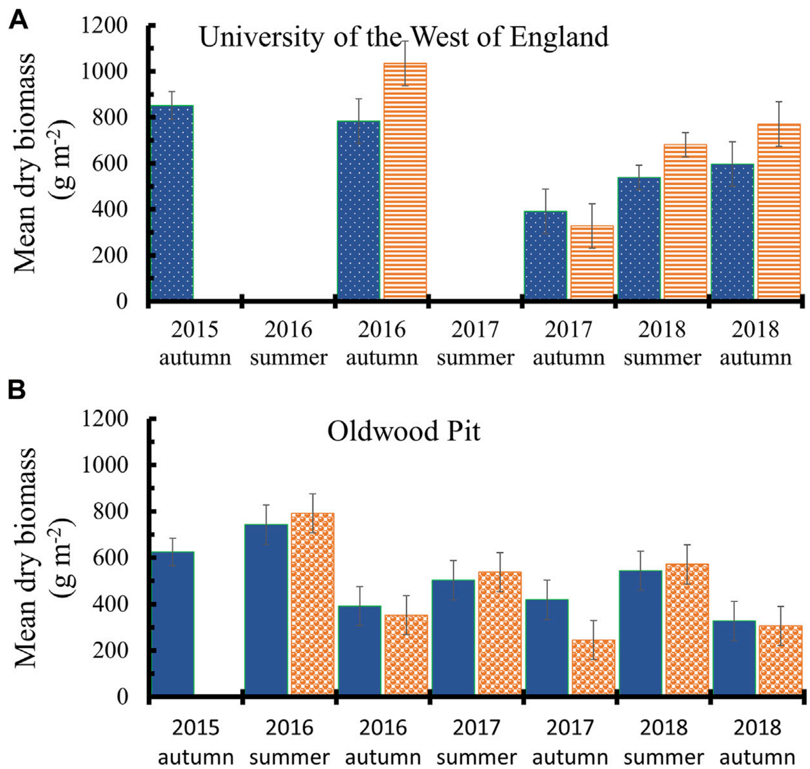


FIGURE 7 | Dry mass of above ground plant material (biomass) (g m^{-2}) harvested at **(A)** UWE and **(B)** OWP. Values are mean ± SE, n = 6, 12 in 2015. Note: at UWE plots were cut in autumn and at OWP plots were cut in early July and early October. There were no shelters in 2015 at the time of biomass sampling so all were essentially Control plots.

Control plots at UWE		RR plots at UWE	
Control plots at OWP		RR plots at OWP	

SE) than in October (340.2 ± 14.6 g m^{-2}), (**Figure 7**). Therefore we have separately analysed the data for summer and autumn biomass.

3.2.3.2 Summer Harvested Total Biomass at OWP

Overall, at OWP in summer, RR plots produced more biomass (633.4 g m^{-2}) than Control plots (596.6 g m^{-2}), and this was statistically significant (p = 0.029) (**Figure 7** and **Supplementary Table S5**). Year had a stronger impact on biomass production than treatment (p = 0.002). In summer 2016, more biomass was collected from both RR and Control plots than in 2017 (p = 0.046) or 2018 (p = 0.088) (**Figure 7** and **Supplementary Table S5**).

3.2.3.3 Autumn Harvested Total Biomass at Oldwood Pits

At OWP. the weight of biomass harvested in the autumn (following late summer cutting to simulate hay removal) was less in RR plots (300.6 g m^{-2}) that in Control plots (379.6 g m^{-2}) (p = 0.000) (**Figure 7**). More biomass was produced in autumn 2016 than in 2017 or 2018 (**Figure 7**). The amount of biomass harvested in the autumn showed a strong interaction between treatment and year (p = 0.028).

3.3 Effect of Reduced Rainfall on Biomass of Different Functional Species Types at University of the West of England and Oldwood Pits

Results are presented for all dead material, live broadleaved plants, live bryophytes and live graminoid plants. Plants with woody stems and pteridophytes were in too few plots for statistical analysis.

3.3.1 University of the West of England

At UWE, overall there was no statistically significant effect of reduced rainfall (RR) on the proportion of biomass from any of the functional groups: all dead material (p = 0.38), and broadleaved plants (p = 0.69), bryophytes (p = 0.33), or graminoid plants (p = 0.08) (**Supplementary Figure S2**). Year had a statistically significant effect on the proportion of bryophyte (p = 0.026). There was no interaction between treatment and year (p values ranged from 0.12 to 0.78).

In samples from RR plots, taking all years together, live graminoid plants made up a slightly smaller proportion of the total biomass (14.3%; 103.28 ± 30.16 g m^{-2}) than in

TABLE 2 | OWP the effect of Reduced Rainfall on the proportion of total dry biomass at OWP from each of dead material and live broadleaved plants, bryophtyes, and graminoid plants. Values in bold with the same letter are statistically significantly different from each other, based on pair-wise comparisons. At p = 0.05:a, b, d; at p = 0.001:c.

Harvest	Control			Reduced rainfall		
	Dry Wt (g m^{-2})	s.d	Proportion	Dry Wt (g m^{-2})	s.d	Proportion
Annual						
Broadleaved plants	183.0	105.2	0.205	235.4	221.7	0.237
Bryophytes	4.6	5.5	**0.005a**	13.3	13.7	**0.017a**
Dead	337.8	159.5	0.344	328	110.5	0.365
Graminoid plants	449.7	216.0	0.445	355.7	201.3	0.381
Autumn						
Broadleaved plants	87.2	51.5	0.233	70.2	46.0	0.241
Bryophytes	2.7	4.7	**0.007d**	8.8	11.7	**0.03d**
Dead	132.5	40.8	**0.351b**	138.2	66.2	**0.448b**
Graminoid plants	156.3	60.8	**0.404c**	82	38.0	**0.277c**

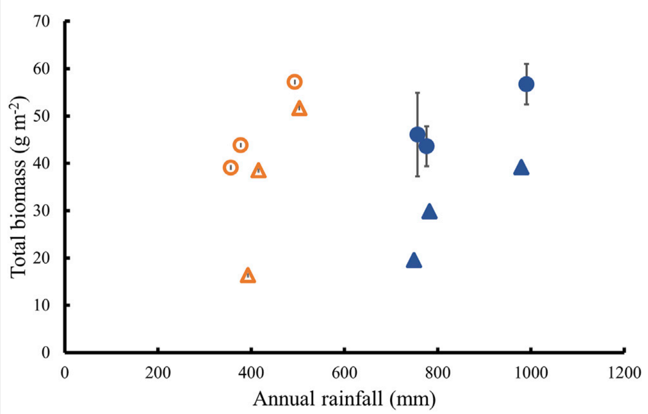


FIGURE 8 | Relationship between total annual biomass production and annual precipitation at UWE and OWP for Control and RR plots. Values shown are mean ± SE; in most cases the error bar is smaller than the symbol.

samples from Control plots (21.5%; 123.73 ± 25.82 g m^{-2}) (p = 0.018).

Year had a highly significant effect on the proportion of biomass from broadleaved (p = 0.007), bryophyte (p=<0.001) and graminoid plants (p = 0.021) (**Supplementary Table S6**). Broadleaved plants were a smaller proportion of total biomass in 2017 (4.6%) and 2018 (2.3%) compared to 2016 (12.4%), while graminoid plants made up a higher proportion of total biomass in 2018 (23.9%) than in 2016 (15.9%) or 2017 (14.2%).

3.3.2 Oldwood Pits

At OWP, RR had no statistically significant effect on the proportion of total annual biomass from any of the functional groups: dead material (p = 0.41), broadleaved plants (p = 0.17), bryophytes (p = 0.11) or graminoid plants (p = 0.43). However, there was a significant difference between years in the proportion of graminoid plants (p = 0.01) and dead material (p = 0.029) (**Supplementary Figure S2**). There was no interaction between treatment and year for biomass of any of the different function groups (p = 0.7–0.9).

At OWP, across all years, in samples from RR plots bryophytes made up a greater proportion of the total annual biomass (1.7%) than in samples from Control plots (0.5%) (**Table 2**). In samples collected from RR plots at OWP in the autumn, bryophytes and dead plant material made up a greater proportion and live graminoid plants a smaller proportion of the total biomass than in samples from Control plots (**Table 2**).

At OWP, year had a strong influence on the proportion of total biomass from each functional group (**Supplementary Table S7**, **Supplementary Figure S2**). Live graminoid plants were a smaller proportion of the annual total biomass (summer and autumn together) in 2017 (41.3%) and 2018 (30.5%) than in 2016 (52%) (**Supplementary Table S7**). Dead material was a larger proportion of total annual biomass in 2018 (42%) than in 2016 (28%) (**Supplementary Table S7**, **Supplementary Figure S2**). In samples collected in the summer, dead plant material was a larger proportion of the total biomass in 2017 (39.1%) and 2018 (39.6%) than in 2016 (21.7%) (**Supplementary Table S7**). Live graminoid plants were a smaller proportion, of the total biomass, of samples collected in summer 2017 (39.5%) and 2018 (32.2%) than in 2016 (61.7%) (**Supplementary Table S7**). In the autumn samples, live graminoid plants were a greater proportion of the total biomass in 2017 (41.5%) than in 2016 (33.1%) or 2018 (27.5%) (**Supplementary Table S7**).

3.4 Biomass and Rainfall

At both sites, the largest amount of biomass was produced in 2016 (**Figure 7** and **Supplementary Tables S4, S5**). Annual rainfall in 2015/16, at both sites, was 120% (990 mm) of the 1961–2017 catchment average in Control plots and 60% (484 mm) in RR (**Table 1**). In 2015/2016, RR plots at both sites received less rainfall than Control plots did in either 2016/2017 or 2017/2018 (**Figure 3**).

There were differences between the sites, and between years in the impact of variations in rainfall amount a on biomass production. In 2017 and 2018 annual rainfall at both sites, in Control plots, was about 92% of the long-term average and in RR plots 46%. At UWE in 2017, when compared to 2016, biomass production from Control plots was 50%, and from RR plots 32%. At OWP in 2017, total

TABLE 3 | Correlations between total annual biomass (g m^{-2}) and rainfall (mm) at UWE and OWP for Control and Reduced Rainfall (RR) plots. n = 18.

Site	OWP				UWE			
Treatment	Control		RR		Control		RR	
Rainfall period	Pearson Correlation	Statistical significance (*p*)	Pear. Correl	Stat. signif. (*p*)	Pear. Correl	Stat. signif. (*p*)	Pear. Correl	Stat. signif. (*p*)
Annual	0.37	0.131	0.52	0.028	0.70	0.001	0.66	0.003
Jan-Mar	0.28	0.255	0.49	0.038	0.77	0.000	0.74	0.000
Apr-Jun	0.37	0.135	0.52	0.028	0.69	0.001	0.65	0.003
Dec-Apr	0.17	0.513	0.39	0.111	0.70	0.001	0.71	0.001
Mar-May	0.096	0.705	0.32	0.200	0.67	0.002	0.64	0.004

TABLE 4 | Annual water productivity at UWE and OWP (g m^{-2} mm).

Harvest year	UWE		OWP	
	Control	RR	Control	RR
2016	0.8	2	1.2	2.4
2017	0.6	0.8	1.2	2.2
2018	0.8	1.8	1.2	2.4

biomass was 81% of the 2016 value in Control plots and 68% in RR plots. In contrast, in 2018 at both sites, biomass production, from Control and RR plots, was 75–77% of that recorded in 2016.

At both sites, for Control and RR plots, the total annual amount of biomass increased with increasing total annual rainfall (**Figure 8**). At UWE, total biomass from Control and from RR plots was strongly correlated with rainfall over each of the five selected periods (**Table 3**). In contrast, at OWP, total biomass from Control plots was not significantly correlated with rainfall, whilst that from RR plots was weakly correlated with annual, January to March and April to June rainfall, but not with December to April or March to May rainfall (**Table 3**). At OWP, autumn harvested biomass from Control plots was not significantly correlated with summer rainfall (Pearson correlation 0.33, $p = 0.18$) and that from RR plots was weakly and negatively correlated with rainfall (Pearson correlation –0.54, $p = 0.02$).

Water productivity (calculated as the amount of biomass for each mm of rain) was greater in the RR plots, at both sites, than in the Control plots (**Table 4**), and greater at OWP than at UWE. Water productivity, with one exception, was similar across all 3 years of the experiment. Water productivity at UWE in 2017 stands out for RR plots, because it was low (**Table 4**). If the rainfall reduction treatment had increased plant water use efficiency, we might have expected the water productivity of the RR plots to increase.

4 DISCUSSION

4.1 Environmental Data

4.1.1 Rainfall

Year-to-year and season-to-season rainfall variation is a normal part of the United Kingdom climate (Kendon et al., 2019) and the variability in rainfall patterns is predicted to become greater over the next twenty to 30 years (Met Office, 2018a). Compared with the annual rainfall for all of England (Kendon et al., 2017, 2018; 2019), the Frome catchment was wetter in 2016, drier in 2017 and similar in 2018 and this is likely a reflection of the catchment location in the western part of the United Kingdom. Total rainfall recorded from Control plots at both sites was similar although with some month-to-month differences between the two sites (**Figure 3**). Rainfall in November and December was greater at UWE than at OWP, which is probably due to a combination of direction of prevailing winds and local orographic effects.

The reduced rainfall (RR) treatment was successful in reducing rainfall within the plots by about 50% (**Figure 3**). Monthly rainfall in the RR plots was within the lower quartile of values for each month recorded in the last one hundred years for the Frome catchment (National River Flow Archive, 2021), but never fell below the one hundred year minimum monthly rainfall.

4.1.2 Soil Moisture

At both sites, soil moisture at 10 cm was more strongly affected by the RR treatment compared to that at 50 cm or 90 cm (**Figure 5**). Other rainfall manipulation studies (Vogel et al., 2013; Picon—Cochard et al., 2014) have also found that rainfall reduction affects soil moisture less in the deeper soil than in the surface layers. In pastures in the United Kingdom and elsewhere, most roots (65–90%) occur in the top 10–15 cm of soil (Macklon et al., 1994; Dawson et al., 2000; Brown et al., 2010), and thus this part of the soil is likely to be depleted of water more quickly during dry periods. In RR and Control plots, at both sites, soil moisture returned to field capacity during the autumn and winter (October–March) period. The return of the soil water content to field capacity in the winter was considered to be one of the most important factors enabling perennial rye grass crops to maintain productivity under dry summer conditions (Grove and Monaghan, 2018).

4.1.3 Air and Soil Temperature and Photosynthetically Active Radiation

The roofs had little effect on average air temperatures (**Supplementary Table S3**). We positioned the temperature sensors to record representative conditions under the roof, but there may have been some shading from the frame and, on cool days or at night, the metal of the frame may have acted as a heat sink (**Supplementary Table S3**). Small increases in average soil temperature under rainfall shelters in winter, and decreases in summer, such as we recorded, have been reported by other workers. In a grassland drought experiment, using frames with roofs to intercept rainfall, soil temperatures at 7 cm were found to be slightly decreased on warm days but increased on cool days (Vogel et al., 2013). Photosynthetically active radiation (PAR) was lower during the middle of the day under the shelter roofs, as has been found in other studies using rainfall shelters (Vogel et al., 2013). The above ground plant biomass production was similar in RR and Control plots, and sometimes slightly higher in the RR plots (**Figure 7**), suggesting that the reduction in PAR was not sufficient to affect productivity.

4.2 Total Biomass

4.2.1 Biomass

Total biomass production in our experiment was similar to other rainfall manipulation experiments that recorded grassland productivity: 200–300 g m^{-2} (Cole et al., 2019) for an unproductive upland calcareous grassland in Yorkshire, United Kingdom; and 800 g m^{-2} from a lowland grassland pasture in Switzerland (Finger et al., 2013). The average yield of grass in United Kingdom is 7.3 t ha^{-1} Dry Matter (Berry et al., 2016). 8.7 t ha^{-1} was taken as the 2010 benchmark value in a modelling study of likely changes in grassland productivity in United Kingdom, associated with climate change (Qi et al., 2018). Thus, the dry mass of above ground plant material in our experiment is comparable with that collected from other rainfall manipulation experiments and with that harvested on United Kingdom farms. Overall, the amount of biomass collected from UWE was slightly less than that collected from OWP (**Supplementary Tables S4**, **S5**). This difference is due to inherent differences in productivity between the two sites, reflecting soil conditions, plant species present and pasture management.

The high plot-to-plot variability in biomass production reflects the species distribution and diversity of the vegetation, and the relatively small areas sampled. The vegetation at both sites was typical for United Kingdom semi-natural grasslands (Sternberg et al., 1999), with 78 species of flowering plants at UWE and 63 at OWP. In grasslands, high plant diversity can increase the resistance of plant productivity to climate extremes, particularly drought (Tilman and Downing, 1994; Sanderson et al., 2007; Klaus et al., 2016); both of our experimental sites were species rich. High coefficients of variation for biomass productivity have been found in other grassland studies, in which small samples were used to estimate productivity, such as 19.2% for an unproductive grassland in Yorkshire, United Kingdom (Grime et al., 2008), and 22% for a lowland limestone grassland in Oxfordshire, United Kingdom (Grime et al., 2000).

4.2.2 Treatment effects on Annual Biomass

At both UWE and OWP, the reduced rainfall (RR) treatment had only a small effect on total annual biomass production when compared to the strong year-to-year variation (**Supplementary Tables S4**, **S5**, **Figure 7**). Other studies have found similar results, for example, in a mesotrophic grassland in Berkshire, United Kingdom, 30% reduction in rainfall (between March and August) had no significant effect on biomass production until the third year of the experiment (Fry et al., 2014; Lee et al., 2014). In Canadian bunchgrass grasslands, excluding rain during the main growing season was associated with a slight increase in biomass production (Carlyle et al., 2014). In a rainfall manipulation experiment on calcareous grassland in Yorkshire, United Kingdom, Cole et al. (2019) found that a 100-years summer drought had no significant effect on biomass production.

4.2.3 Treatment effects on Biomass Production in Spring and Early Summer

RR plots, at OWP, produced slightly more biomass than Control plots. A review of anticipated changes to grassland associated with climate change (Hopkins and del Prado, 2007) suggested that on sites in North and Northwest Europe, where water is not a limiting resource, increased winter temperatures would be likely to increase herbage growth. Computer modelling of grass yields in Ireland indicated that early season growth of grass, especially in the West of the country, was likely to increase with climate change (Holden and Brereton, 2002). Soil temperatures in the RR plots were slightly higher during the winter (**Figure 6**), but as rainfall, even in the RR plots, was sufficient to return the soil to field capacity over the winter period, there was no water limitation that might have reduced early season growth.

4.2.4 Treatment effects on Late Summer (Autumn Harvested) Biomass Production at Oldwood Pits

At OWP, after the late summer cutting that simulated hay removal, there was lower biomass from the reduced rainfall (RR) plots in all years (**Figure 7**) suggesting that reduced rainfall was inhibiting regrowth of the sward. In a phenology study at OWP, during 2015/2016, in late June, *Lolium perenne* (L.) plants in RR plots were taller by about 10 cm, than *L. perenne* plants in Control plots, suggesting greater growth in the early growing season. However, after the plots were cut in early July, *L. perenne* plants in RR plots grew more slowly, and in early September were 10 cm shorter than plants in Control plots (Cairney, 2016).

4.2.5 Rainfall and Biomass Production

At both UWE and OWP, for Control and RR plots, the amount of biomass tended to increase with increasing rainfall (**Figure 8**). We observed no further increase in biomass once rainfall exceeded around 550 mm per year. Grass crops in United Kingdom are reported to use around 600–900 mm water per year (Grove and Monaghan, 2018). Intensively managed pastures, such as rye grass leys that have only one or two high yielding hybrid varieties of rye grass, produce more than 20 t ha^{-1} (Jones and Humphreys, 1999). These rye grass pastures are fertilized, continually grazed or harvested several times each year, and need up to 900 mm water per year to sustain production of grass (Grove and Monaghan, 2018). Our results (**Figure 8**) suggest that the water requirement of the non-intensively managed permanent pastures that we studied, in the Bristol Frome catchment, may be 550–600 mm water per year.

In a meta-analysis of long-term ecological studies in the United States of America, above ground net primary production was found to be strongly correlated with annual precipitation (Knapp and Smith, 2001). Although in our experiment the total biomass in Control plots increased with increasing rainfall, it was never higher than in the RR plots, even in the wettest year. Other authors (Wilcox et al., 2017; Matos et al., 2020) considered that the relationship between rainfall and productivity is complex, with productivity saturating at high rainfall, and this appears to be shown by our results.

In grasslands, there is a positive feedback between grasses and soil water content (Matos et al., 2020). A continuous grass layer reduces evaporation and run-off of water, therefore soil water content increases; this leads to better vegetation growth. Above the threshold, when water supply is not a limiting factor for plant growth, further rainfall will move through the soil, replenish ground water reserves, and into drainage channels and rivers. Thus, grasslands play an important role in the water cycle. In the United Kingdom, if the area of permanent pasture as a proportion of agricultural land falls by more than 5%, farmers may be required to reinstate permanent grass (Rural Payments Agency, 2020). Computer modelling of the likely effects of future changes in land use combined with climate change have indicated that reducing the area under grass in the Frome catchment could reduce ground water recharge (Afzal and Ragab, 2019).

The annual pattern of monthly rainfall was very different for each of the three study years (**Figure 3**). Rainfall during the cooler months when evaporation and evapotranspiration is low is important for recharging groundwater reserves (Afzal and Ragab, 2019). In United Kingdom pastures, 65–90% of grassroots are in the surface 10–15 cm of the soil (Macklon et al., 1994), and growth is influenced by incident rainfall as well as the amount of stored soil moisture. At UWE total biomass from Control and from RR plots was strongly correlated with rainfall over each of the periods selected (**Table 3**), suggesting that both soil water reserves and incident rainfall influence biomass production at UWE. In contrast, at OWP even in RR plots, biomass production was not strongly correlated with rainfall, suggesting that the vegetation at OWP makes more use of stored soil water than incident rainfall (**Table 3**).

If the rainfall reduction shelters had altered the way that the plants utilized water, we might have expected the water productivity to increase over time but this did not happen. For RR plots at UWE, 2017 stands out because the water productivity was so low (**Table 4**). At UWE in 2017, biomass production in Control and RR plots was less than in 2018 (**Figure 7**) but the total annual rainfall was similar in both years (**Figure 3**). Thus the amount of annual rainfall cannot explain the differences in productivity among years. At OWP, we asked if biomass production between July and September, after cutting the vegetation in late June/early July, was correlated with rainfall in July, August and September. However, at OWP, the smallest amount of regrowth was recorded from the RR plots in the 2016/2017 July to September season when the rainfall total was the highest (**Figures 3**, **7**). This suggests that the amount of incident rainfall was not the only factor limiting productivity.

Although, studies of grasslands in United States found productivity to be strongly correlated with annual precipitation (Knapp and Smith, 2001), other meta-analyses investigating the effects of drought or reduced rainfall on grassland productivity that included studies from a wider geographical area (Beier at al., 2012; Ward et al., 2016) have found considerable heterogeneity in the responses of grasslands to reduced rainfall. Many studies in these reviews are from semi-arid environments (Knapp and Smith, 2001; Beier at al., 2012; Wilcox et al., 2017), with relatively few studies in regions where annual rainfall is unlikely to limit productivity (Matos et al., 2020). Other studies of United Kingdom grasslands have shown that reducing summer rainfall has little effect on biomass production over periods of a few years (Grime et al., 2000; Fry et al., 2014). On an unproductive grassland in Northern England, even after 13 years of reduced summer rainfall, effects on the vegetation were smaller than those associated with year-to-year fluctuations in climate (Grime et al., 2008). If temperatures continue to rise as predicted (Met Office 2018a), the associated rise in evapotranspiration is likely to increase the amount of water used by plants. If plant demand for water exceeds the amount available (water stored within the soil combined with incident rainfall during the growing season) then there are likely to be some changes in plant species composition of grasslands and eventually in productivity. However, it is difficult to know over what time-scale this might happen. Modelling of the likely impacts of climate change up to 2050s suggested that the productivity of permanent pastures in Great Britain will rise (Qi et al., 2018). In a longer (100 years) modelling study of climate change impacts, including reduced summer rainfall, on grass yield in Ireland, Holden and Brereton (2002) foresaw no catastrophic impacts, but noted that yield might increase in the north and decline in the south and east of Ireland. Many managed grassland systems have high adaptive potential; in North and North West Europe, future climate change may lead to increased herbage growth (ADAS, 1997; Hopkins and del Prado, 2007).

4.3 Treatment effects on Contribution of Different Functional Groups to Total Biomass

The reduced rainfall treatment had few significant effects on the proportions of biomass from different functional groups at either site (**Supplementary Figure S2**, **Table 2**). At UWE, live graminoid species were a smaller proportion of biomass, in samples from RR plots compared to Control plots (**Supplementary Figure S2**). This difference may reflect earlier senescence of grasses in the RR treatment during the summer. Summer drought reduced the proportion of perennial grasses in a recently established pasture in Oxford, (Grime et al., 2000). At OWP, based on annual biomass, there was no change in the proportion of live graminoid species or broadleaved plants (**Supplementary Figure S2**). A similar result was found in a well-established grassland in Yorkshire where reduced rainfall had no effect on the proportion of perennial grasses or perennial forbes (Grime et al., 2000; Grime et al., 2008). At OWP, we recorded a small increase in the proportion of bryophytes in RR plots (**Table 2**), but this effect was similar in size to the variation among years (**Supplementary Table S7**).

Year-to-year variation in the proportion of biomass contributed by different functional groups was equal to, or greater, than the effects associated with reduced rainfall, as has been noted in other grassland studies (Grime et al., 2000; Grime et al., 2008).

4.4 Soil Moisture and Biomass

In 2015/2016 at both sites, and in Control and RR plots, soil water was freely available to plants until June 2016, but in 2016/2017, soil water was only freely available until April 2017, and in 2017/2018 only until May 2018 (**Figure 4**). In both 2016/2017 and 2017/2018, the plants would likely have experienced some level of water stress during the spring growing season. At UWE, a comparison of the monthly soil moisture content (**Figure 5**) and the soil moisture characteristic curve for the Worcester series soil (**Supplementary Figure S1**) suggested that in 2016/2017 between April and September, only a small proportion of soil water was available to the plants and this limited growth. The soil moisture characteristic curve is steep so that plants would experience sudden water stress. The soil moisture characteristic curve of Dale series soil at OWP, indicated that the Dale series soil has more plant available water (between −59 kPa and −491 kPa) than the Worcester series soil. The Dale soil moisture characteristic curve has a less steep slope than the Worcester series soil, so that plant water stress would have developed more slowly.

Soil moisture stress reduces plant growth through effects on turgor and on photosynthetic activity (Van Peer et al., 2004). A review of the effects of drought on the growth of forage grasses in Poland (Staniak and Kocon, 2015) found that spring droughts often reduced the early regrowth of meadow swards, while summer drought reduced the second regrowth of meadows. We recorded a similar result at OWP, with the smallest amount of regrowth in 2017, when soil moisture tension increased (and soil water availability decreased), earlier in the year compared to 2016 or 2018.

If rainfall cannot move through the soil profile, water may accumulate causing the soil to become water logged. This can lead to decreases in soil pH, oxygen depletion, and changes in nutrient availability that negatively affect plant growth and can lead to decreases in plant species diversity (Michalcová et al., 2011). The soil at OWP is gleyed (Findlay, 1976) indicating that the soil is prone to waterlogging. We recorded greater decreases in soil moisture % at 50 cm in the RR plots at OWP than in the Control plots (**Figure 5**), and it maybe that the small increase in biomass production that we observed in the RR plots is a response to a reduction in the extent of waterlogging.

4.5 Vegetation and Management

Differences in vegetation and management between the two field sites may partly explain why the early season dry conditions of 2016/2017 affected biomass production at OWP less than at UWE. The pasture at OWP is at least 80 years old and carefully managed through sheep grazing and a regular hay cut. At UWE, although the pasture is 30–40 years old, it had not received regular management, and the change from animal grazing to an annual hay cut occurred just 4 years before this study. It is likely that the vegetation was still adapting to the new management regime. At OWP, the sward was tightly knit with many perennial nitrogen fixing species, such as, *Trifolium repens*, *T. pratense,* and *Lotus corniculatus.* These species are able to take up water from about 30% deeper in the soil than rye grass, enabling them to withstand dry conditions (Grieu et al., 2001). At UWE, the sward was dominated by vigorous but tussock forming grasses, such as *Dactylis glomerata* and *Arrhenatherum elatius*, and many of the nitrogen fixing plants present are shallow rooted annual species, such as *Vicia hirsuta* (L.) and *V. tetrasperma* (L.). Other studies have shown that well-established pastures are less affected by water shortages, than younger less established pastures (Grieu et al., 2001; Fridley et al., 2011), and newly planted pastures are likely to be more sensitive to lack of summer rainfall. In a one-year-old pasture (in Ireland) 10 weeks of rainfall exclusion, starting in July, dramatically reduced biomass (Picon–Cochard et al., 2014). Intensive land use has been shown to increase negative effects on grassland associated with rainfall reduction (Stampfli et al., 2018). The UWE and OWP sites are both extensively managed, and this is likely to have contributed to their resilience to rainfall reduction.

4.6 How Well did the Experiment Achieve Its Aim?

The aim of the experiment was to understand how predicted changes in the climate, especially a decrease in summer rainfall, may affect the productivity of permanent pastures in the South West of England. Although we reduced rainfall by about 50% relative to incident rainfall, during the experiment, this was only for 3 years and was, therefore, not the same as reducing rainfall to 50% of the long-term average. In our experiment, the reduced rainfall values were within the range of rainfall values recorded over the last one hundred years. Several authors have suggested that well-established grassland communities are already adapted to environmental stress (Grime et al., 2008; Matos et al., 2020); because, for rainfall, long-term trends are smaller than inter-annual variations.

In the Bristol Frome catchment and the rest of the United Kingdom, future summer rainfall is predicted to decrease, but winter rainfall is predicted to increase (Afzal and Ragab, 2019; Met Office, 2018a); our experiment reduced rainfall throughout the year. During the winter months, pasture water use is small. Reducing rainfall by 50% did not impact biomass production or change the relative amount of species functional groups because, during the winter period, even 50% of the available rainfall was more than that needed to replenish soil water reserves. At both OWP and UWE, the soil had returned to field capacity in March of each year, the start of the main growing season (**Figures 4**, **5**). A return of the soil to field capacity during the winter is considered crucial for crop growth in the following spring (Grove and Monaghan, 2018).

A longer experimental period is needed to separate long-term trends from inter-annual variation but, of the eleven long-term experiments on grassland in the United Kingdom in 2014, only two sites (Buxton Climate Change Impacts Laboratory and Peaknaze) were investigating the impacts of climate change, and both are on agriculturally unproductive upland grasslands (Ecological Continuity Trust, 2015). In our study, we excluded rainfall throughout the year but United Kingdom climate change predictions (Met Office, 2018a) indicate that winter rainfall is likely to increase and further work is needed to try understand how, or if, this will counteract the reduction in summer rainfall. Increased winter rainfall may increase the duration of winter waterlogging, and intense storms during the summer may cause episodes of summer waterlogging. Further studies are needed to understand the interactions between waterlogging and drought.

5 CONCLUSION

At the two sites we studied, OWP and UWE, 50% reduction in incident rainfall did not reduce annual above ground dry matter (biomass) production or alter the biomass proportions from different plant functional types. Regrowth of vegetation after a summer hay cut was reduced, but there was not a simple relationship between rainfall amount and regrowth. At both sites, annual biomass slightly increased under reduced rainfall indicating that over the 3 year term of the experiment, these pastures are resilient to water stress. Other studies of well-established and species rich grasslands have also indicated pasture resilience and suggested that reduced rainfall during the summer may lead to increased productivity (Grime et al., 2000; Hopkins and del Prado, 2007; Grime et al., 2008; Fridley et al., 2011; Van Looy et al., 2016). Our results suggest that very dry conditions early in the year, such as in 2017, are more likely to reduce productivity, than are dry conditions in late June or early July after grasses have flowered. However, as has been noted in other studies (Knapp and Smith, 2001), separating inter-annual variation in productivity from trends in productivity related to long-term rainfall patterns was difficult.

Our sites were extensively managed; more intensively managed pastures, where two to four grass cuts may be taken each year, might be more adversely affected by reduced summer rainfall. OWP and UWE are relatively species-rich pastures; the productivity and resilience of species-poor pastures might be more sensitive to reduced rainfall. Encouraging species diversity in pastures, even at the cost of overall reduced productivity, is often considered an insurance against environmental stress (Sanderson et al., 2007).

Looking to the future, our results indicate that well-established, species-rich pastures are likely to be able to tolerate drier summers, at least over 3 years. However, because increased variability in weather conditions is predicted (Met Office, 2018a) farmers may need more flexibility in the way that they manage pastures. Agri-environmental schemes may need to consider this.

DATA AVAILABILITY STATEMENT

The datasets used in this study are available on application to Dry@uwe.ac.uk.

AUTHOR CONTRIBUTIONS

LM planned the DRY project; JT designed the experiment; JT, SA, and AG planned the sampling and site management regimes; SA collected and analysed the data and prepared the first draft manuscript; SA and JT revised the manuscript with input from AG and LM.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.686668/full#supplementary-material

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The Influence of the North Atlantic Oscillation and East Atlantic Pattern on Drought in British Catchments

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Drought events are influenced by a combination of both climatic and local catchment characteristics. In Great Britain the North Atlantic Oscillation (NAO) has long been recognised as the leading mode of climate variability, and studies have also noted the role of the East Atlantic Pattern (EA) as a secondary mode. This study aimed to develop an understanding of the combined influence of the NAO and EA on rainfall distribution and magnitude and the variable nature of meteorological to hydrological drought propagation. Initially, this study explores correlations between teleconnection indices and standardised precipitation and streamflow indices for 291 catchments across Great Britain, before focusing on nine case study catchments for further analysis. For each case study catchment, we use quantile regression and an analysis of drought frequency to explore the combined influence of the NAO and EA on drought conditions. Through a convergence of evidence from these analyses we make three observations. Firstly, in the winter months both the NAO and EA exert an influence on drought conditions, however there is spatial variability in the relative influence of the NAO and EA; the NAO has a stronger influence in the north-west, whilst the EA has a stronger influence in the southern and central regions. Secondly, in the summer months, less distinctive spatial differences were found, with higher probability of drought conditions under NAO+ phases, which however can be enhanced or moderated by the EA. Finally, as a result of catchment characteristics there is spatio-temporal variability in the propagation of meteorological to hydrological drought. Our findings suggest that by considering the NAO and EA in combination, we can better describe climate and drought variability. We conclude by noting the potential implications our study has on the role of monthly teleconnection forecasts in water management decision making in Great Britain, and acknowledge the current limitations associated with incorporating such understanding.

Keywords: drought, North Atlantic Oscillation, East Atlantic Pattern, climate, teleconnections, hydrology

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INTRODUCTION

Drought is a significant hydrometeorological hazard which can have severe socio-economic and environmental impacts (Nagarajan, 2010). Recent work has continued to advance our understanding of drought events, their spatio-temporal propagation through the hydrological cycle, and their impacts (Barker et al., 2016; Parry et al., 2016; Van Loon et al., 2016, Barker et al., 2019; Parsons et al., 2019; Tanguy et al., 2021). Droughts are typically classified on the basis of underlying physical processes and environmental/socio-economic impacts. These include meteorological drought (low precipitation), soil moisture or agricultural drought (low soil moisture), hydrological drought (low discharge and groundwater), and socio-economic drought (where there is a substantial impact on water resources affecting society) (Wilhite and Glantz, 1985; Van Loon, 2015). Conceptually these "drought types" have a sequential progression over time from meteorological to hydrological (and socio-economic) drought.

The spatiality of drought events is complex in Britain, as is the propagation of rainfall to flows within catchments. Distinctive differences in both rainfall and flow regimes have been found between the north-western and south-eastern areas of the country which are related to a range of climatological and hydrological variables (Burt and Howden, 2013; Folland et al., 2015; Chiverton et al., 2015; Barker et al., 2016; Rust et al., 2018; West et al., 2019; West et al., 2022; Svensson and Hannaford, 2019). Tanguy et al. (2021) identify NW/SE differences in the characteristics of meteorological drought events in Britain (Figure 1 of Tanguy et al., 2021). Notably, when examined with short rainfall accumulation periods, shorter and less severe droughts were found in the north-western areas, whilst longer and more severe droughts were found in the south-eastern areas. Although it should be noted that using longer rainfall accumulation periods resulted in less distinctive differences between the NW and SE (Tanguy et al., 2021).

Spatial patterns in the propagation of meteorological to hydrological drought is further complicated as it is influenced by both climate and catchment characteristics (Van Loon and Laaha, 2015). Barker et al. (2016) found that streamflow in the NW is sensitive to short meteorological droughts, such as those identified by Tanguy et al. (2021), due to the highly responsive nature of catchments in this region (Chiverton et al., 2015). Meanwhile low flows in the southern and eastern parts of the country are more strongly related to rainfall deficits over longer time periods due to their catchment characteristics and baseflow dominance (Barker et al., 2016).

Droughts are inherently driven by climatic processes, and for Great Britain and most of northern and western Europe, the North Atlantic Oscillation (NAO) atmospheric-oceanic circulation has long been identified as the leading mode of climate variability (Sweeney and O'Hare, 1992; Hurrell and Van Loon, 1997; Rodwell et al., 1999). The NAO is defined by two meridional diploes—the Icelandic Low and Azores High/Anticyclone. When the sea level pressure (SLP) difference between these two locations is greater than average the NAO is said to be in a positive phase (NAO+), whilst a weaker than average SLP difference represents a negative phase (NAO−) (Hurrell et al., 2003). Significant correlations have been reported between North Atlantic Oscillation Indices (quantitative measures of the phase and magnitude of the NAO - NAOI) and rainfall in Britain. For example, significant positive correlations have been found in the north-west of the country during winter (Wilby et al., 1997; Fowler and Kilsby, 2002; Afzal et al., 2015; Rust et al., 2018) and West et al. (2019) report significant increases/decreases in winter rainfall (200–300 mm) in the north-west associated with NAO+/− phases, relative to when the NAO is in a weak neutral state (defined as half the standard deviation plus/minus the long term mean of the NAOI (Berton et al., 2017)). Generally, winter correlations are weaker, and there is greater variability in the NAO-rainfall response, in the southern and eastern areas (Rust et al., 2018; West et al., 2021a).

The influence of the NAO is typically reported as being weaker in the summer months compared to winter (Folland et al., 2009). However spatially consistent rainfall responses to the NAO have been observed in summer across Great Britain, although these correlations are typically negative and weaker (Folland et al., 2009; Hall and Hanna, 2018; West et al., 2019). It should be noted however that summer correlations between the NAO and rainfall can vary depending on the calculation method of the chosen NAOI (Pokorná and Huth, 2015; West et al., 2019).

The East Atlantic Pattern (EA) has also been acknowledged to have an impact on European climate and has been referred to as a southward shifted NAO-like pattern (Comas-Bru and McDermott, 2014; Mikhailova and Yurovsky, 2016). The EA is noted as having a well-defined monopole at approximately 55°N; 20–35°W (Barnston and Livezey, 1987; Moore and Renfrew 2012; Comas-Bru and McDermott, 2014; Mellado-Cano et al., 2019), the SLP conditions at which have the potential to influence the location and strength of the NAO dipoles (Moore et al., 2011). Studies have noted that the phase and magnitude of the EA also influences rainfall spatial distribution and volume across Europe, and consequently by using a combination of the NAO and EA we may be able to describe winter climate variability more accurately (Comas Bru and McDermott, 2014; Mellado-Cano et al., 2020). In Great Britain, positive correlations have been found between the EA and rainfall, which are typically stronger in the southern and central regions (Casanueva et al., 2014; Hall and Hanna, 2018; West et al., 2021b).

As described above, north-west/south-east differences have been reported when exploring drought characteristics and propagation in Britain (Barker et al., 2016; Tanguy et al., 2021). Similar NW/SE spatio-temporal patterns have been found when exploring the propagation of NAO-driven rainfall deviations to streamflow in catchments (Burt and Howden, 2013; Rust et al., 2021a). Catchments in the north-west are more sensitive to NAO-rainfall deviations, whilst catchments in the southern regions are less susceptible due to their geology, terrain and landcover characteristics which moderate flows (West et al., 2022). Spatially and temporally variable NAO signals have also been detected in groundwater levels across aquifers in Britain (Lavers et al., 2015; Rust et al., 2019) and fluvial water temperatures (Wilby and Johnson, 2020). As far as we are aware, no study has explored at similar large scales the propagation of EA-rainfall signatures.

The above discussion describes the complex interplay between climate and hydrological systems, which manifests in spatio-temporal variability in rainfall, flow responses, and subsequent drought characteristics and propagation, generally along a N/S or NW/SE gradient in Britain. This study aims to bring together understandings of the influence of the NAO and EA on rainfall distribution and magnitude, and the variable nature of meteorological to hydrological drought (i.e., rainfall-streamflow) propagation. In doing so we present new insights into the influence of these two teleconnections on drought in British catchments and how this varies in space and time.

Developing our understanding of the potential effect of the NAO on low rainfall conditions, and how these deficits propagate through catchments, may help us to improve water management decision making and prepare for potential drought events. Forecasting skill for the winter NAO has improved in recent years (Baker et al., 2018; Parker et al., 2019; Athanasiadis et al., 2020; Smith et al., 2020), and there is increasing potential to include the NAO as a factor in monthly streamflow forecasting/ modelling (UK Hydrological Outlook, 2020; Donegan et al., 2021). However, we acknowledge further work is required to understand how teleconnection forecasting might be fully utilised given the spatio-temporal variability in NAO− rainfall responses (West et al., 2021a; Rust et al., 2021b), and we are unaware of any similar forecasting skill improvements having been reported for the EA.

METHODS

Data

Standardised indicators are commonly used for monitoring a range of different hydrometeorological/hydrological variables, such as precipitation, evapotranspiration, streamflow and groundwater (Bachmair et al., 2016). Standardised indicators are effective for hydrological monitoring as they are scaled in relation to local wetness/dryness (relative to a standard or baseline period) and can be calculated over a range of months (the accumulation period). For drought monitoring and assessment in particular, standardised indicators have been used in wide range of research and applications (Hannaford et al., 2011; Bachmair et al., 2016; Huang et al., 2017; Dhurmea et al., 2019; Parsons et al., 2019; Yeh, 2019; Mehr et al., 2020).

In this study we use two standardised indicators: The Standardised Precipitation Index (SPI) and Standardised Streamflow Index (SSI), both of which have been used in drought research in Great Britain (Barker et al., 2016; Barker et al., 2019). Both timeseries were downloaded from the United Kingdom Centre for Ecology and Hydrology (Tanguy et al., 2017; Barker et al., 2018) for the period January 1950-November 2015. The SPI and SSI datasets are calculated using interpolated historic rainfall (Met Office 5 km rainfall grids) and reconstructed streamflow datasets (UKCEH—Smith et al., 2018). The rainfall was fitted to a Gamma Distribution whilst a Tweedie Distribution was used for streamflow (Tanguy et al., 2017; Barker et al., 2018). Both have a common standard period of 1961–2010 and were calculated using a one-month accumulation period (SPI-1 and SSI-1). Positive SPI-1/SSI-1 values indicate higher mean monthly rainfall/flows relative to the 1961–2010 standard period, whilst negative values indicate lower mean monthly rainfall/flows. The SSI-1 data were downloaded for 291 catchments across Britain which vary in geography, size and physical characteristics. The SPI-1 data for each of these 291 catchments were derived by area-weighting the national 5 km gridded SPI-1 dataset.

The NOAA Climate Prediction Centre calculates monthly indices for a range of atmospheric-oceanic circulations, including the NAO and EA (NOAA, 2021). The CPC use a modelling approach based on a rotated principal component analysis (RCPA) to calculate their monthly teleconnection indices (after Barnston and Livezey, 1987), avoiding any limitations with using indices directly calculated using *in-situ* SLP measurements (Pokorná and Huth, 2015). The teleconnection indices from the CPC have been used in studies exploring the impact of atmospheric-circulations on low rainfall and drought conditions globally (Irannezhad et al., 2015; Huang et al., 2017; Abiy et al., 2019; Amini et al., 2020; Oñate-Valdivieso et al., 2020; Hassan and Nayak, 2021). Monthly NAO and EA indices were download for the period January 1950-November 2015 (NOAA, 2021).

The first analytical stage of this study (correlation and quantile regression) explores the relationship between each of the two teleconnections and meteorological/hydrological drought. In these initial analyses the NAO and EA are treated individually. Later analysis, quantifying the frequency of different drought severities, explores the interaction between the NAO and EA and the combined effect of different teleconnection phases.

Monthly NAOI-Rainfall and NAOI-Flow Correlation Analyses

The first stage of this research sought to examine the influence of the NAO and EA on catchment rainfall (quantified by the SPI-1) and streamflow (quantified by the SSI-1), and how their respective influence changes in space and time across the 291 catchments. Spearman correlation coefficients were calculated between the two teleconnection indices and SPI-1 and SSI-1 values for each catchment and calendar month, over the period January 1950-November 2015. Distinctive spatio-temporal differences were observed across the correlation results, representing the general influence of each of the two teleconnections.

Case Study Catchments

To develop a more detailed understanding of the combined effect of the NAO and EA on meteorological drought, and how rainfall deficits propagate through to hydrological drought, nine case study catchments were selected for further analysis. One catchment from each of the Met Office Climate Districts was chosen to ensure a spatially representative sample across Great Britain. The Climate Districts represent areas of relatively homogeneous climate and have been used in similar research (Wilby et al., 1997; Simpson and Jones, 2014; West et al., 2019). The catchments were chosen as they vary not only geographically, but also represent a range of physical characteristics such as size, terrain and geology. The representativeness of the nine case study catchments was evaluated using a similarity analysis (described below). **Figure 1** presents the nine case study catchments and **Table 1** summarises their key physical and hydrological characteristics.

Similarity analysis (Esri, 2021a) was used to assess the representativeness of each of the nine case study catchments

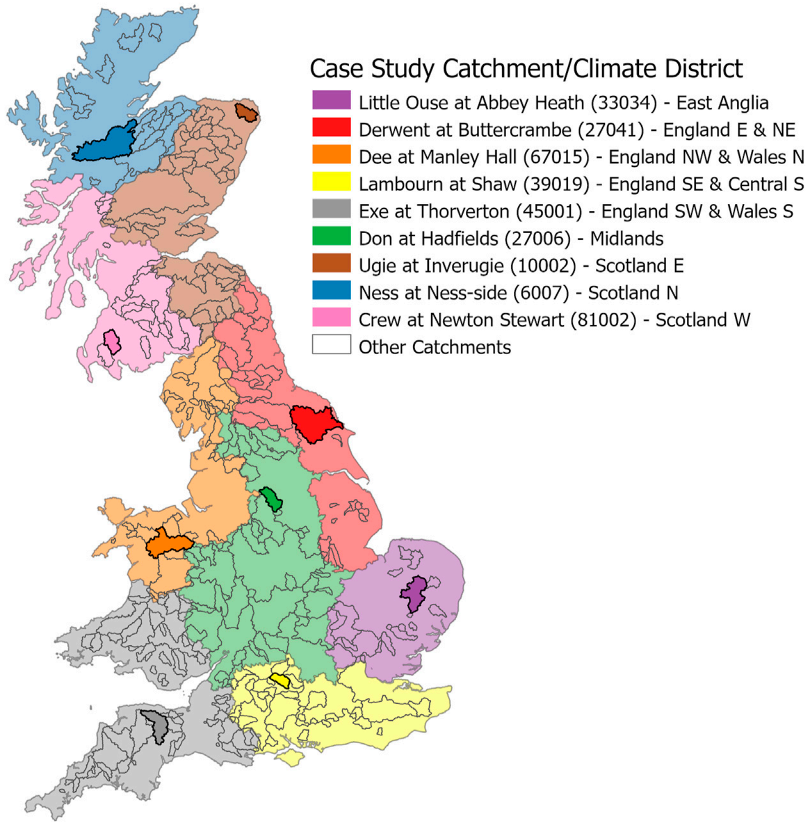

FIGURE 1 | Location of the nine case study catchments. Shading indicates the Met Office Climate Districts for Great Britain. Numbers in brackets are the Catchment ID from the United Kingdom National River Flow Archive.

in terms of their rainfall and flow responses to the NAO and the EA. This analysis gives an indication of how similar their meteorological and hydrological drought characteristics might be to the other 290 catchments, both within and beyond their associated Climate District. The similarity analysis algorithm was first applied to the two NAO and EA SPI-1 correlation time series for each of the nine case study catchments, and secondly to the NAO and EA SSI-1 correlation time series. The algorithm first standardises the selected correlation coefficients for each catchment - this standardisation uses a z-score transformation where the mean of all of the coefficients is subtracted from each value and divided by the standard deviation. This standardised value is then subtracted from the coefficients of the case study catchment, the difference squared and totalled, creating a similarity index (Esri, 2021a). Using this index, the 290 catchments were ranked from most to least similar and mapped.

Spatial autocorrelation in the similarity rank values was assessed using the Global Morans I statistic. The Global Morans I evaluates whether the spatial distribution of similarity rank values across the 290 catchments (not including the case study catchment) is more clustered or dispersed than would be expected in a random spatial distribution of the same values (Esri 2021b). The Global Morans I statistic requires a conceptualisation of how each catchment is spatially related to its neighbours. Due to the variability in the size of each catchment (Esri 2021c), a fixed distance band threshold which maximises spatial autocorrelation within the similarity rank values was used (Esri 2021b; Esri 2021c). This was a distance of 50 km from the geometric centroid of each catchment.

We undertook two separate analyses to investigate the influences of the NAO and the EA individually on meteorological drought conditions, and how this propagates to hydrological drought within each of the nine case study catchments, firstly using quantile regression analysis, and secondly drought severity frequency analysis.

Quantile Regression Analysis

A standard generalised linear regression model would assume that the NAO or EA have an equal influence on both wet and dry conditions (high/low rainfall and flows). The use of a quantile regression model allows for an assessment of the relationship between each teleconnection index and low (negative) SPI-1/SSI-1 values at different quantile levels, allowing for a more complete understanding of the influence of the teleconnection on low rainfall and flow conditions in the case study catchments (Amini et al., 2020).

We performed quantile regression using 99 quantiles between the NAO and EA indices and the catchment SPI-1 and SSI-1 values. We extracted the quantile regression

TABLE 1 | Summary of case study catchment characteristics (data from the United Kingdom National River Flow Archive).

Catchment (NRFA ID)	Climate District	Average annual rainfall (1961–1990) (mm)	Elevation (mAOD)	Landcover (% coverage)	Bedrock geology permeability (% coverage) (HP = high permeability, MP = Mixed permeability, LP = low permeability)	Size (km^2)	Base Flow Index
Ness at ness-side (6007)	Scotland N	1,765	• Min = 7 • Max = 1,109.6	• Woodland = 16.97 • Arable = 1.22 • Grassland = 13.33 • Mountain/Heath/Bog = 61.58 • Urban = 0.06	• HP Bedrock = 0 • MP Bedrock = 9.82 • LP Bedrock = 90.18	1839.1	0.61
Cree at Newton Stewart (81002)	Scotland W	1757	• Min = 5.2 • Max = 843	• Woodland = 49.09 • Arable = 0.33 • Grassland = 39.73 • Mountain/Heath/Bog = 9.05 • Urban = 0.76	• HP Bedrock = 0 • MP Bedrock = 0 • LP Bedrock = 100	368	0.28
Ugie at Inverugie (10002)	Scotland E	812	• Min = 9.5 • Max = 233.7	• Woodland = 11.35 • Arable = 43.89 • Grassland = 34.59 • Mountain/Heath/Bog = 8.49 • Urban = 1.56	• HP Bedrock = 0 • MP Bedrock = 2.44 • LP Bedrock = 97.56	325	0.64
Exe at Thorverton (45001)	England SW and Wales S	1,249	• Min = 27.6 • Max = 516.8	• Woodland = 14.97 • Arable = 12.85 • Grassland = 66.71 • Mountain/Heath/Bog = 2.76 • Urban = 2.37	• HP Bedrock = 0 • MP Bedrock = 15.65 • LP Bedrock = 84.35	600.9	0.5
Dee at Manley Hall (67015)	England NW and Wales N	1,367	• Min = 28.10 • Max = 878.2	• Woodland = 17.51 • Arable = 1.23 • Grassland = 62.96 • Mountain/Heath/Bog = 14.87 • Urban = 1.00	• HP Bedrock = 0 • MP Bedrock = 4.48 • LP Bedrock = 89.30	1,013.2	0.54
Little Ouse at Abbey Heath (33034)	East Anglia	607	• Min = 8.10 • Max = 94.60	• Woodland = 15.33 • Arable = 63.25 • Grassland = 16.33 • Mountain/Heath/Bog = 0 • Urban = 5.03	• HP Bedrock = 99.73 • MP Bedrock = 0.27 • LP Bedrock = 0	688.5	0.8
Don at Hadfields Weir (27006)	Midlands	1,014	• Min = 32.3 • Max = 543.4	• Woodland = 15.66 • Arable = 6.17 • Grassland = 35.64 • Mountain/Heath/Bog = 18.83 • Urban = 20.23	• HP Bedrock = 0 • MP Bedrock = 43.38 • LP Bedrock = 0	373	0.49
Lambourn at Shaw (39019)	England SE and Central S	736	• Min = 72.4 • Max = 260.3	• Woodland = 10.26 • Arable = 53.72 • Grassland = 30.27 • Mountain/Heath/Bog = 0.10 • Urban = 2.40	• HP Bedrock = 97.33 • MP Bedrock = 0 • LP Bedrock = 0	243.1	0.97
Derwent at Buttercrambe (27041)	England E and NE	765	• Min = 9.50 • Max = 453.2	• Woodland = 15.43 • Arable = 41.46 • Grassland = 26.76 • Mountain/Heath/Bog = 12.11 • Urban = 3.10	• HP Bedrock = 2.68 • MP Bedrock = 51.45 • LP Bedrock = 44.16	1,586	0.7

FIGURE 2 | Monthly correlations between the NAO and SPI-1/SSI-1 for the 291 catchments across Great Britain. Note the difference between the significant positive correlations in the NW during winter (DJF), compared to the more spatially homogenous negative correlations in summer (JJA).

coefficients for SPI-1/SSI-1 quantiles below 0.2 (Amini et al., 2020), which equated to standardised index values <−1 in all cases. This analysis was undertaken for both winter (DJF) and summer months (JJA). This allowed for an assessment of the nature and strength of the winter/summer relationship between the two teleconnections and meteorological (low SPI-1) and hydrological (low SSI-1) drought in the case study catchments.

Drought Severity Frequency Analysis

The second stage of this research moved beyond looking at the individual effect of the NAO and EA and explored their

FIGURE 3 | Monthly correlations between the EA and SPI-1/SSI-1 for the 291 catchments across Great Britain. Note the difference in strength between the positive correlations in the during winter (DJF) compared to the slightly weaker correlations in summer months (JJA).

combined influence. A frequency analysis quantifying the relationship between the phase of the two teleconnections and low SPI-1 and SSI-1 values was undertaken, which compliments the correlation and quantile regression analyses above. For the winter (DJF) and summer months (JJA) we plotted the NAO and EA indices and examined the associated spatio-temporal patterns in low (negative) SPI-1 and SSI-1 values. We also calculated the frequency of mild ($0 > \text{index} < -1$), moderate ($-1 > \text{index} < -1.5$) and severe ($\text{index} < -1.5$) drought (Doesken and Kleist, 1993) under different combinations of NAO and EA phases.

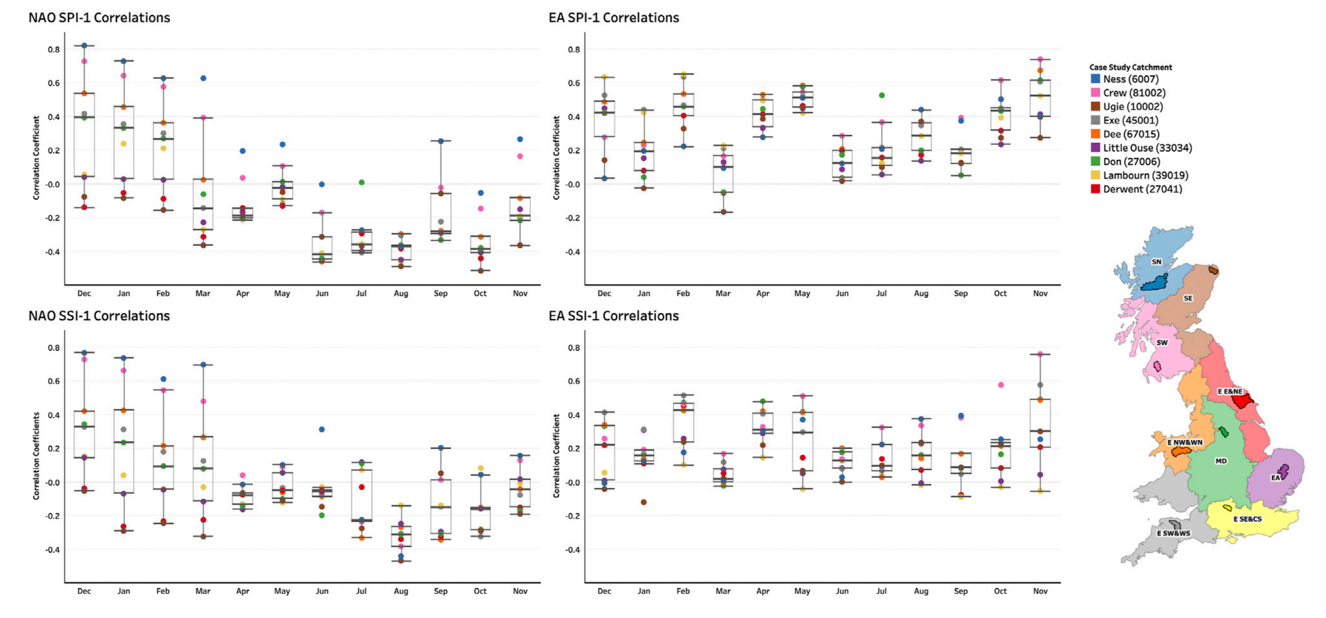

FIGURE 4 | Monthly correlation analyses between the NAO/EA and catchment SPI-1 and SSI-1 values for the nine case study catchments.

As in previous research (e.g., Comas-Bru and McDermott; Berton et al., 2017; West et al., 2021a), the monthly teleconnection index values were classified. Months with teleconnection index values > 0.25 were classified as positive phases, whilst months with index values <−0.25 were classified as negative phases. Months with index values falling between these two thresholds were classified as neutral phases. This classification produces nine possible combinations of NAO and EA phases. Phase frequency analysis allowed us to then assess the influence of the combined teleconnections on drought conditions for each of the nine case study catchments, and to identify any associated seasonal and spatial trends.

RESULTS

Monthly Correlation Time Series

The first stage of the research explored the individual effect of the NAO and EA on rainfall and flows using correlation and regression analyses. **Figure 2** presents the analysis of monthly correlation between the NAO and SPI-1 and SSI-1 values for 291 catchments across Great Britain. The NAO has strong positive correlations between both the SPI-1 and SSI-1 in catchments in the north-western region during the winter months (DJF). In the southern and eastern catchments weaker correlations are found, although these catchments do show stronger negative NAO SPI-1/SS-1 correlations in the spring (MAM). During the summer months (JJA) more spatially consistent negative correlations are found, however differences in the SPI-1 and SSI-1 correlation time series are more pronounced. In the southern and eastern areas, catchments show stronger negative correlations between the NAO and SPI-1 than SSI-1. Autumn months (SON) are also marked by negative correlations and a transitioning back to the winter north-west/south-east pattern described above. The spatio-temporal correlation patterns indicate that in the winter months NAO− phases have an influence on meteorological drought conditions in the north-western catchments, which propagates through to hydrological drought in streamflow. In the summer months the effect of the phase of the NAO is reversed, with negative correlations indicating that NAO+ phases have a stronger meteorological drought control. However, the propagation of these negative NAO SPI-1 correlations to SSI-1 correlations varies spatially (West et al., 2022), indicating that the propagation of monthly NAO− driven meteorological drought to hydrological drought is more limited.

Figure 3 shows the comparable correlation monthly time series between the EA and catchment SPI-1 and SSI-1 values. Notable spatio-temporal differences between the monthly NAO time series (**Figure 2**) and the EA SPI-1/SSI-1 correlations were found. In the winter months (DJF) positive EA correlations are present across most of Great Britain, although coefficients generally strengthen from north to south. These positive correlations persist into the spring (MAM). The summer months (JJA) are also marked by mostly positive correlations, although of a weaker strength than in the winter months. The positive relationship of the EA index with catchment SPI-1 and SSI-1 values indicates that EA- phases are likely to be associated with meteorological drought conditions, which as with the NAO correlations, variably propagate to hydrological drought conditions.

Figure 4 presents the monthly correlation analyses in **Figures 2**, **3** for the nine case study catchments. The spatio-temporal patterns across the correlations in the case study catchments align with the above discussion. For example, in the winter months the Ness and Crew in the north-west show strong positive correlations between the NAO and SPI-1, whilst the Exe in

FIGURE 5 | Similarity analysis results based on the NAO/EA SPI-1 correlation time series mapped in **Figures 2**, **3**. The case study catchment is highlighted in yellow. Catchments with lower values indicate those which have greater similarity in their NAO/EA monthly correlations to those of the case study catchment. Catchments with higher values indicate those which have NAO/EA correlations which are less similar.

the south has stronger winter correlations between the EA and SPI-1. As outlined above the NAO correlations are reversed in the summer months, with the majority of case study catchments showing negative correlations. Meanwhile the EA generally remains positively correlated with both SPI-1 and SSI-1 throughout the year. The moderation of rainfall-streamflow propagation is also exemplified in **Figure 4** by the Lambourn catchment as it shows a stronger correlation between the EA and SPI-1 than the EA and SSI-1.

Similarity Analysis

Figures 5, **6** present the results of the similarity analysis between the various correlation time series for the case study catchments. In both figures the catchment is highlighted in yellow, with the remaining 290 catchments ranked from most similar to least similar. Catchments with lower values indicate those which have a greater similarity in their individual NAO and EA monthly correlation time series (mapped in full in **Figures 2**, **3**) to those of the case study catchment. Catchments with higher values indicate those which have monthly correlation time series which are less similar to the case study catchment.

Figures 5, **6** show that each case study catchment is generally well representative of its respective Climate District (**Figure 1**) in terms of the correlation between the two teleconnections and SPI-1 and SSI-1 values. For example, **Figure 5** shows that the Ness and Crew catchments in Scotland North and Scotland West are generally representative of correlations between the two teleconnections and SPI-1 for catchments in the north-western area, and the Exe and Lambourn represent catchments in the south-west and central southern areas of Britain well.

Table 2 presents the results of the Global Morans I statistic for each of the similarity rank datasets mapped in **Figures 5**, **6**; where the z-score is positive and *p*-value significant, the similarity rank values are more clustered than would be expected if the underlying spatial processes were random (Esri 2021b). Our results show that this is the case for all 18 (two per case study catchment) similarity rank value datasets. The Morans I Index provides an indication as to the strength of the spatial autocorrection, with higher values indicating greater clustering of similarity rank values.

Across all nine case study catchments, the Morans I Index (**Table 2**) was found to be greater for the SPI-1 correlation similarity rank values than for the SSI-1 similarity rank values, although it should be noted that the SSI-1 values were still spatially autocorrelated, albeit with a weaker strength. For example, in **Figure 5**, for the Exe catchment we can see higher SPI-1 similarity rank values across the south-west and southern central areas, indicating more similar teleconnection SPI-1 correlations. Whilst in **Figure 6** the similarity rank values for the SSI-1 correlations for the same area are more spatially

FIGURE 6 | As per **Figure 5**, but showing the results of the similarity analysis based on the NAO/EA SSI-1 correlation time series.

TABLE 2 | Results of the Global Morans I statistical analysis for the similarity rank values mapped in **Figures 5**, **6**. Where the z-score is positive and *p*-value significant then the similarity rank values are more clustered than would be expected if the underlying spatial processes were random. The Morans I Index indicates the strength of the similarity rank value clustering.

Catchment	Correlation similarity rank values	Morans I index	z-score	*p*-value
Ness at Ness-side (6007)	SPI-1	0.735	26.34	0.005
	SSI-1	0.623	22.31	0.005
Cree at Newton Stewart (81002)	SPI-1	0.782	27.98	0.005
	SSI-1	0.763	27.32	0.005
Ugie at Inverugie (10002)	SPI-1	0.847	29.03	0.005
	SSI-1	0.753	25.81	0.005
Exe at Thorverton (45001)	SPI-1	0.874	31.25	0.005
	SSI-1	0.629	22.56	0.005
Dee at Manley Hall (67015)	SPI-1	0.776	27.79	0.005
	SSI-1	0.673	24.13	0.005
Little Ouse at Abbey Heath (33034)	SPI-1	0.845	30.29	0.005
	SSI-1	0.794	28.48	0.005
Don at Hadfields Weir (27006)	SPI-1	0.785	28.05	0.005
	SSI-1	0.588	21.05	0.005
Lambourn at Shaw (39019)	SPI-1	0.868	31.07	0.005
	SSI-1	0.719	25.75	0.005
Derwent at Buttercrambe (27041)	SPI-1	0.827	29.61	0.005
	SSI-1	0.791	28.28	0.005

variable. This is likely a result of the characteristics of catchments which may moderate rainfall-flow propagation, such as geology, terrain and landcover (Chiverton et al., 2015; Barker et al., 2016; West et al., 2022).

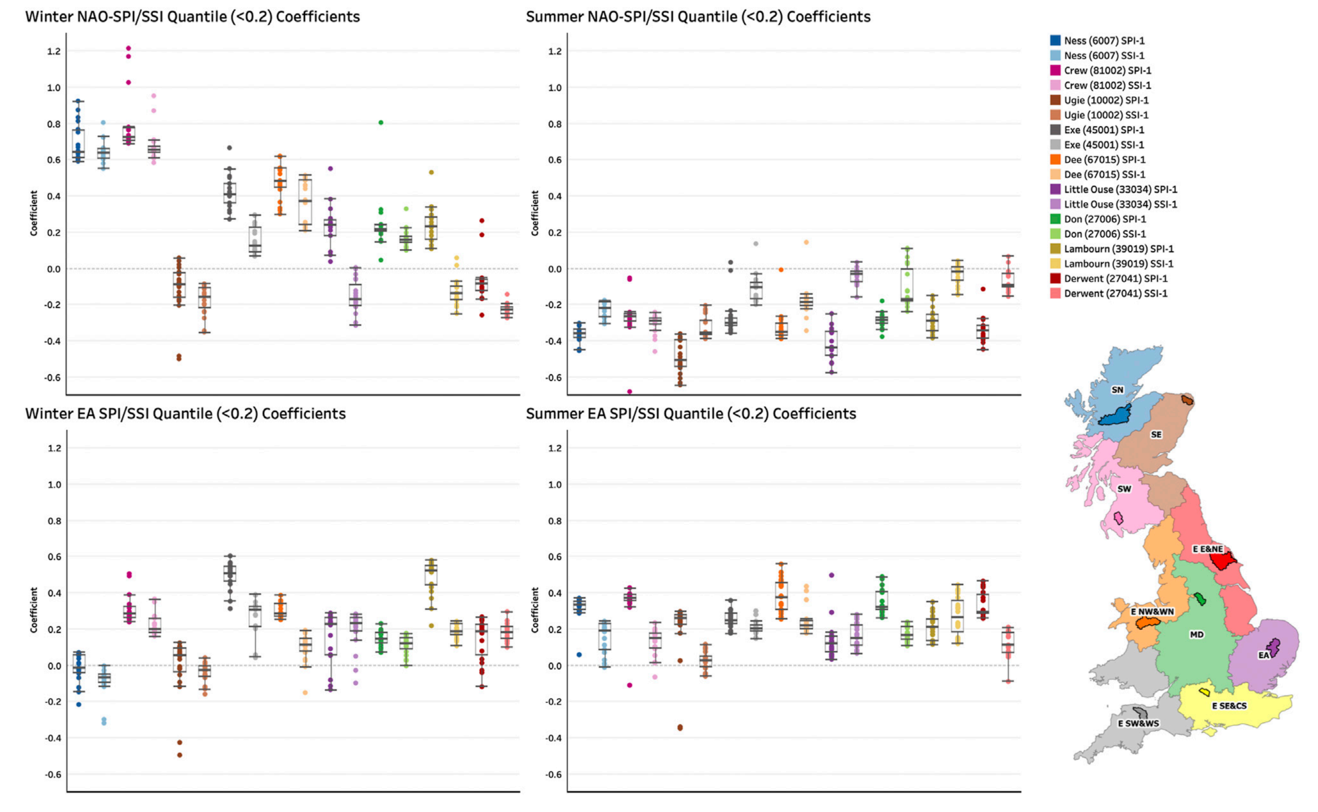

FIGURE 7 | Extracted quantile coefficients between the NAO/EA indices and SPI-1/SSI-1 values. Coefficients were extracted for quantiles <0.2, the range of these quantile coefficients is represented in this figure as box plots.

Quantile Regression Analysis

Figure 7 presents the results of the quantile regression analysis between the teleconnection indices and the SPI-1 and SSI-1 values for the nine case study catchments. **Figure 7** shows the coefficients for quantiles <0.2. These results give an indication of the direction (sign) and strength of the statistical relationship between the NAO and EA indices and meteorological and hydrological drought conditions (i.e., low SPI-1 and SSI-1 values) in the case study catchments.

As with the monthly correlation analyses (**Figures 2**, **3**) the quantile regression coefficients for low SPI-1/SSI-1 values demonstrate the relative influences of the NAO and EA on drought conditions, which varies in space (across the country) and time (across the seasons). Catchments in the north-west (the Ness and Crew) have a very strong positive relationship between the NAO and low SPI-1 values, indicating that NAO− conditions result in meteorological droughts in these catchments. Similar relationships are observed in these catchments between the NAO and SSI-1 values. This highlights the responsive nature of catchments in this region; meteorological droughts propagate through the catchments resulting in hydrological drought. Case study catchments in the southern and central regions of Great Britain show weaker positive relationships between the NAO and drought conditions, however the EA has an equal, and in some cases such as the Exe stronger, positive EA-drought relationship.

As discussed in relation to the correlations in **Figure 4**, the quantile regression analysis evidences the moderating effect of catchment characteristics in limiting the propagation of meteorological to hydrological drought. For example, the Lambourn in the winter EA plot in **Figure 7**—where a moderately strong positive relationship between the EA and meteorological drought is not replicated with the comparable SSI-1 coefficients.

The extracted summer quantile coefficients further corroborate the monthly correlation analyses in **Figure 4**. The NAO has a weaker negative summer relationship with low SPI-1 values which is generally consistent across the case study catchments; suggesting that NAO+ phases, to an extent, influence summer meteorological drought. The EA retains its positive relationship, suggesting EA- phases may produce meteorological drought conditions in summer. For both teleconnections the propagation of summer meteorological to hydrological drought varies in space and time which we suggest is related to the characteristics of the catchment and the extent to which these moderate rainfall-flow propagation.

Drought Severity Frequency Analysis

In this stage of the research, we moved beyond quantifying the individual effect of the two teleconnections to examine the combined influence of NAO and EA phases. **Figure 8** shows

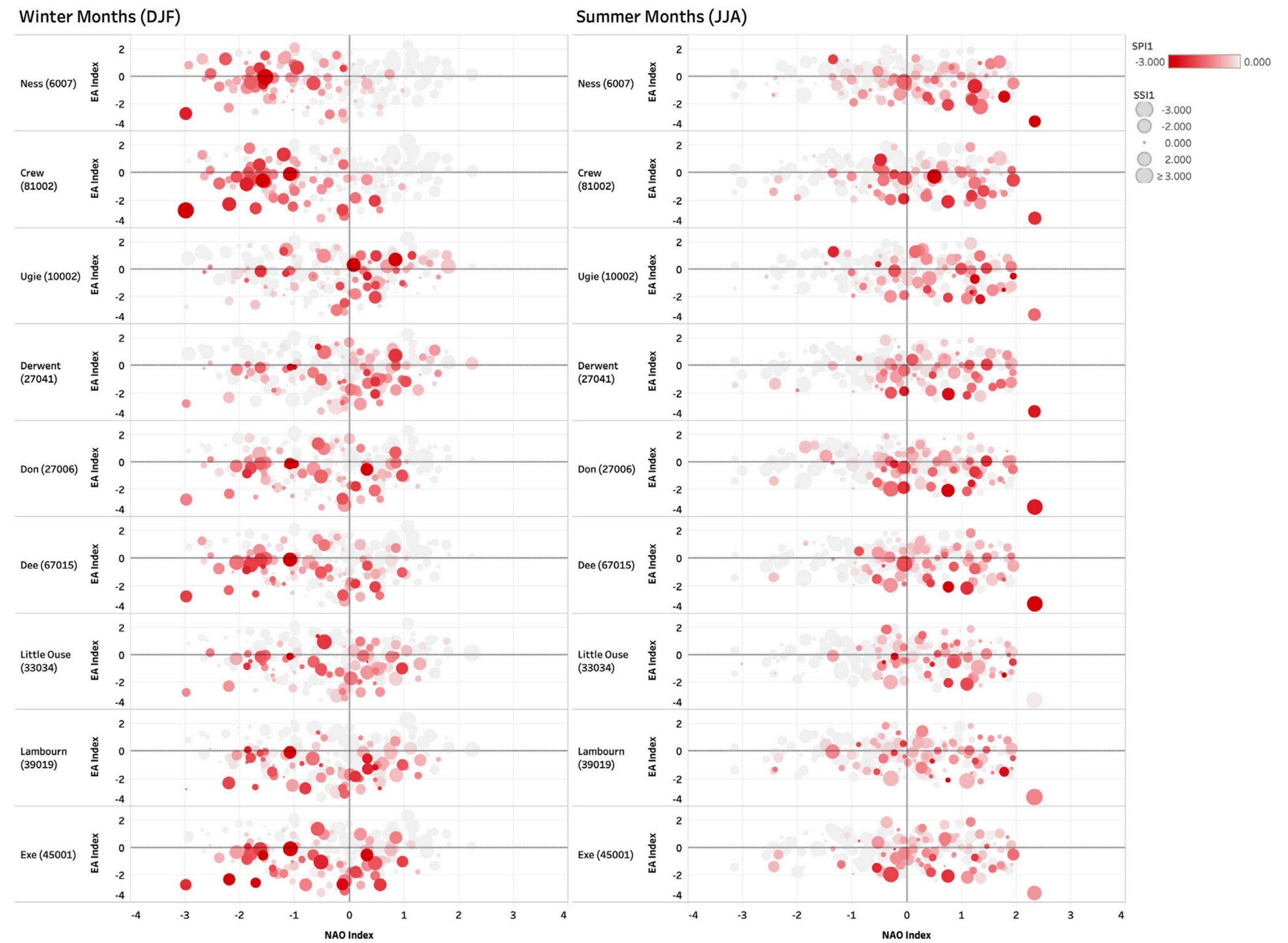

FIGURE 8 | Seasonal teleconnection index plots for winter (DJF) and summer (JJA). The points are coloured by the catchment SPI-1 value, whilst the size represents the SSI-1 value. Large red points indicate both meteorological and hydrological drought, whilst a small red point suggests meteorological, but not hydrological, drought.

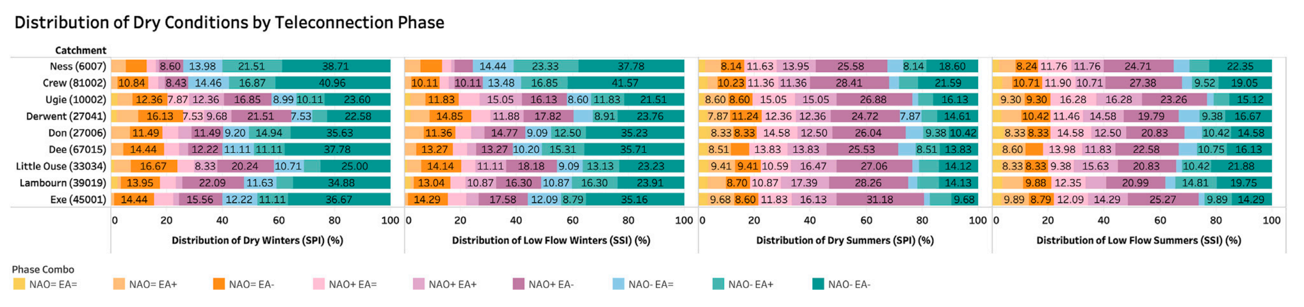

FIGURE 9 | Distribution of dry events (negative SPI-1 and SSI-1 values) under different phase combinations of the NAO and EA for the winter and summer months. Values represent the percentage of time dry events occur under the different phase combinations.

seasonal plots for winter (DJF) and summer (JJA) of the NAO and EA indices for each case study catchment. Each point represents 1 month and is coloured based and the catchment SPI-1 value, and sized per the SSI-1 value. A large red point therefore indicates both meteorological (low SPI-1) and hydrological drought (low SSI-1) conditions, whilst a small red point suggests meteorological drought conditions, but less severe or no hydrological drought.

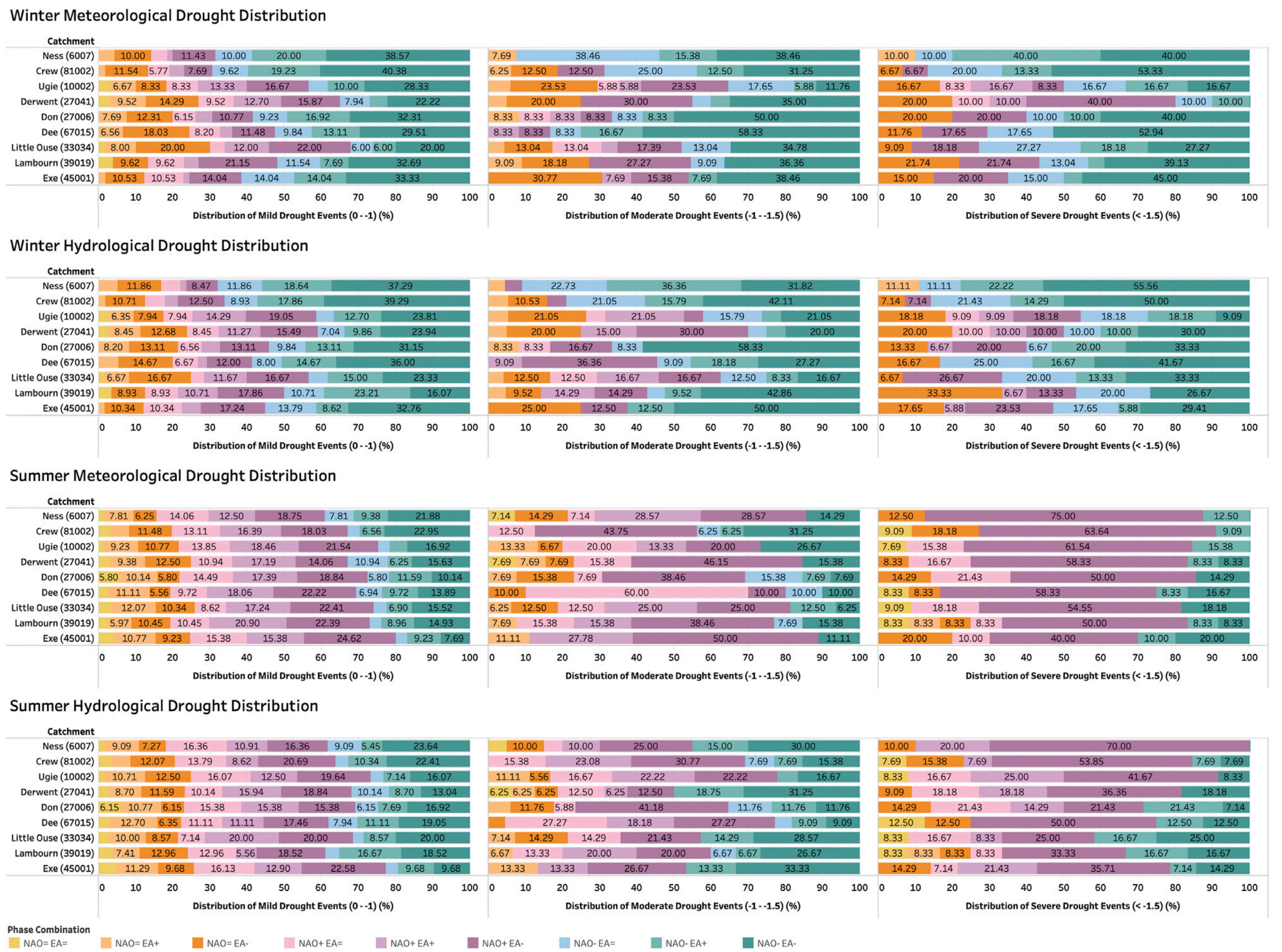

FIGURE 10 | Distribution of mild (0 > index < −1), moderate (−1 > index < −1.5) and severe (index < −1.5) droughts under phases combinations of NAO and EA. Values represent the percentage of time drought events of different severities occur under the different phase combinations.

Figure 9 shows the percentage occurrence of dry/low flow conditions (negative SPI-1 and SSI-1 values) under each of the NAO/EA phase combinations for the winter and summer months. **Figure 10** shows the distribution of these occurrences across mild, moderate and severe drought classes.

Analysis of the teleconnection indices (**Figure 8**) and drought severity frequency analysis (**Figures 9**, **10**) support the correlation and regression analyses (**Figures 4**, **7**), revealing distinctive spatio-temporal patterns in the relative influence of the NAO and EA on drought conditions in the case study catchments. Notably the occurrence of dry events when both the NAO and EA are in a weak neutral state is very low (**Figure 9**), highlighting the importance of the phases of the NAO and EA on the occurrence of drought in the case study catchments.

The climate districts of Scotland North and Scotland West are represented in this analysis by the Ness and Crew catchments. **Figures 8–10** highlight the clear influence the NAO has on meteorological and hydrological drought conditions in these two catchments as explained by the quantile regression analysis, with NAO− phases being clearly associated with drought conditions. The effect of the EA during winter in these catchments, and north-western Scotland generally, appears to be limited. For example, in the Ness catchment during winter 68.57% of mild and 90% of severe meteorological droughts occur when the NAO is in a negative phase, independent of the phase of the EA (**Figure 10**). The occurrence of drought events in these catchments when the NAO is in a positive phase is minimal, with no severe meteorological droughts in the Ness associated with NAO+ phases. The occurrence of hydrological droughts in these two catchments also show a strong relationship with NAO− phases (**Figures 9**, **10**).

In the summer months the direction of the relationship between the NAO and drought is reversed, with low rainfall/flow conditions being associated with NAO+ phases (**Figure 9**). Differences in the occurrences of the mild and severe drought severity classes under different phase combinations of the NAO and EA are more notable in the summer months (**Figure 10**). These differences are associated with the phase of the EA, suggesting that the teleconnection has a moderately stronger influence in the summer, relative to the winter months. Mild drought conditions can be associated with a larger range of NAO and EA phase combinations (**Figure 10**), possibly because of higher temperatures and other hydrometeorological factors/ variables (Van Loon, 2015) not considered in this study. However severe meteorological drought conditions in the Ness catchment only occur when the EA is also in a negative phase, and 91% of severe droughts in the Crew are associated with EA- conditions (**Figure 10**). Similar relationships between the phase of the NAO and EA and hydrological drought occurrence are also observed in the Ness and Crew.

Less clear teleconnection-drought patterns are found in the Ugie catchment in Scotland East, however **Figure 8** does suggest a weak relationship between drought conditions and NAO+ phases, but with greater variability than the influence of the NAO in Scotland North and Scotland West during winter as described above. Drought conditions have a similar frequency of occurrence under different NAO/EA phase combinations (**Figures 9**, **10**). However as in the Ness and Crew catchments, in the summer months meteorological droughts have a higher frequency of occurrence when the NAO is in a positive phase, with severe meteorological droughts associated with a combination of NAO+ and EA- conditions.

The southern and central areas of Great Britain show notably different teleconnection-drought patterns to the northern/north-western catchments. The Exe catchment, representing the England South-West and Wales South Climate District, shows a stronger relationship between the EA and winter drought conditions than it does for the NAO. For example, 80% of severe meteorological droughts during winter in the Exe are associated with EA- phases (**Figure 10**). A very small proportion of severe meteorological droughts in the Exe are associated with a positive phase of the EA. In contrast, summer meteorological droughts have a higher rate of occurrence under NAO+ conditions. 70% of severe meteorological drought events in the Exe occur under NAO+ conditions, the majority of which are also associated with EA- phases (**Figure 10**).

Whilst in the Exe catchment the influence of the teleconnections on both meteorological and hydrological drought is relatively similar (**Figure 9**), the Lambourn catchment, representing the England South East and Central South Climate District, illustrates the role of catchment characteristics in moderating drought propagation. In terms of meteorological drought, the Lambourn has similar EA drought relationships to the Exe (demonstrated by the similarity analysis in **Figure 5**). However, there is a weaker teleconnection-drought relationship with flows (SSI-1). The occurrence of hydrological drought is more evenly distributed across the different phase combinations of the NAO and EA (**Figures 9**, **10**), indicating that catchment characteristics, in the case of the Lambourn highly permeable bedrock (**Table 1**), limits the propagation of meteorological to hydrological drought.

Catchments in the eastern districts, the Little Ouse and Derwent, show teleconnection-drought relationships similar to the Exe and Lambourn. In the Little Ouse catchment, for example, meteorological droughts have a higher rate of occurrence under EA- conditions during winter, with 62% of dry events being associated with EA- phases (**Figure 9**). Summer drought relationships are also similar, for example 58.3% of severe summer meteorological droughts are associated with a combination of EA- and NAO+ phases in the Derwent (**Figure 10**).

Winter meteorological droughts in the Midlands and England North West and Wales North Climate Districts, represented by the Don and Dee catchments, are influenced more clearly through a combination of the NAO (which generally has a greater influence in the north-western areas) and the EA (which generally has a stronger southern influence). Winter meteorological droughts in these case study catchments are associated with both NAO− and EA- phases (**Figures 8**, **9**). In the Dee for example, 83.34% of severe meteorological droughts in winter are associated with NAO− phases, however half of these are also associated with EA- conditions (**Figure 10**). Propagation to hydrological drought in the Dee is relatively clear, possibly due to low permeability bedrock and steep topography (**Table 1**). EA- phases have an association with droughts in these catchments during the summer months, in combination with NAO+ phases for the more severe drought classes (**Figure 10**).

DISCUSSION

This study aimed to explore the relative influence of the NAO and EA on meteorological drought in British catchments, and whether these rainfall deficits propagate to hydrological drought. We examine both the individual effect of the NAO and EA through correlation and regression analyses, and the frequency of drought events of varying severities under different NAO and EA phase combinations. Based on the convergence of evidence across the results of this study we make three main observations which will be discussed in turn.

The first observation relates to the variable influence of both the NAO and EA during the winter (DJF) months. Our analyses highlight that the NAO has a strong influence on meteorological drought conditions in the north-western catchments during winter, as found in previous correlation-based studies (Wilby et al., 1997; Rust et al., 2018; West et al., 2019). In these catchments NAO− phases are generally associated with meteorological droughts, shown by the Crew and Ness (**Figures 8**, **9**). When the NAO is in a negative phase the SLP difference between the Icelandic Low and Azores High is weaker than normal resulting in a more northerly jet stream, which in turn limits the movement of low pressure systems north-westerly across the Atlantic region (Hurrell et al., 2003). This results in low rainfall over the north-western regions of Britain (West et al., 2019). In the southern, eastern and central areas the NAO has a less consistent influence on rainfall (West et al., 2021a), however strong positive correlations with the EA were found in these areas (**Figures 3**, **4**). In the southern catchments, the Exe, Lambourn and Little Ouse, meteorological droughts are generally more associated with EA- conditions (**Figures 8**, **9**). These findings suggest that NAO− and EA- conditions result in the driest winter conditions nationally with the NAO has a stronger meteorological drought influence in the north-western areas, whereas the EA has more influence in the southern and central areas. Moore et al. (2013) analysed the effect of the phase of the EA on the strength and location of the NAO dipoles, finding that NAO−/EA- phase combinations results in higher than average SLP at the Icelandic Low action point, and an extended area of high pressure in the region producing drier conditions.

Our second observation relates to the differences in the summer months (JJA) compared to the spatial variability described above for winter. In the summer, the NAO has a more spatially homogenous influence on rainfall in Great Britain and correlations are of the opposite sign to those in the north-west during winter (Hall and Hanna, 2018; West et al., 2019). NAO+ phases have been associated with drier summer conditions, as the North Atlantic storm track is shifted northerly, and easterly winds bring warm continental air from Europe (Folland et al., 2009). The correlation coefficients mapped in **Figure 3** and quantile regression results in **Figure 7** show that the effect of the EA during summer is weaker than during winter, however a positive relationship is still present for most of the 291 catchments. During the summer months there is a higher frequency of drought occurrence under NAO+ conditions across all nine case study catchments (**Figure 9**). However, differences in drought severity are associated with the phase of the EA, with severe meteorological droughts having a higher frequency of occurrence under a combination of NAO+ and EA- phases (**Figure 10**). This suggests that the phase of the EA can enhance (notably EA- conditions) or moderate drought conditions associated with summer NAO+ phases. As far as we are aware no study has yet mapped the influence of EA phases on the NAO dipoles and North Atlantic storm track during the summer months. However, if the NAO+/EA- phase combination during summer results in a similar strengthening of the Azores High as is the case in winter (Moore et al., 2013), then this may potentially explain the more extreme dry conditions found under this phase combination in this study.

Our final observation relates to the propagation of meteorological to hydrological drought, a process influenced by both climate and catchment characteristics (Van Loon and Laaha, 2015; Barker et al., 2016). Our analyses show spatio-temporal differences between the two teleconnections influence on meteorological and hydrological drought; we interpret these differences as being a function of the geography and characteristics of catchments, such as terrain, geology and landcover. In the winter in the north-west the rainfall deficits as a result of NAO− phases propagate to streamflow resulting in hydrological drought. Catchments in the north-west are responsive to rainfall due to topographic and geological characteristics (Chiverton et al., 2015) and so short meteorological droughts in this area (as identified by Tanguy et al., 2021) quickly propagate to low flows. Our analyses also identify cases where there is limited meteorological to hydrological drought propagation, particularly in catchments in the southern and central regions. For example, in the Lambourn catchment which is underlain with highly permeable bedrock (**Table 1**), a notably stronger EA-drought relationship was identified with rainfall than with flows (**Figures 7**, **9**). We suggest that some catchments, depending on their geography and characteristics, are potentially more resilient to drought propagation, with the influence of the NAO and EA on both rainfall and streamflow varying in space and time due to catchment characteristics (West et al., 2022). However, we acknowledge that this observation is based on our interpretation of the difference in meteorological and hydrological drought occurrence in our analyses, and we have not undertaken an analysis explicitly quantifying the effect of catchment characteristics.

In recent years our ability to predict the NAO several months in advance has improved, especially during the winter months (Baker et al., 2018; Athanasiadis et al., 2020; Smith et al., 2020). This study demonstrates that this improved predictive ability might be useful in water resource management planning. For example, if several months in advance of winter the NAO was forecast to be in a strong negative phase, water authorities could prepare for a higher probability of meteorological and hydrological drought onset in the highly responsive catchments in the north-west.

However, NAO predictive skill has largely only improved during its stronger winter phases, and as far as we are aware, no improvements have been made in EA prediction. This has implications for regional forecasting and the inclusion of teleconnection indices in water management decision making. This is especially true in the southern, central and eastern regions where our analysis demonstrates the clear influence of the EA on meteorological and, more variably, hydrological drought conditions, particularly in the summer months where the phase of the EA can enhance or lessen drought severity associated with NAO+ phases. Our analysis therefore supports the findings of Hall and Hanna (2018), who suggest that even highly accurate NAO forecasts might have a limited role in water management decision making especially in the southern, central and eastern areas of Great Britain, and Comas-Bru and McDermott (2014), who suggest that a combination of both the NAO and EA may be able to explain (hydro)climatic variability more accurately.

In this study we have used relatively new long-term historic datasets for rainfall and flows (Tanguy et al., 2017; Barker et al., 2018) to explore associations between the NAO and EA on monthly drought conditions in British catchments. There is scope to utilise these datasets and the analytical approaches used in this study to explore how the NAO/EA-drought relationship has changed over time and might change in the future with climate change, especially given the positive EA index trend identified in studies (Mikhailova and Yurovsky, 2016). Further in this study we have explored a specific monthly drought scenario relating to the monthly teleconnection indices (NOAA, 2021). As the SPI/SSI datasets used in this study have indices published over longer accumulation periods (representing different drought duration/severity) there is potential to explore the association between teleconnections and rainfall/flows over different periods of time. Future research might also explore the association of drought conditions in catchments with other atmospheric-oceanic circulations such as the Scandinavian Pattern and East Atlantic/West Russia Pattern for which monthly indices are modelled by NOAA (NOAA, 2021) and rainfall correlations have been found across the North Atlantic and European region (Krichak and Alpert, 2005; Comas-Bru and McDermott, 2014).

CONCLUSION

This study aimed to explore the influence of the NAO and EA North Atlantic teleconnections on meteorological drought in British catchments, and the extent to which these rainfall deficits propagate through catchments resulting in hydrological drought. Based on evidence from our analyses we highlight three main observations from this study:

1) During the winter months there is spatial variability in the relative influence of the NAO and EA on drought conditions, with NAO− phases resulting in higher drought probability in the north-western areas (regardless of EA phase), and EA- phases being associated with higher drought probability in the southern and central areas.
2) There is less spatial variation in the relative influence of the NAO and EA during the summer months, with drought conditions associated with NAO+ phases across most catchments. Although we find that the phase of the EA can moderate or enhance this, with severe meteorological droughts being associated with a combination of NAO+ and EA- phases.
3) There is spatio-temporal variability in the propagation of meteorological to hydrological drought, with streamflow in catchments in the north-west typically being more responsive to rainfall deficits, whilst catchments in the southern and central regions have higher hydrological drought resilience.

Our study has implications relating to the role of monthly teleconnection forecasts in water management decision making in Great Britain, however, we acknowledge the current limitations associated with incorporating such understanding.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: SPI Data: https://catalogue.ceh.ac.uk/documents/233090b2-1d14-4eb9-9f9c-3923ea2350ff. SSI Data: https://catalogue.ceh.ac.uk/documents/58ef13a9-539f-46e5-88ad-c89274191ff9. NAO/EA Data: https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml.

AUTHOR CONTRIBUTIONS

HW, NQ, and MH contributed to the conception and design of this research. HW completed the data generation, analysis, and presentation of the results. Initial findings were shared by HW and refined amongst all authors. HW led on the writing of the manuscript, with commentary and feedback from all authors throughout the writing process. All authors agreed the submitted version of the manuscript.

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Representation of Drought Events in the United Kingdom: Contrasting 200 years of News Texts and Rainfall Records

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This paper combines evidence from the analyses of large sets of newspaper material and long-term rainfall records to gain insights into representations of drought events in the United Kingdom, between 1800 and 2014. More specifically, we bring together two different, though complementary, approaches to trace longitudinal patterns in the ways drought events have been measured and perceived, focusing specifically on the duration, spatial extent, and intensity of each event. The power of the combined approach is demonstrated through three case studies (1911–1913, 1940–1945, and 1947–1949), in which we explore the available evidence in more detail and explore the impacts of the droughts upon the British population. Using corpus linguistics methods, we examined four sets of newspaper material: 1) the British Library 19th century newspaper corpus, 2) *The Times* 20th century corpus (both i and ii with over five billion words), 3) 4,986 texts from British broadsheet papers (3.8 million words) and 4) 2,384 texts from tabloids (1.1 million words). An independent analysis of meteorological drought was undertaken using three sources: 1) the England and Wales Precipitation (EWP) series (back to 1800), 2) a statistically reconstructed version of the EWP which is more reliable in the early record (pre-1870), and 3) a high resolution gridded dataset (back to 1862) which is aggregated to NUTS1 regional scales. Meteorological droughts were assessed using the Standardised Precipitation Index, which allowed us to appraise drought intensity, severity and duration. We found an overwhelming agreement between the corpus data and meteorological records. For the very few cases of disparity between the corpus and rainfall data, there were in most cases plausible explanations. All in all, the present study demonstrates the power of the combined approach, presenting evidence on a scale that would not otherwise be possible, thus contributing to a better understanding of how drought is perceived, in addition to how it is traditionally "measured".

Keywords: drought, water scarcity, historic droughts, corpus linguistics, discourse analysis, precipitation, standardised precipitation index (SPI), long-term meteorological records

1 INTRODUCTION

Historical meteorological and hydrological records are the foundation of drought and water resources management. In the United Kingdom (UK), as elsewhere, water utilities and regulators have for a long time used the worst observed 'drought of record' to stress test drought plans and water supply systems (Environment Agency, 2015). Given concerns over climate change impacts on water availability, the "duty of resilience" (Water Act, 2014) now requires water utilities to test their resilience to events more extreme than those observed in past records (such as 1 in 200 or 1 in 500 years drought; Water Act, 2014). Risk estimation for such rare drought events, outside the envelope of past variability, requires simulation methods (typically stochastic simulations based on Weather Generators, e.g., Serinaldi and Kilsby, 2012)—but ultimately the credibility of these methods rests on a proper understanding of historical drought occurrence. Historical records are also an essential baseline of past hydroclimatic variability, against which changes due to anthropogenic warming can be identified and projected into the future.

The United Kingdom has a relative abundance of long-term meteorological records, and these have been used in drought assessments for many decades, as far back as Wright and Jones (1982). The seminal study of Marsh et al. (2007) identified major droughts in England and Wales back to the late 18th century, using selected rainfall records and other hydrometric datasets. These authors identified many 18th and 19th century droughts that were more severe than recent droughts. Jones and Lister (1998); Jones et al (2006) used long rainfall series to reconstruct streamflows back to the 1850s in 15 catchments in England and Wales and found broadly similar patterns. Barker et al. (2019) identified similar droughts with a comprehensive dataset of over 107 streamflow reconstructions across the United Kingdom. Other authors have adopted a more regional focus, often focusing on individual rain gauges but going back over very long periods. For example: Todd et al. (2013) for southeast England back to 1,697; Spraggs et al. (2015) for East Anglia back to 1798; Lennard et al. (2016) back to the 1880s in the Midlands; Harvey-Fishenden et al. (2019) for Chatsworth in the Peak District back to 1760.

One of the most important long-term rainfall records in the United Kingdom is the England & Wales precipitation (EWP) series (Wigley et al., 1984), which was used by many of the long-term drought assessments listed above. More recently, Murphy et al. (2020a) challenged the earlier parts of these records using an independent reconstructed approach and developed a reconstructed series for England and Wales, Scotland and Ireland, which were also used to identify "forgotten droughts" such as 1765–1768 and 1834–1836 (Murphy et al., 2020b).

While the United Kingdom has a good coverage of long rainfall records compared to many countries, there is still a relative sparsity of gauges in the 19th century and earlier. One of the issues with such long rainfall records is this sparseness coupled with likely biases in the earlier records (as exposed by Murphy et al., 2020a). There is therefore a significant benefit of evaluating drought histories from these records alongside independent sources of evidence.

Prior to the 20th century it is very difficult to corroborate rainfall or other hydroclimatic series as alternative sources become much more uncertain further back in time. Given the lack of readily available datasets, significant research effort is required to generate appropriate primary sources for comparison. Dendrochronology is beginning to provide a credible alternative (e.g., Loader et al., 2020) but has serious limitations (notably it is necessarily only available for the summer half year). For the most part, documentary sources provide one of the best approaches to examine historical droughts and compare them with rainfall datasets. Typically, such approaches have used a selective approach to find appropriate sources from archives, diaries, the news media and so on (e.g., Noone et al., 2017; Harvey-Fishenden et al., 2019; Murphy et al., 2020b).

The present study innovates by bringing together two fundamentally different, but complementary, approaches to trace past occurrences of drought events in the United Kingdom. We combined the analysis of long-term meteorological records with a corpus analysis of newspaper material, spanning from 1800 to 2014.

Past studies have typically identified precipitation droughts and then sought documentary evidence to confirm them. While useful, the approach opens up the possibility of confirmation bias. The corpus approach, in which large volumes of textual data (corpora, sg. corpus) is searched and processed to investigate a research question (McEnery and Hardie, 2012), provides a crucial advantage over previous studies. We analyse all the available data by means of corpus linguistics methods, rather than simply seeking corroboration, or otherwise, for one suspected drought. The method allows for large-scale observation, objectivity, consistency of analysis and the possibility to transform the frequency data gained from the corpus using statistical analyses to provide inference about issues such as representation. Importantly for this paper, the availability of substantial corpora covering long periods of time is greatly increasing, with organizations such as the British Library providing access to machine readable text of newspapers from the past.[1]

The present analysis builds on corpus analyses of the representation of drought in 19th century British newspapers in McEnery et al. (2019, 2021), which contrasted evidence gathered from corpus material against the hydrological evidence provided by Cole and Marsh (2006) and Marsh et al. (2007). McEnery et al. (2019, 2021) demonstrate the effectiveness of the corpus linguistic method to identify drought events in the United Kingdom during the 19th century, when rainfall records were sparse and fragmentary. While allowing us access to crucial information about past droughts, these analyses also identified droughts that had not been captured by hydrological approaches. In the present paper, we also take advantage of improved meteorological datasets and more robust statistical assessments of past drought severity than Cole and Marsh (2006) and Marsh

[1]See https://www.bl.uk/collection-guides/british-newspaper-archive.

et al. (2007). We use the Standardised Precipitation Index applied to annual (SPI-12) and seasonal (SPI-3) time scales, which roughly captures hydrological/groundwater droughts and agricultural droughts, respectively.

This paper innovates by presenting evidence of the representation of drought in UK newspapers with unprecedented scale and depth. By combining the evidence gathered from the newly-available corpus material with robust drought assessment from long-term meteorological records, we add both further insight and, at times, confidence to previous work on past occurrence of droughts in the United Kingdom, thus contributing to a better understanding of how drought is perceived, in addition to how it is traditionally "measured". To demonstrate the power of the combined approach, we selected three points in time as case studies (1911–1913, 1940–1945, 1947–1949) and explored the available evidence in more detail, focusing on the duration, spatial extent, intensity, and impacts of each event (see **Section 7** for details).

This paper is organised as follows. The first two sections detail the data and methods of analysis used for this study. We then provide an overview of results yielded by each approach (**Section 4** and **Section 5**). **Section 6** combines the results and is followed by a discussion of three case studies (**Section 7**). The paper concludes with a discussion on the strengths and contributions of the combined approach.

2 DATA

2.1 Newspapers

We used four independent corpora to examine the discourse around drought in the UK press. In part this is to allow us access to a dataset with both range (covering a variety of newspapers where possible) and scale. However, our data represents a patchwork quilt. We are limited by the range of available data. To use corpus techniques, we need machine readable versions of the newspapers we wish to study. Digital newspapers are a late 20th century phenomenon—analysis of newspapers prior to that depends on the efforts of others who have undertaken digitization of printed materials by running optical character recognition (OCR) software across newspapers. Digitization efforts now mean that we are able to cover, with a varying range, the period from 1800 to the present.

For the 19th century, we used the British Library 19th Century newspaper collection. With over five billion words of data, the 19th Century Corpus contains a range of national and regional newspaper titles published from 1800 to 1899, although with some gaps in the data. These were caused by 1) not all titles being published throughout the century or 2) poor quality ink or paper rendering reasonably reliable OCR impossible. For most of the 20th century the range is narrower, as we have access only to one newspaper—*The Times*. The 20th Century Corpus therefore contains articles published by *The Times* between 1900 and 1999, which total over five billion words in 30,757 texts. From 1990 onwards, digital newspapers are the norm, so we were able to achieve a greater range. We used 4,986 articles (3.8 million words) published by major broadsheet newspapers (The Broadsheet Corpus) and 2,384 articles (1.1 million words) published by contemporary tabloids (The Tabloid Corpus).

Readers interested in a fuller description of the composition of each set and the methods and procedures required in the preparation of the texts should refer to: Baker et al. (2020a) and McEnery et al. (2019, 2021) for the 19th Century Corpus, Baker et al. (2020b) for the 20th Century Corpus, and (Dayrell et al., 2020a, 2020b) for the Broadsheet and Tabloid Corpora. The 19th and the 20th Century Corpora were processed using *CQPweb*, Lancaster University's software platform for large-corpus analysis (Hardie, 2012). For the Broadsheet and Tabloid Corpora, we used the software package *LancsBox* (Brezina et al., 2015).

2.2 Rainfall Records

Several sources of precipitation data were used in this study. To provide a complete long record view of the whole 1800–2014 period, the monthly England & Wales Precipitation series (hereafter: EWP; Wigley et al., 1984)[2] was used. In addition, for 1800–2000 we used a statistically reconstructed version of the EWP developed by (Murphy et al., 2020a; hereafter: M2020-EWP) which has been advanced as an alternative that is more reliable in the early record (pre-1870) due to significant underestimation of the EWP in this period (see Introduction). To provide a more detailed spatial picture, albeit for a shorter period 1862–2014, the gridded Historic Droughts (hereafter: HD) Standardised Precipitation Index dataset was used (Tanguy et al., 2017).

3 METHODS

In this section, we describe the methods used by each approach separately: the corpus linguistic methods used to examine the newspaper material and the rainfall records used to identify meteorological droughts. We then explain the procedures for combining the two approaches.

3.1 Corpus Linguistics Methods

The corpus linguistic analysis started by calculating the relative frequency of the word 'DROUGHT' across each corpus. Small capitals indicate the different forms of the word (*drought*, *droughts*, *droughty* or *drought-**) as well as the archaic form *drouth(s)* which was used between 1800 and 1950 and gradually died out throughout the 20th century.

The relative frequencies were calculated per year in relation to the overall number of words for the specific year, considering the frequency of DROUGHT per one million words for the 19th and 20th century data and per 10,000 words for the Broadsheet and Tabloid Corpora. This means that we have normalised the data to take into account size difference in individual years within each corpus. The different scales were needed because the corpora are of different nature. The 19th and 20th Century Corpora contain all issues published by the selected newspapers in a particular year

[2]https://www.metoffice.gov.uk/hadobs/hadukp/data/download.html.

whereas the Broadsheet and Tabloid Corpora contain only articles that make reference to droughts. As described in **Section 3.3**, we then transformed and combined these time series to obtain a single long time series covering the full study period, 1800–2014.

The frequency distribution of the word over time gives us a rough indication of the amount of attention that droughts have received in the UK press from 1800 to 2014. If we accept that newsworthiness is closely associated with the occurrence of a drought and that while the drought lasts it will remain newsworthy, we can assume that years in which the word DROUGHT was salient are the years when the United Kingdom experienced a drought. While these assumptions have been found to be generally true (McEnery et al., 2019, 2021), the approach may still produce some false positives, meaning that qualitative analysis is still necessary to confirm or refute the trends indicated by the initial figures. Close reading of the data is therefore needed to confirm whether the reporting was, in fact, about the existence of a drought in the United Kingdom in that specific point in time. We then examined the articles which were highlighted as being concerned with a drought in the United Kingdom to construct the newspaper narrative of a year of drought in terms of its duration, spatial extent, intensity and impacts. These procedures are illustrated more explicitly in the case studies (**Section 7**).

3.2 Rainfall Records

Here, we use the Standardised Precipitation Index (SPI) (McKee et al., 1993) to identify meteorological droughts. A key advantage of the SPI is that, by virtue of the standardisation process, it enables comparison between locations and between different times of year. The method transforms the original monthly precipitation data so that the SPI is symmetrically distributed around zero (with standard deviation = 1), with a negative SPI denoting drier than normal conditions and a positive SPI wetter than normal conditions. McKee et al. (1993) denotes $0 > SPI > -1.0$ as mild drought, $-1.0 \geq SPI > -1.5$ as moderate drought, $-1.5 \geq SPI > -2.0$ as severe drought and $SPI \leq -2.0$ as extreme drought.

The SPI is flexible in that precipitation can be aggregated across a range of timescales (e.g., 1, 3, 6, 12 months), which are relevant for different types of drought impacts. Typically, droughts can be observed in precipitation deficits before soils (agricultural drought), streamflow (hydrological drought) and groundwater. The approach to computing the SPI is described elsewhere (e.g., Svensson et al., 2017). The SPI is fitted here using the Gamma distribution, using the SCI package in R (Gudmundsson and Stagge, 2016) and using the 1961–2010 period for estimating the standardisation parameters (1961–2000 for the M2020-EWP data). We focus on the SPI-12 and SPI-3 (i.e., 12- and 3-months aggregations), with the former representing an approximately annual, long duration drought timescale, and the latter an approximately seasonal timescale. SPI aggregations are referred to with the final month in the accumulation. For example, the August 1976 SPI-12 refers to the aggregation from September 1975 to August 1976.

First, for the EWP and M2020-EWP data, the SPI was calculated for the entire monthly precipitation series, resulting in monthly SPI time series. For the HD dataset, the SPI were spatially averaged for each of the twelve UK Nomenclature of Territorial Units for Statistics 1 (NUTS1) regions. NUTS regions (at different levels of spatial aggregation such as the relatively large NUTS1 regions) are defined standard geographical regions in the European Union[3].

Drought events were then identified and characterised using criteria set out in Barker et al. (2019), based on event characteristics defined by Noone et al. (2017). Drought events were defined as three or more consecutive months with negative SPI values, with at least 1 month in the suite of negative values falling below a threshold of −1.5 (equating to "severe" drought; Barker et al., 2016). For each extracted event, the following event characteristics were calculated (see **Figure 1**):

- Duration (number of months),
- Accumulated deficit (the absolute value of the sum of SPI values across the event duration),
- Mean deficit (accumulated deficit divided by duration), and
- Maximum intensity (the minimum SPI value during the event).

Due to the seasonal focus of the study, events with a duration of less than 3 months (i.e., one or two months) were removed. As the accumulated deficit and mean deficit were derived from the SPI, they represent relative deficits and not absolute precipitation deficits (for example, as millimetres or a volume). The extracted events were ranked by each event characteristic (i.e., duration, accumulated deficit, mean deficit and maximum intensity), separately. The top 10 events for each characteristic and accumulation period were identified for the HD dataset, whilst for the SPI derived from EWP/M2020-EWP the top 15 events were extracted given the substantially longer series. When ranking by duration, tied events were also sorted by the accumulated deficit, so the longest events with the most severe accumulated deficit ranked highest.

3.3 Combining the Two Approaches

We combined the two approaches by 1) carrying out a correlation analysis, 2) extracting extreme events from both types of data and comparing them in a table, and 3) through case studies.

3.3.1 Correlation Analysis

A simple visual comparison of how the corpus and climate datasets corresponded to each other was made by overlaying the two time series in a single plot. These time series were then used to carry out an objective numerical correlation analysis.

It is important to note that the four different corpora are based on different underlying source data, and their scales (frequencies of occurrence of the word DROUGHT) are different. The four datasets were therefore normalised so that they all

[3]https://data.gov.uk/dataset/4977ad50-f78e-49be-9cf7-fa0adec4b9f8/nuts-level-1-january-2018-full-extent-boundaries-in-the-united-kingdom.

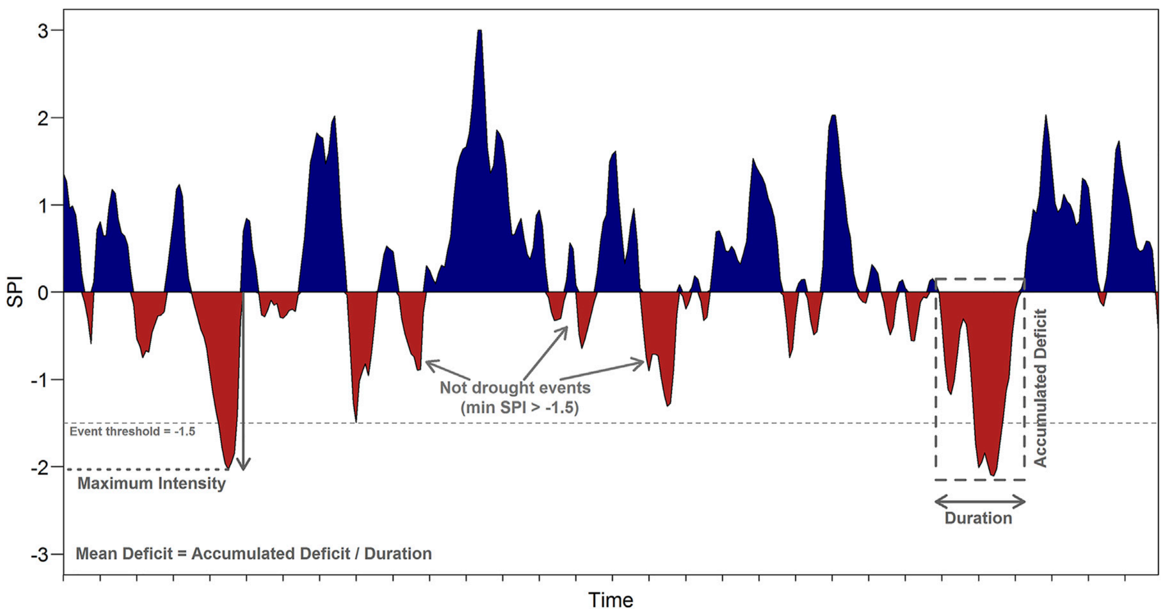

FIGURE 1 | Conceptual diagram illustrating drought event identification and characteristics (NB *x* axis ticks represent years, but SPI data are on a monthly time step).

had a mean of zero and a standard deviation of one before they were concatenated into a single corpus series, as described below. There also seems to be a trend in the frequencies with time for the original corpus data (**Figure 2**)—particularly for the 19th Century Corpus—which may affect both the magnitude of the peaks and the background "noise". The 19th century Corpus data is made up of data from eight different newspaper titles, some of which are regionally focused. This means that coverage of drought may have been driven, or influenced, by the interests of a specific region—for example, an emphasis on the impact of a drought on agricultural yields. What is more, fewer titles were available for the beginning of the century. These inhomogeneities meant that we considered the increasing frequencies to be an artefact of the data, and we de-trended each corpus dataset separately.

Once all the datasets followed the same distribution, they were concatenated into a single series from 1800 to 2014, providing a standardised corpus index series. To achieve this, five steps were carried out:

(1) Log-transform the data to make the distribution symmetrical.
(2) De-trend the data to remove, for example, the upward trend with time during the 19th century (see **Figure 2**).
(3) Standardise the data so that the distribution has a mean = 0 and a standard deviation = 1.
(4) Average the Tabloid and Broadsheet data, which have been transformed according to Steps 1–3. This new averaged time series was then re-standardised according to Step 3, as the averaging would have shrunk the variance to be less than one.
(5) Finally, concatenate the 19th, 20th, and 21st century time series into a single long time series, 1800–2014.

Step 1 was carried out because the original corpus data have a positive skewness. That is, there are several very large values (creating a long upper "tail" to the distribution) but no correspondingly extreme small values, as the frequencies have a lower bound at zero. To remove the skewness and create a more symmetric distribution, the data were log-transformed. Before the log-transform was applied, a small number (1.0) was added to all the values to avoid taking the logarithm of zero (which is mathematically undefined). This did not affect the final results however, as in Step 3 we shift the distribution to have a mean = 0.

In Step 2, we removed any linear trend from the data by carrying out a linear regression and replacing the original data values with the residuals from the linear regression. In Step 3, we standardised the residuals by first subtracting their mean and then dividing by their standard deviation. As a result of these steps, each individual corpus series had a normal distribution with mean = 0 and standard deviation = 1, i.e., a N (0,1) distribution.

The SPI time series are by definition normally distributed, but we de-trended them as described in Step 2 above. Using the SPI time series and the single long corpus time series, we explored how these two datasets relate to each other, both visually (in time series plots) and numerically. For the objective numerical analysis, we used the Pearson correlation coefficient, as the data are normally distributed. There was significant autocorrelation in the corpus data for a lag of 1 year (=0.25 at the 5% level for a two-sided test). As such, we used a block permutation method (e.g., Hesterberg et al., 2005) to estimate significance levels for the cross-correlations between the corpus and SPI data. A two-year block size and 999 resamples were used for a one-sided significance test.

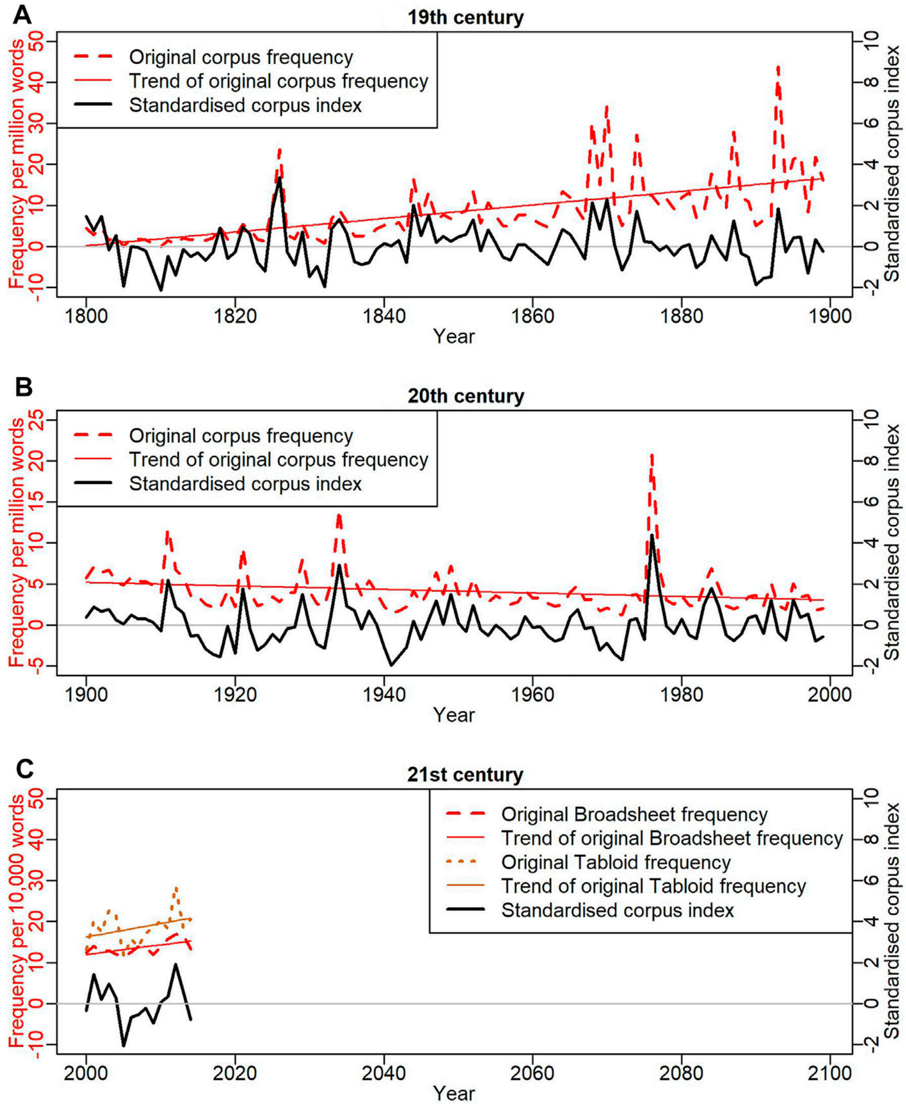

FIGURE 2 | Relative frequencies of the word DROUGHT and the corresponding standardised corpus index for **(A)** The 19th Century Corpus, **(B)** The 20th Century Corpus and **(C)** The 21st Century Corpus (with the Broadsheet and Tabloid corpora combined).

We used different subsets of the SPI-12 and SPI-3 datasets for the cross-correlation analysis with the corpus data. Using only the time series of December SPI-12, rather than the complete SPI-12 time series, results in a single annual value that is completely concurrent with the annual (January–December) corpus data. We also investigated different lags for the SPI-12 series, as newspaper reporting may lag the developing drought. For example, the annual time series of SPI-12 to November covers the 12-month period that precedes the corpus series by 1 month, the annual time series of SPI-12 to October precedes the corpus series by 2 months, etc. For the SPI-3 data, we extracted the annual minimum SPI-3 from all the twelve SPI-3 values in each year to capture the driest 3-month period within each year, assuming newspapers may find short and sharp droughts equally newsworthy as longer ones. There is a short lag of 2 months implicit in this analysis, as the minima are extracted from the SPI-3 aggregations ending in the calendar months January to December (i.e., start months from November to October).

3.3.2 Comparing Droughts in a Tabular Format

In addition to the correlation analysis, which takes into account the data from all years in the data series, we also analysed how the most extreme years in the corpus and the SPI datasets matched up. Using the original corpus data (i.e., not de-trended and standardised), we listed the years for which the word DROUGHT showed the highest frequencies in each corpus: top 15 in each the 19th and the 20th Century Corpora and top five frequencies in each of the Broadsheet and Tabloid Corpora, given the latter corpora cover a shorter period of time. These thresholds were established to keep the analysis manageable while ensuring that we would not overlook events that received reasonable attention in the press. Similarly, we listed all years for which the EWP SPI-12 rainfall records fell below −2 and hence indicated the occurrence of an extreme drought in the United Kingdom.

The next step was to combine the results in a table format. We retrieved the frequency of DROUGHT for all years for which the rainfall records indicated the occurrence of a drought, irrespective of its saliency in the corpus. Similarly, we examined the rainfall records for years in which DROUGHT peaked in the newspaper data, regardless the severity of the meteorological drought. Here, the goal was to determine 1) whether the peaks in the corpus material corresponded to meteorological droughts in the United Kingdom and 2) whether there were any meteorological droughts not captured by the corpus records. The process was thus iterative, moving from one type of data to another until we had results from both approaches for all selected years and any divergence between results was examined further. This included, for example, further investigating the state of the concurrent seasonal SPI-3 droughts (both severe and extreme). We anticipate that while comprehensive, the method may still have left out events that were not as prominent in either approach.

3.3.3 Case Studies

To demonstrate the power of the combined approach, we carried out three different case studies for the years: 1911–1913, 1940–1945, and 1947–1949. Here, we analysed the discourse through close reading of the corpus material and combined the results with the hydrological evidence gathered from the rainfall records for those specific years.

4 RESULTS

This section starts by presenting the results of each approach separately. **Section 4.1** offers an overview of the references to drought events in UK newspapers and **Section 4.2** presents the precipitation records for the period under analysis. We then combine the two approaches in **Section 4.3**.

4.1 References to Drought in the UK Press

Figure 2 shows how the relative frequency of the word DROUGHT fluctuated throughout time. Note that the *y*-axis scale changes from one figure panel to another. There are several unequivocal peaks throughout the centuries, and a number of other smaller peaks which are less well defined. The specific years of these peaks are listed in **Supplementary Appendix S1**. Importantly, the frequency distribution of the word DROUGHT is only an initial indication of the reporting of a drought event. As explained in **Section 3.1**, close reading of the material is needed in order to confirm, or refute, the occurrence of a drought indicated here.

4.2 Rainfall Records

Figure 3 shows the relative severity of precipitation droughts in the regional SPI-12 series for the HD dataset. Across this dataset, the same droughts as identified in previous studies emerge, e.g., 1975–1976, 1933–1934, 1921–1922 and the "Long Drought" period from the late 1880s to about 1910 (Marsh et al., 2007; Barker et al., 2019).

For duration, the most severe events are actually the early 1970s (1973–1974)—rather than the well-known 1975–1976 event, the 1960s, the 1990s for many regions, and periods within the "Long Drought". The years 1933–1934 also feature prominently. These events also occur in the accumulated deficit series, although this features greater rankings for 1933–1934 and 1921–1922 (in southern England), while 1975–76 is also featured. These three latter events, along with 1995–1997, are also the most prominent for mean deficit and intensity. The corresponding figure for the SPI-3 accumulation is shown in **Supplementary Figure A2.1**.

Figure 4 shows the relative severity of precipitation droughts for the EWP and the M2020-EWP dataset according to the four event characteristics. While some of the most severe 20th century droughts shown in HD dataset are also represented (1920s, 1930s, 1976, in **Figure 3**), there are fewer droughts in the post-1976 era. The 19th century sees the major drought of the 1850s which pre-dates HD. This appears as the worst drought according to duration and accumulated deficit, and also features in the rankings of other characteristics. In addition, there are several prominent droughts in the early 1800s.

There are significant differences in the M2020-EWP compared with the EWP. An immediately obvious discrepancy is in the duration of the droughts, which are considerably longer for the original EWP dataset (**Figure 4A**) than for the M2020-EWP reconstruction (**Figure 4E**). Taking all the identified droughts into consideration (not just the top-ranking 15), the average duration of the SPI-12 EWP droughts is 25.2 months compared with 16.8 months for the M2020-EWP droughts. For the SPI-3 accumulation, the average durations are 6.9 and 6.3 months, respectively.

For example, a drought around 1850 is present in the EWP, but not in the M2020-EWP. Further, Murphy et al. (2020a) identified the 1830s as experiencing a very severe drought in terms of intensity (the most severe on record) but that does not feature in the EWP. This is also apparent in the corresponding analysis of the shorter, and often sharper, droughts of the SPI-3 series (**Supplementary Figure A2.2**). However, the droughts of the early 1800s do not feature at all in M2020-EWP, and instead much higher rankings are attained by more recent droughts—notably those of the 1970s and 1990s.

4.3 Cross-Correlation Analysis of the Corpus and SPI Time Series

Figure 5 shows the concatenated, de-trended and standardised corpus time series (January-December) and the lagged time series of August SPI-12 (i.e., covering the 12-month period from September-August). It can therefore potentially capture a dry winter with no recharge to reservoirs or groundwater, followed by a dry summer.

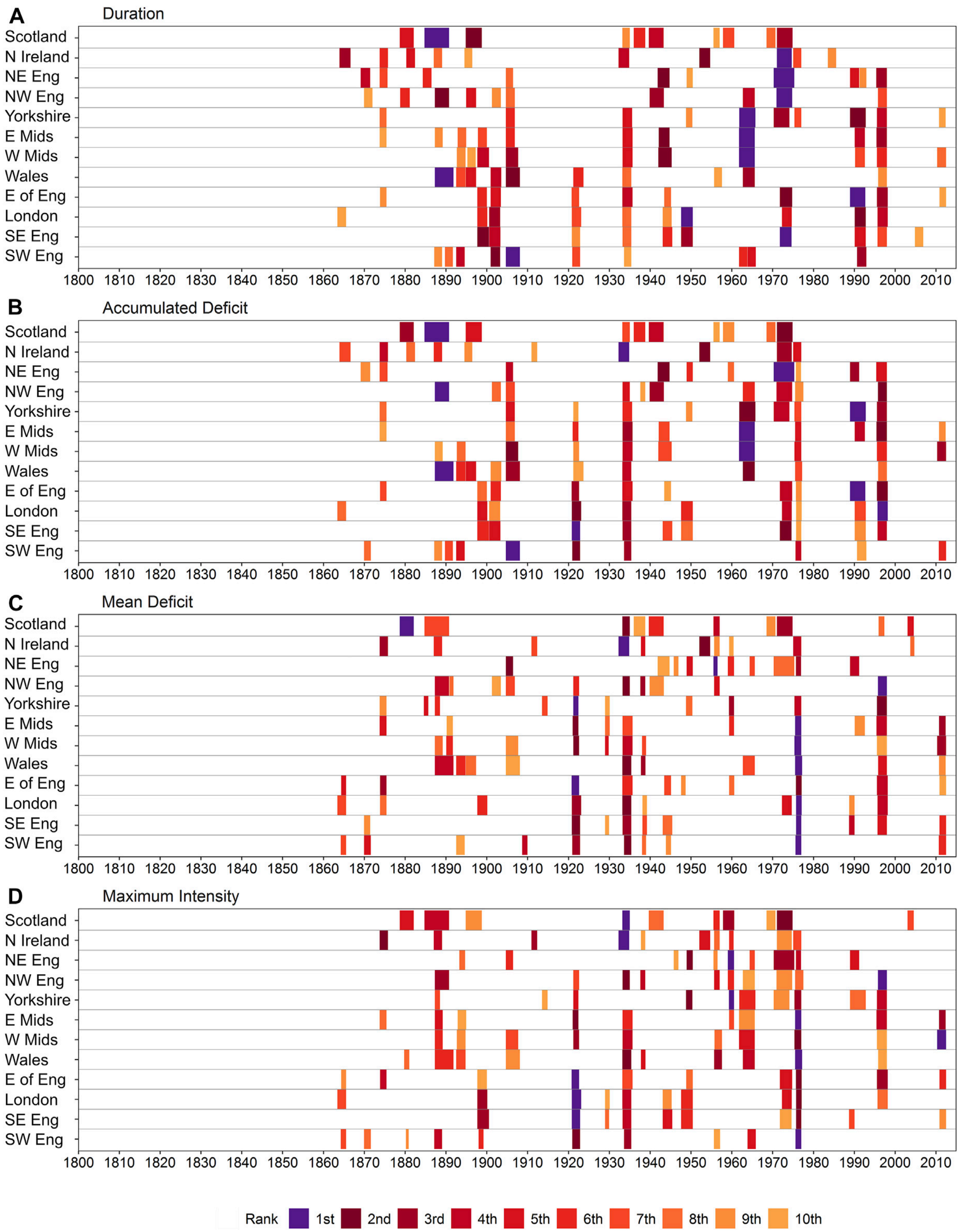

FIGURE 3 | Top 10 extracted drought events for the HD SPI-12 series from 1862 to 2014 using a threshold of −1.5, for UK NUTS1 regions which are ordered roughly from north to south on the *y*-axis. For each region and drought characteristic, the bars are coloured according to the event rank; darker shades represent high-ranking, i.e., more severe, events.

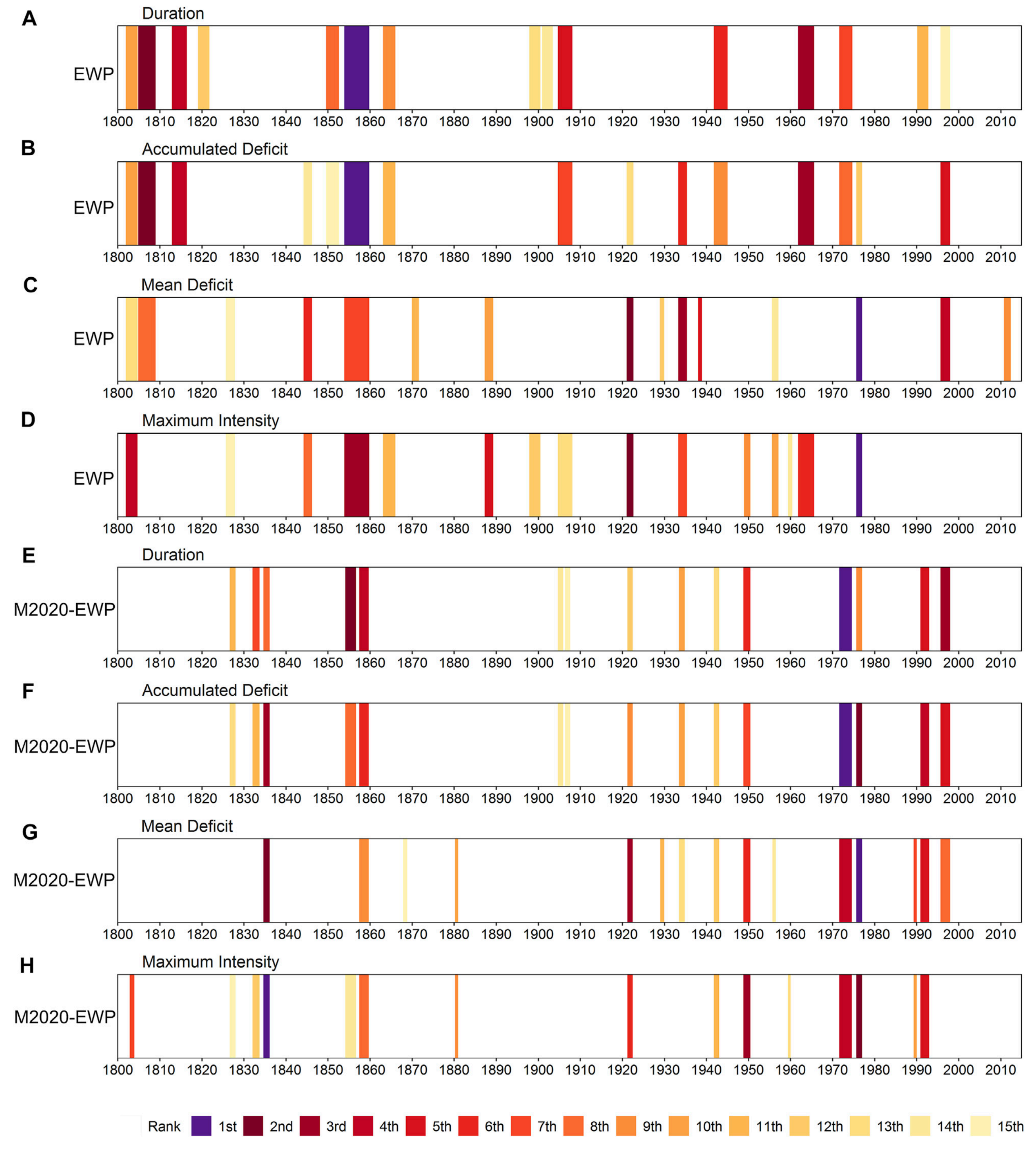

FIGURE 4 | Top 15 extracted drought events for SPI-12 derived from the 1800–2014 EWP series **(A–D)** and the 1800–2000 M202020-EWP series **(E–H)** using a threshold of −1.5. For each of the four drought characteristics, the bars are coloured according to the event rank; darker shades represent high-ranking, i.e., more severe, events.

This would be very newsworthy as many major droughts (in the English lowlands especially) are associated with dry winters, even if the impacts typically become manifest in the following summer. For the EWP data, the cross-correlation is strongest for this four-month lag ($r = -0.29$, significant at the 0.001 level), whereas for the reconstructed M2020-EWP data the correlation is marginally stronger for the SPI-12 series to September (but still rounding to $r = -0.26$, significant at the 0.002 level). The lag may also reflect a

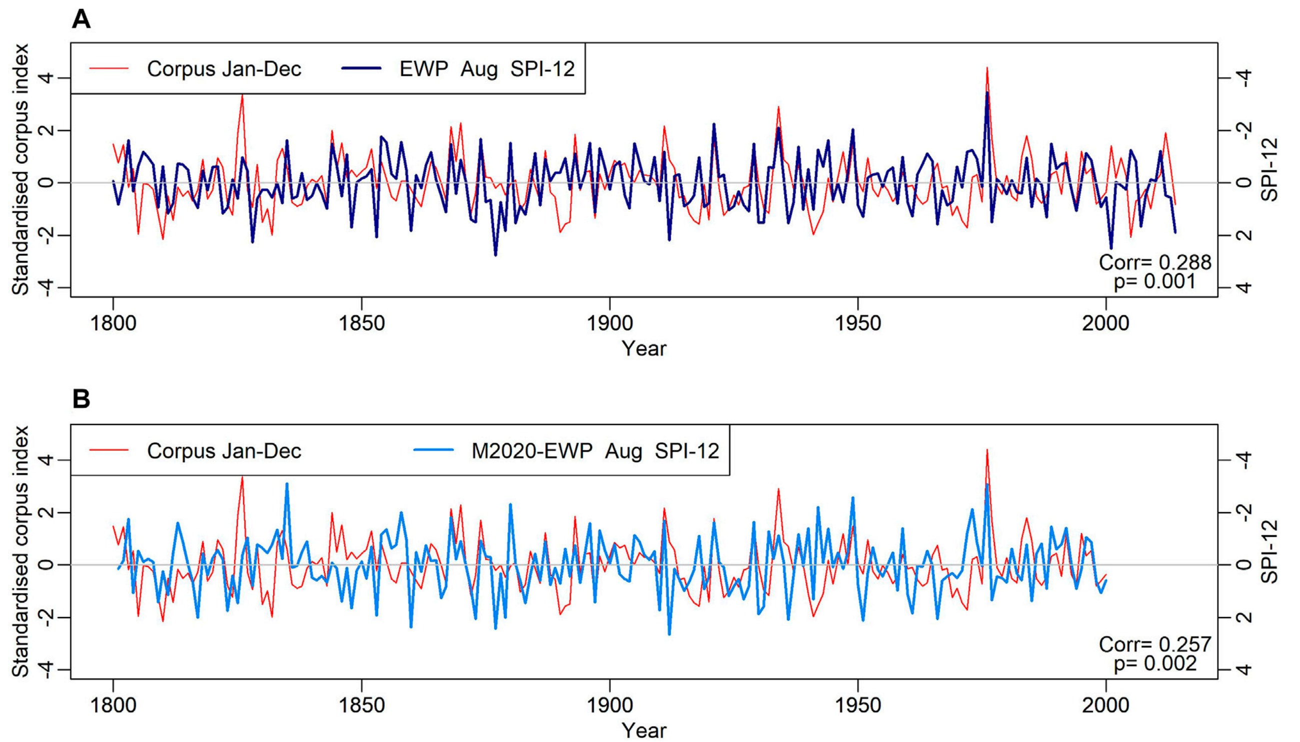

FIGURE 5 | Time series of standardised annual corpus linguistics data and of August SPI-12, i.e., the 12-month period preceding the January—December corpus data by 4 months. The SPI-12 is calculated from the EWP data, and from the M2020-EWP data. Note that the scale for the SPI-12 (right-hand side) is reversed in order to overlay the corpus data as well as possible. To reflect this in positive correlations, the SPI-12 data were multiplied by -1.

delay in the newspaper reporting until the droughts are properly underway, as discussed later in this section.

Figure 6 shows the corpus time series versus the annual minimum SPI-3, which captures precipitation droughts of a shorter duration than SPI-12. Here, the cross-correlation with the corpus series is stronger for the reconstructed M2020-EWP series ($r = -0.30$) than for the original EWP ($r = -0.28$). Particularly, the M2020-EWP series reconstruction is in better agreement with the newspaper coverage of droughts in the early 19th century. Murphy et al. (2020a) identified this period in the original EWP series as having too low winter precipitation due to gauge under-catch of snowfall and a high incidence of snow (pre-1870), and as having too high summer precipitation totals (pre-1820) probably due to a low station network density and less certain data at key stations. However, there is a prolonged period in the 1840s where the M2020-EWP differs from both the corpus data and the original EWP (**Figures 5**, **6**).

In **Supplementary Appendix S1**, we list all years for which at least one approach indicated the occurrence of a drought event in the United Kingdom between 1800 and 2014, providing the relative frequency of the word DROUGHT in the corpus and the rainfall record for each year.

5 DISCUSSION

Overall, we found a general agreement between the corpus data and the rainfall records. In the vast majority of cases, there is supporting evidence of drought in the precipitation records when the frequency of the word DROUGHT increases in the newspaper corpora. For example, for the 1933–1935 period, precipitation records indicate that a severe drought started to affect most of the United Kingdom towards the end of 1933, persisted throughout 1934 and continued in some parts of England in 1935. The relative frequency of the word DROUGHT doubled between 1932 and 1933 (from 2.3 to 5.5 occurrences per one million words), peaked high in 1934 (14.1 occurrences), and dropped to the previous level in 1935 (6.0 occurrences).

However, it is important to note that the frequency of DROUGHT does not always reflect the intensity and/or spatial extent of an event. For example, the precipitation records indicate a severe drought across most of the United Kingdom for the first half of 1956, but the frequency of DROUGHT did not spike in that specific year (3.1 instances per a million words). Although evidence was not substantial, the corpus data confirms that a severe drought affected many parts of the United Kingdom in 1956. There was a report on a drought in the southwest due to a dry and sunny March (*The Times*, 02.04.1956), and another on an absolute drought in East Anglia and shortage of water supplies in Glasgow in early May (*The Times*, 08.05.1956). Also, despite the low relative frequency of DROUGHT in 1964 (2.4 instances), *The Times* did mention a severe winter drought in February (Extract 1) and again in November.

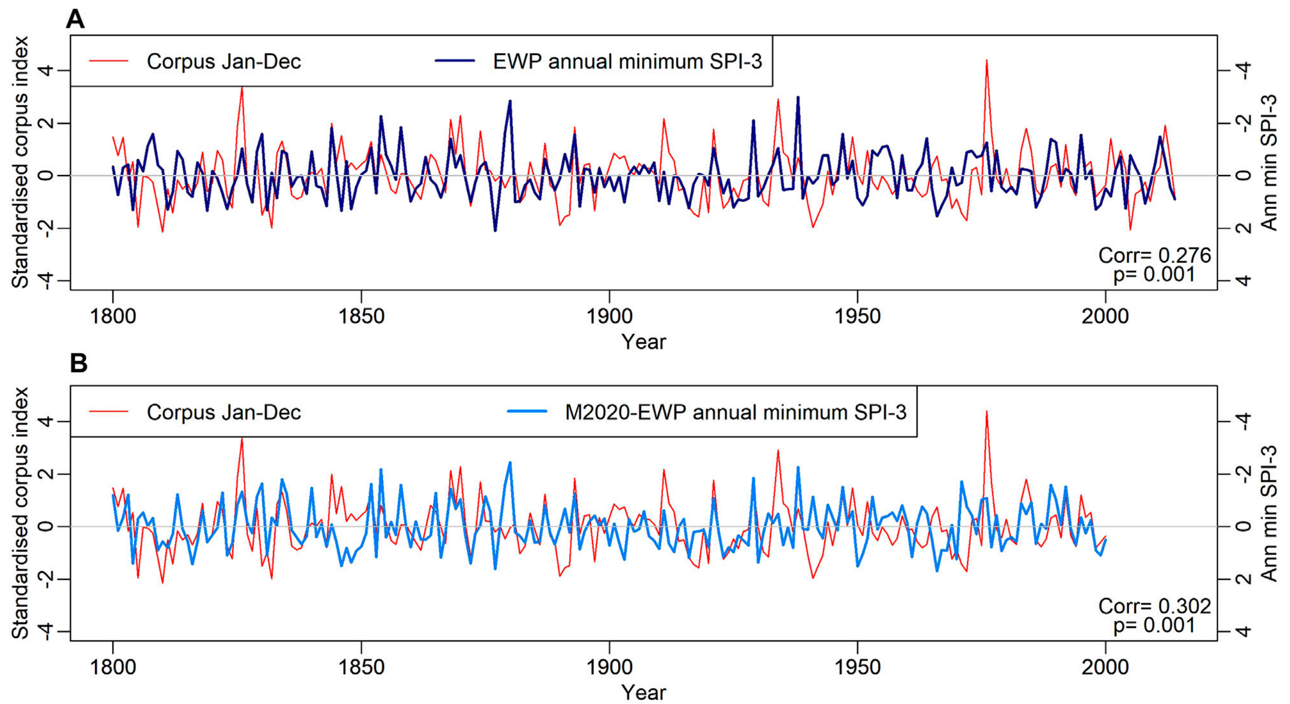

FIGURE 6 | Time series of standardised annual corpus linguistics data and of annual minimum SPI-3. The SPI-3 is calculated from the EWP data, and from the M2020-EWP data. Note that the scale for the SPI-3 (right-hand side) is reversed in order to overlay the corpus data as well as possible. To reflect this in positive correlations, the SPI-3 data were multiplied by −1.

> 1) *Weekly instead of daily baths were urged on Nottingham's population today to avoid water rationing in Britain's driest winter drought for 35 years.* (The Times, 17.02.1964)

A plausible explanation for these cases is the measure of newsworthiness. Mentions in a newspaper may be related to the competing news values operating at a given time since, as Bednarek and Caple (2017: 35) observe, news values influence selection, drive coverage and dominance practice. There is also likely a lag between the precipitation deficit being observed and the drought impacts reported. Firstly, because it takes some time for soil-, surface- and groundwater stores to be depleted, typically several months before river flows in southeast Britain are affected (Barker et al., 2016). Secondly, drought impacts may go unreported during the early stages of a drought, but once it is established the reporting may be more complete (Bachmair et al., 2016). The year of 1912 is a clear example. Despite the salient frequency of DROUGHT, references are mostly attributed to discussions of the impacts of the 1911 drought.

For three occasions (1803, 1805, 1827), there were long-lasting extreme droughts in the EWP dataset that did not seem to have been reported in the press. This may be because, before 1870, the EWP dataset likely under-estimates the amount of winter precipitation falling (Murphy et al., 2020a). The potential gauge under-catch of snowfall, and higher incidence of snowfall, during this period are accounted for in the M2020-EWP reconstructions, which show a closer similarity to the corpus data (**Figure 5B** and **Figure 6B**). But the apparent under-reporting in the newspapers may be also related to gaps in the 19th century data (see McEnery et al., 2019, 2021). For these specific years, the corpus contains texts from the *Ipswich Journal* and *Hampshire Chronicle* only and there was hardly any occurrences of DROUGHT in them.

There were also five cases (1846, 1903, 1912, 2013, and 2014) for which the word DROUGHT peaked in the corpus data but the precipitation metric used in this study did not indicate the occurrence of a drought. With the exception of 1903, all other 4 years are false positives, that is, there was hardly any evidence in the corpus material that the United Kingdom experienced a drought in those years. In 1912, 2013, and 2014, many references to drought were attributed to discussions around the impacts of a drought in previous years (1911 and 2012, respectively). In 1846 as well as in 2013 and 2014, the word DROUGHT was frequently mentioned in contexts other than a meteorological drought, such as in relation to drought-resistant plants or extreme weather events due to climate change. Although scanty, there is evidence in the corpus data that the whole of Scotland, north England and parts of Wales were affected by a drought in 1903 (Extract 2).

> 2) *Scotland, even more that than Wales, was afflicted by drought and cold in the spring and early summer of the present year* (The Times, 10.08.1903)

It is also important to note that McEnery et al. (2019, 2021) has indicated four other droughts during the 19th century which were not captured by the precipitation-based classification of major droughts of Marsh et al. (2007). These droughts occurred: 1) in Scotland in 1821, spreading to other parts of the country in 1822; 2) in Southern England in 1834; 3) in Scotland in 1850, developing to southern England in 1851 and on to northern England in 1852; 4) across England, Scotland and perhaps parts of Wales in 1880, persisting in southeast England in the summer of 1881. They are not shown in **Supplementary Table A1.1** because the frequency of DROUGHT fell below the frequency threshold used in this study (i.e. top 15, see **Section 3.3**), and there was no extreme drought (SPI < 2) in the EWP SPI-12 time series.

However, there are severe, and even extreme, droughts in the SPI-3 time series in either or both of the original EWP and the reconstructed M2020-EWP datasets for all of these four time periods (and in the HD dataset for the latter). Neither of the datasets covers Scotland in the early part of the 19th century, but the M2020-EWP dataset confirm that there is a moderate to extreme SPI-3 drought from March to June 1822. Both the original EWP and the M2019-EWP SPI-3 series show two to three consecutive months of severe or extreme drought bookending the period April 1834 to January 1835, and this was highlighted by Murphy et al. (2020b) as a "forgotten drought" alongside various documentary/newspaper sources of impacts. The original EWP series show severe drought for a single SPI-3 accumulation in March 1850 and for November to December 1851, and both the EWP and M2019-EWP series show extreme drought for the SPI-3 accumulations ending in April and May 1852. The regional HD dataset show extreme drought in the SPI-3 records for all of the United Kingdom in December 1879 and January 1880, and severe to extreme SPI-12 drought in northern and western parts from August to October 1880. However, there is only moderate SPI-3 drought in southern England in summer 1881.

6 CASE STUDIES

We now explore three periods of time in more detail. Given that many other drought events such as the 1920s and 1930s are well covered in previous literature, these specific periods were chosen mainly for the lack of information about them. At the same time, they illustrate the richness of the corpus approach, especially when combined with the meteorological observations, by providing significant detail on regional differences and fine-scale temporal evolution of the droughts. They are:

(1) The years of 1911 and 1913: While the frequency of the word DROUGHT peaked in 1911 (third highest frequency in the 20th century) and figured on the 15th place rankings in 1913, the meteorological data suggest that shorter regional droughts occurred during these years, rather than extreme and long-lasting drought (except in Northern Ireland in 1911).
(2) The period between 1940 and 1945: The frequency of DROUGHT between 1940 and 1945 was among the lowest in the 20th century corpus (see **Figure 2**). This is perhaps not surprising, given that the country was at war. Competition for the available space in the press would have been fierce. However, the meteorological data suggest some rather long-lasting droughts did occur (e.g., **Figures 3**, **4**).
(3) The years of 1947 and 1949: These are years in which the two approaches coincide. The frequency of DROUGHT ranked 13th and 6th places in the 20th century respectively and the rainfall records indicate meteorological droughts occurred.

In the following descriptions the meteorological droughts are assessed based on the complete monthly time series of SPI-3 and SPI-12 from the regional HD dataset. Heatmaps of the HD dataset for the 3 and 12-months accumulations are shown in **Figure 7** for the period from 1910 to 1950.

6.1 The years of 1911 and 1913

Based on the HD SPI-3 records, two relatively short droughts occurred in 1911 and 1913, the first affecting mainly the south of England and the Midlands, and the second mainly the north and the west of the United Kingdom (**Figure 7A**). These regional records suggest that normal to moderately dry conditions (~0 > SPI-3 > −1) occurred across most of the United Kingdom from February to October 1911 (i.e., in the 3-month periods ending in these months). However, severe drought (SPI-3 < −1.5) spread from the west Midlands, where it occurred intermittently from May to September, to cover all of the Midlands and southern England in September. Northern Ireland experienced severe drought in the 3-month period to October, but more importantly, the SPI-12 records show that the prolonged period of moderately dry conditions had accumulated into extreme drought in the SPI-12 accumulations ending in August to October 1911 (**Figure 7B**). This was followed by a wet period from November 1911 to June 1913, when the regional SPI-3s were largely positive across the United Kingdom. However, mild to moderate drought conditions then again developed swiftly across most of the country for the SPI-3 accumulation to July 1913, reaching severe or extreme levels in parts of the north and west (including southwest England) from August to October. By November 1913 the SPI-3 conditions were again more normal.

In the corpus data, references to drought indicated that a drought began in the 1911 spring and continued into summer, affecting mostly southern Britain. *The Times* first reported that the country was suffering from drought on 27 April 1911; by June, the situation had become more serious (Extract 3). A different article from the same day stated that the worst hit counties were Cambridgeshire, Worcestershire, and Cheshire, where it was feared that both the hay and the corn crops would be short.

> 3) *In many English districts less than half an inch of rain has fallen during the past four weeks, and in some places less than a quarter of an inch.* (The Times, 05.06.1911)

By July, the drought had affected the prices of Hampshire and Dorset Down ewes (*The Times*, 17.07.1911) and the south of England was reported to have experienced a severe drought which resulted in deficiency of grass, thus endangering the milk supply

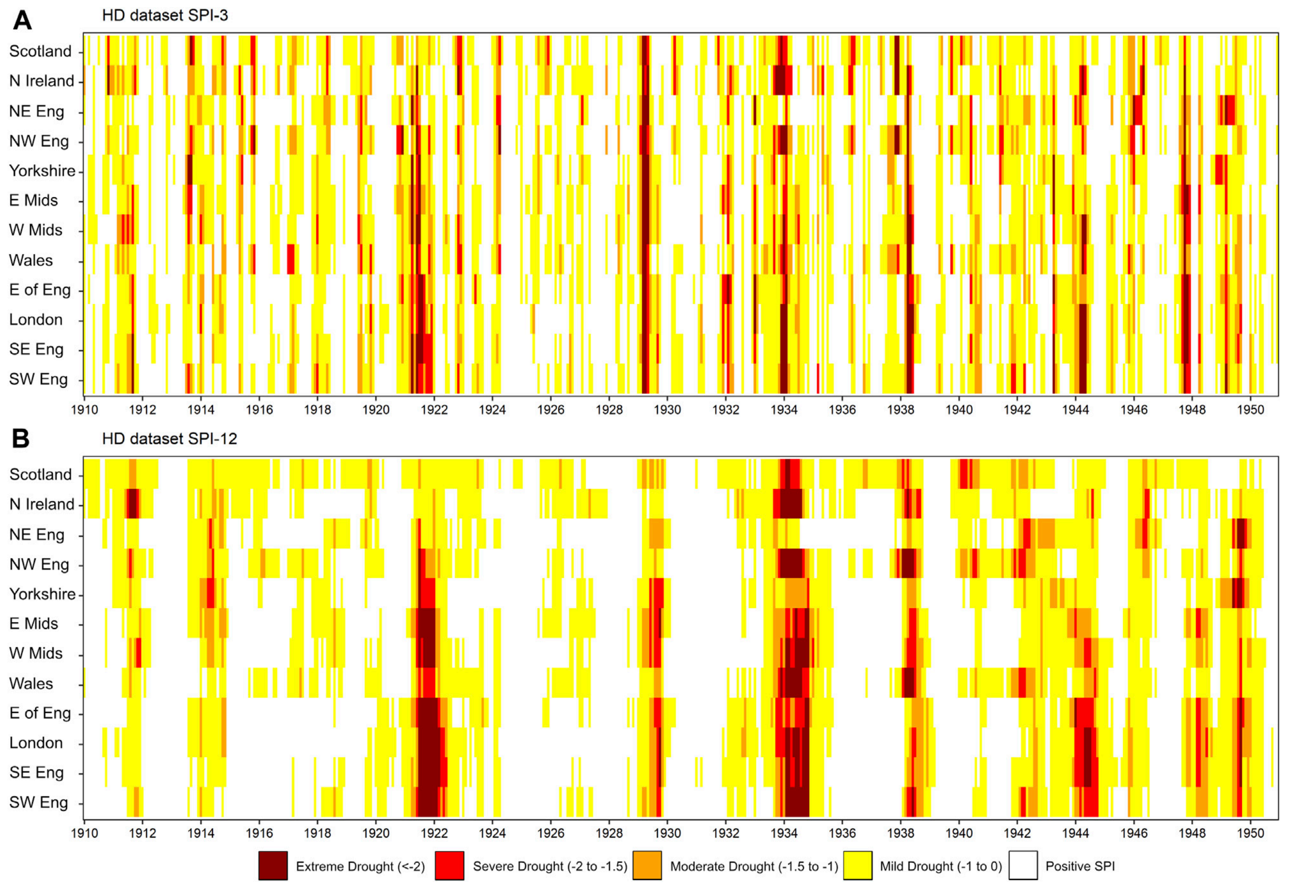

FIGURE 7 | Heat maps of the HD dataset from 1910 to 1950, showing continuous monthly time series of SPI accumulations of 3 **(A)** and 12 **(B)** months for UK NUTS1 regions which are ordered roughly from north to south on the *y*-axis. Darker shades indicate lower SPI values, i.e., more extreme precipitation deficits.

(*The Times*, 24.07.1911). The effect on crops, meanwhile, was described as being more varied (Extract 4).

> 4) *The corn has ripened rapidly and the binders are hard at work, and on account of the continued hot weather carting will be practicable a few days after cutting. Mangel wurzel have done very well, but swedes and kale have practically failed on account of the drought. There are fair supplies of cabbage and rape for the sheep, but the former have not hearted well for want of rain.* (The Times, 31.07.1911).

The droughty weather had continued to affect parts of southern England throughout August, when it reached Scottish pastures and crops (*The Times*, 07.08.1911). By mid-September, it was reported as having reached northern Britain, causing shortage of water supplies (*The Times*, 12.09.1911). Although this drought is not visible in the SPI-3 records of the HD dataset, the SPI-12 records to August 1911 suggest that moderate to severe drought affected Scotland and northern England over the previous 12 months (**Figure 7**). Even moderate rainfall deficits over such an extended period would eventually result in low reservoir levels and lead to problems with water supply. The long-term drought was worst in Northern Ireland, where the SPI-12 shows severe to extreme drought for the 12-months accumulations ending in July to November 1911 (**Figure 7B**). We found only two articles reporting this drought (*The Times*, 10.07.1911 and 18.09.1911).

The corpus data suggests that at the end of September, Britain experienced heavy rain showers but they were not evenly spread throughout the country. A retrospective report of November 1911 suggested that the south of England had been most severely affected by the drought but it had also affected Northern England and Scotland.

Several references to drought in 1913 reflected back to the impacts of the 1911 drought and short drought periods in 1912. Reference to a drought in 1913 first appeared on 17 June, when *The Times* mentioned a tournament took place in Roehampton although the grounds had been suffering from continued drought. Further evidence came in early July, with a report that the drought had been especially severe in Dorset (*The Times*, 07.07.1913). It gradually spread to other parts of England and the impacts on crops were still felt throughout

August, particularly regarding corn yields (*The Times*, 09.07.1913, 02.08.1913, 04.08.1913, 12.08.1913).

In agreement with the meteorological data, the corpus data suggests that by mid-August the drought had reached Scotland and the west and southwest of the United Kingdom. Shortage of water supplies was reported in the Vale of Glamorgan and various parts of Scotland (*The Times*, 12.08.1913, 13.08.1913, 21.08.1913). Drought conditions persisted across most of Great Britain until late August, with Scotland hit the hardest (*The Times*, 22.08.1913). There was serious shortage of water in Glasgow (*The Times*, 21.08.1913), the Lochaber Loch and the Caledonian Canal reached unusually low levels (*The Times*, 21.08.1913, 25.08.1913, 27.08.1913), and fishing in the River Tay was seriously affected (*The Times*, 19.11.1913). The drought was officially broken all over the country on 25 August 1913, with heavy rain and thunderstorms in the following week (*The Times*, 01.09.1913). There were signs that the drought continued in northern England into September, but evidence was not substantial. However, the effect of the summer drought was still felt in the following months, especially in relation to agricultural yields across England (*The Times*, 10.09.1913, 06.10.1913, 11.10.1913, 14.10.1913).

6.2 1940 to 1945

Three episodes of long-lasting SPI-12 droughts occurred during the period 1940–1945, starting in the northwest and finishing in the southeast. The HD SPI-12 accumulations ending in February to August 1940 show moderate to severe droughts in Scotland and northwest England, and were made up of two incidences of shorter droughts (**Figure 7B**). The HD SPI-3 records reveal severe droughts in the wider northwest of the United Kingdom for the 3-month periods ending in October 1939 and June 1940 (**Figure 7A**).

The second SPI-12 drought affected northern Britain, Wales and Southwest England, with moderate to severe magnitudes for the 12-months accumulations ending in November 1941 to September 1942. In this case the worst SPI-3 droughts reached severe magnitude and affected northern England and Northern Ireland in the 3-month periods ending in June and July 1941, and Southwest England bookending the period November 1941 to April 1942 (**Figure 7**).

The last SPI-12 drought in this period reached extreme magnitudes in the southeast corner of England, while severe drought affected the wider south and central England, Wales and Northern Ireland in the 12-month periods ending January to October 1944 (**Figure 7B**). This long and widespread drought started with a single extreme SPI-3 accumulation to April 1943, affecting eastern and southern England. It ended with three consecutive extreme SPI-3 accumulations ending in March to May 1944 for southern England, West Midlands, Wales and Northern Ireland, although most of the United Kingdom was affected by drought to some degree (**Figure 7A**).

References to drought in the corpus material in the years of 1940–1942 related mostly to the reporting on the impacts of the drought in southern England in the late 1930s (1937–39). Apart from scanty mentions of drought conditions in specific locations, there was no evidence in the corpus data of a severe drought in the United Kingdom until the summer of 1942, when *The Times* reported various droughty periods across southern England between April and June. Reference to a drought in other parts of the country was only seen once, in an article on 7 September 1942 which mentioned a drought earlier in the year had affected oat yields and potato crops in East Lothian. This sole report is the only corpus evidence of a drought that in the meteorological record mainly affected the north and west of the United Kingdom. The short durations of the reported droughts in southern England, lasting only a few weeks and being interspersed by significant amounts of rainfall, may account for these droughts not showing up in the HD SPI-3 records.

From spring 1943 to the end of 1945, the newspaper reports largely agree with the droughts observed in the meteorological HD dataset. On 13 April 1943, *The Times* reported a 31 days' drought in the Thames catchment. Another article mentioned that London suffered from a drought between 19 June and 6 July that year, which ended with a heavy rainfall (*The Times*, 17.07.1943). By August 1943, the drought conditions spread to other areas and started to affect the farming industry across Suffolk, Hampshire, Cornwall (*The Times*, 09.08.1943), East Anglia, Suffolk and Norfolk (*The Times*, 13.09.1943).

A retrospective report in early 1944 (*The Times*, 11.01.1944) highlighted that the flow of the Thames was much below the average as winter rainfall in the last three months of 1943 was not sufficient. The article also mentioned the impact on crops, exacerbated in times of war when the country was dependent on its own crops. Another article on 15 February 1944 mentioned deficiency in rainfall in England and Wales in the summer of 1943 which caused shortage of water supplies, while Scotland and Northern Ireland experienced substantial excesses of rainfall.

From April to August 1944, there were various reports of widespread drought conditions across the United Kingdom between March and July, with southeast England and east Midlands hit the hardest. A report on 12 April 1944 framed it as one of the driest March in the United Kingdom in the 20th century. The drought affected the whole of England – and the south, southeast and east in particular – threatening milk supplies. The flow of the Thames was at its lowest level on record for that time of the year and Londoners were asked to keep consumption of water to a minimum (*The Times*, 06.05.1944). By June, restrictions on the use of water in the London area were introduced (Extract 5) and remained in place until October (*The Times*, 12.10.1944).

> 5) "*The Metropolitan Water Board decided yesterday to suspend until further notice authority to consumers to use hoses, outside taps, or sprinklers for watering gardens, allotments, or sports grounds, for washing vehicles or streets, or for any ornamental fountain.*" (The Times, 17.06.1944)

From the end of June to mid-October, *The Times* focused on impacts of the drought on farming. The drought affected milk supplies (*The Times*, 28.06.1944) as well as wheat, corn and potato crops in southern England, especially in Norfolk, Suffolk and Hertfordshire (*The Times*, 10.07.1944). Fruit stocks were scarce (*The Times*, 26.08.1944), and sugar beet and potato crops in southwest counties were below average (*The Times*, 09.10.1944).

References to drought were scanty in 1945 and revolved mainly around the impacts of the 1944 drought. On 9 May 1945, *The Times* reported that although reservoirs had not been fully replenished, there was little chance that the country would face water problems in 1945.

6.3 The years of 1947 and 1949

The SPI-3 records from the HD dataset show severe to extreme meteorological drought throughout the United Kingdom in the 3-month periods ending in September to December 1947, with October being extreme in all regions except Scotland where it was severe. For the longer-duration SPI-12 this translated into severe drought in the 12-month periods ending in March and April 1948, for southeast England and east Midlands (**Figure 7**).

In 1949 the SPI-3 accumulation to March was severe to extreme in all areas except the northwest where the drought varied from mild to moderate. In northeast England, SPI-3 droughts remained severe until June 1949, and scattered values of moderate to severe SPI-3 droughts occurred in Wales and southern England until September (**Figure 7A**). The generally dry conditions in 1949 resulted in all areas except Scotland, Northern Ireland and east Midlands experiencing at least one severe or extreme SPI-12 accumulation ending between June and November 1949. The most spatially widespread extreme drought occurred for the SPI-12 accumulation to September (**Figure 7B**).

In the corpus data, the first reference to a drought in the United Kingdom in 1947 appeared in late June, when *The Times* reported on potato shortage due to a drought in the main producing areas of Lincolnshire, Cambridgeshire and Norfolk (*The Times*, 26.06.1947). A report some days later (*The Times*, 07.07.1947) alerted that hard winter followed by a drought had brought poor harvest prospects for farmers throughout the country, especially for wheat, barley, oat, potatoes and sugar beet crops.

An absolute drought was reported in central and northeast Scotland in August and there were record hours of unbroken sunshine in several towns across the country (*The Times*, 13.08.1947). A week later, the drought had spread southwards, with hardly any rain recorded in most parts of Britain (*The Times*, 19.08.1947), reducing water levels in reservoirs (*The Times*, 20.08.1947). At the end of August, the United Kingdom experienced scorching temperatures and a severe widespread drought, which persisted through the first week of September (*The Times*, 25.08.1947, 29.08.1947, 02.09.1947). A retrospective report on 1 September 1947 described the previous month as the sunniest and driest August on record.

The drought started to break down in most of Scotland and Northern Ireland on 4 September 1947 and the rain gradually moved down towards northwest England and Wales, reaching southwest and southeast England a couple of days later (*The Times*, 04 to 08.09.1947). The rain remained negligible in other parts of the country, where the drought was only broken in mid-September (*The Times*, 18.09.1947, 19.09.1947). A month later, *The Times* reported that drought conditions had started to develop again in parts of southeast England and East Anglia (*The Times*, 11.10.1947, 20.10.1947). It was referred to as the third drought in the country in 1947.

The impacts of the 1947 drought were widely reported. It had a marked effect on the milk production from July onwards, with acute shortage in Lincoln, Northampton and the Midlands (*The Times*, 23.08.1947). There were reports of an increasing number of farmland fires in Derbyshire and rejection of milk supplies as farmers had no water for cooling (*The Times*, 26.08.1947). By mid-September, pastures were still bare and scorched in most of the country, except in Wales and southwest England. Milk supplies became short (*The Times*, 11.09.1947, 15.09.1947, 16.09.1947) and only regained force in December (*The Times* 27.10.1947, 15.12.1945, 29.12.1947).

The drought also affected salmon production in estuaries in northern Scotland (*The Times*, 06.09.1947) and the farming industry in East Anglia, Nottinghamshire and northern Scotland where the yields of sugar beet, turnips, and swedes were below average, and kale and cabbage were substantially damaged (*The Times*, 11.09.1947, 15.09.1947, 16.09.1947). Later that year, there were reports of poor wheat yields, especially in Devon and Dorset (*The Times*, 06.10.1947, 20.11.1947).

A retrospective article on 31 December 1947 stated that the British Isles had had the warmest and driest August since 1881, especially in east Kent and east Suffolk; Scotland had the driest August since 1869. The dry weather persisted until autumn, with absolute drought over most of Britain. It was the driest October on record for most of England and Wales, causing the flow of the Thames to reach very low levels.

The first indication of drought conditions in 1949 appeared on 8 June, when *The Times* reported that rainfall had prevented the drought from damaging cherry crops in Kent. In mid-June, large parts of Ireland, Scotland, Wales, and the western England experienced absolute drought and high temperatures (*The Times*, 18.06.1949). By the end of the month, dry weather and high temperatures prevailed across the entire country, with absolute droughts covering the whole of England, Wales and great part of Scotland (*The Times*, 27.06.1949, 28.06.1949).

The drought started to break on 29 June 1949, when heavy rain fell in Yorkshire, later spreading to much of northeast England, north Lancashire and the Lake district (*The Times*, 29.06.1949, 30.06.1949). The dry weather and high temperatures persisted in other parts of England and Wales (*The Times*, 04.07.1949). On the 5 July, thunderstorms were reported in eastern Scotland and steady rain across various parts of the country, but droughty conditions persisted in Devon, Cornwall, south and west Wales, Lancashire, Yorkshire and the Channel Islands (*The Times*, 06.07.1949). By mid-July, the drought had been confined to southeast England (*The Times*, 15.07.1949).

The effects of the drought on water supplies were felt throughout the country from late June 1949, with campaigns to persuade people to reduce water consumption in north Yorkshire and south Durham (*The Times*, 27.06.1949), Kent and parts of Sussex (*The Times*, 29.06.1949), and London (*The Times*, 01.07.1949). Restrictions on water use were introduced in London early July and south Wales late that month (*The Times*, 04.07.1949, 06.07.1949, 26.07.1949).

Milk yields in Somerset, Lincolnshire and Cumberland shrank and there was an increased number of heath and plantation fires across Berkshire and Dorset (*The Times*, 06.07.1949 and 11.07.1949). Overall, agricultural production remained stable, despite some disappointing yields of potato and sugar beet crops in Gloucestershire, Hampshire, Oxfordshire and Surrey (*The Times*, 11.07.1949, 08.08.1949, 12.08.1949, 12.09.1949), and vegetable crops were scarce (*The Times*, 20.09.1949).

Rainfall was deficient again in most parts of Britain in mid-September 1949, except west-Scotland and some parts of the Midlands; with an absolute drought in Kent, Norfolk and Suffolk (*The Times*, 13.09.1949). Water supplies in London, Birmingham, Manchester, and Derbyshire were at risk (*The Times*, 15.09.1949, 16.09.1949). Hosepipe bans were introduced in London (*The Times*, 17.09.1949 and 19.09.1949) and a drought order was granted to the Metropolitan Water Board for additional abstraction from the Thames (*The Times*, 20.09.1949). By mid-October, rainfall and the flow of the Thames had increased but not yet sufficient for restrictions to be lifted (*The Times*, 12.10.1949). Despite the strain on water supplies, the 1949 drought was not ranked as the most severe drought in Thames records as the average flow was higher than in the same period in the years of 1921, 1934 and 1944 (*The Times*, 11.10.1949).

7 CONCLUSION

The present study demonstrated how corpus linguistics in combination with precipitation metrics can be used to examine the representation of drought in the United Kingdom, presenting evidence going back as far as 1800, with unprecedented scale and depth. On balance, our conclusion is that the combined approach was mutually informative. Bringing together two entirely different, but highly complementary, approaches allowed a more confident assertion of conclusions.

We found an overwhelming agreement between the corpus data and meteorological records in relation to when a drought event occurred in the United Kingdom. With very few exceptions, there are plausible explanations for the few cases in which the corpus and rainfall data diverged in relation to the existence of a drought in the United Kingdom (see **Section 6** and **Section 7**). The analysis demonstrates that newspapers tend to talk about dry weather conditions more frequently during periods in which the meteorological records indicated the existence of a drought in the United Kingdom. This is important because, while serving as a rich source of information, newspapers pose the challenge of working with a narrative driven by news values and the interests of a publishing house. In addition to the level of attention paid to drought relative to other concerns, the reality presented in the press may be only partial or even distorted and skewed. By cross-examining the newspaper material with long-term meteorological data, we were able to check our corpus observations against reality. Conversely, the newspaper material complemented the meteorological data by indicating droughts which had not been captured by precipitation metrics, especially in the 19th century when rainfall records were sparse and uncertain (see **Section 6**), as well as adding significant richness to our understanding of drought development, severity and impacts. Crucially, in a departure from past studies, the corpus approach provides a longitudinal rather than event-based approach, and an *objective* rather than *selective* assessment of evidence from the news media, with which to benchmark the meteorological drought analysis.

Through the case studies, it becomes evident that, despite the consistency of results, subtle differences emerged when we cross-examined the characteristics of each event from the two perspectives taken. The newspaper narrative does not always coincide with the meteorological data in all aspects regarding the intensity and/or spatial extent of the analysed events, perhaps due to the interests and remit of *The Times* in the selected years. For example, while the meteorological data indicated that the 1911 drought hit Northern Ireland the hardest, *The Times* focused mainly on the impacts of the drought in southern England, devoting little attention to other parts of the country.

The analysis has also highlighted differences between the two approaches in relation to the duration of events. Long-lasting drought events do not appear to elicit as much newspaper coverage as intense, but shorter droughts. As illustrated by the case studies, newspapers often describe droughts as lasting only a few weeks, or even days, which is too short for our shortest meteorological measure, the SPI-3, to capture. This may be explained by the media attention cycle as the issue becomes most relevant when its impacts are felt more evidently by the population. This aspect was especially evident in the 19th century data, when dry weather conditions were a matter for concern due to its impacts on agriculture and cattle farming (McEnery et al., 2019, 2021). Interestingly, the reconstructed M2020-EWP series better reflects the corpus data in the early part of the 19th century, than the original EWP series does. Also, the duration of the extracted droughts is considerably shorter for the M2020-EWP dataset than for the original EWP dataset. Both these issues are probably at least partly due to the wetter winters found by Murphy et al. (2020a) in the M2020-EWP compared with the EWP dataset for the period pre-1870.

Regarding impacts of droughts, the corpus analysis allowed us to delve into the narrative around the effects and scope of the selected events, as the case studies demonstrate. However, it is important to stress that while the corpus data offers perspectives on the droughts as they were perceived at the time, some caution is warranted as it was our only source of impact information. Additional benefits could be achieved by contrasting and complementing the newspaper narrative with other sources, such as journals, diaries or other archives (as done in Noone et al. (2017) and Harvey-Fishenden et al. (2019)).

Future studies could also explore the context of droughts in specific regions using the combined approached presented here. This could have the additional advantage of using local newspapers, which may bring new information about localised impacts and responses to droughts. Also, it goes without saying that the analysis would gain in quality if other events were explored in more detail. Finally, a worthwhile future avenue would be application of corpus methods to pre-1800 sources, to complement existing work on multi-centennial drought assessment from documentary sources (e.g., droughts from southeast England from 1,200–1700; Pribyl, 2020).

On balance, this paper demonstrates the power of combining corpus linguistics with meteorological metrics on a scale that would not otherwise be possible, thus contributing to a better understanding of how drought is perceived, in addition to how it is traditionally "measured".

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. The datasets are not made available in the article or supplements, but most are open datasets available from the links below, or if not open, contact details are provided. The newspaper datasets are made available for registered users of CQPWeb, Lancaster's software platform for large-corpus analysis. Instances of the word "drought" in the newspaper corpora are available from the Historic Droughts project pages on the UK Data Service. See https://historicdroughts.ceh.ac.uk/content/datasetsdatasets. Specifically: 1) https://reshare.ukdataservice.ac.uk/853195/, 2) https://reshare.ukdataservice.ac.uk/853196/, 3) https://reshare.ukdataservice.ac.uk/853399/4) https://reshare.ukdataservice.ac.uk/853403/. The precipitation data is available from: 1) Historic Droughts Rainfall: https://catalogue.ceh.ac.uk/documents/af1db516-3411-416f-9c51-5ab99d912f8a, 2) England and Wales Precipitation: https://www.metoffice.gov.uk/hadobs/hadukp/, 3) Murphy et al. (2020a) dataset was secured from the authors of the paper. Interested parties should contact the lead authors of the article, https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.6208.

AUTHOR CONTRIBUTIONS

CD, JH, and TM conceived and designed the study. CD led on the 20th and 21st C corpus analyses, HB on the 19th C analysis. CS, LB, and MT conducted analysis of the rainfall data. CS and CD conducted the integrated analysis. CD, CS, and JH wrote the manuscript, with contributions from all authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.760147/full#supplementary-material

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Dynamic High Resolution Hydrological Status Monitoring in Real-Time: The UK Water Resources Portal

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Understanding the current hydro-meteorological situation is critical to manage extreme events and water resources. The United Kingdom Water Resources Portal (UKWRP) has been developed to enable dynamic, interactive access to hydro-meteorological data across the United Kingdom, including catchment daily rainfall (near), real-time daily mean river flows, groundwater levels, real-time soil moisture data, and standardised climate indices. The UKWRP offers a way of exploring the full range of river flow and rainfall variability, including comparing current conditions to those in the past, from droughts to floods. A variety of different plotting capabilities mean users can view and explore data in different ways depending on their requirements. Here we discuss the mechanisms and the engagement undertaken to develop the UKWRP, in addition to the technical issues and solutions of bringing multiple data sources and types together, how the data are processed, stored and published to deliver an integrated tool for water resources management. The UKWRP enables all water users–from farmers, to water companies to members of the general public–to view and explore the data used by regulators to manage water supplies. We demonstrate how the UKWRP can be used to monitor the hydrological situation, using recent examples of both floods and droughts, and enables consistent messaging and universal access to data and information. Finally, we discuss the decisions the information provided in the UKWRP can support, and possible future developments. The UKWRP is aimed at the United Kingdom water research and management community, but we envisage that the Portal (and the development pathway and technical solutions reported here) could provide a useful exemplar for similar systems in other international settings.

Keywords: water resources, early warning, status monitoring, drought, floods

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1 INTRODUCTION

Hydrological data are the foundation of effective water resources management and underpin decision-making across a wide range of sectors. The acute water management problems of the 21st Century, from national through to global scales, can only be tackled through improved access to hydrological data, of appropriate quality and with the requisite timeliness needed to support decision-making on the ground (e.g. Dixon et al., 2020). Increasingly, there is a need for hydrological datasets (including rainfall, river flows, groundwater levels and soil moisture) to be available ever closer to real-time, and at very high spatial resolutions to support local-scale decision making. At the same time, new monitoring technologies and informatics tools are enabling rapid advances in the delivery of hydrological data when and where it is needed (Tauro et al., 2018). There is therefore a need for systems that capitalise on this potential, operating at the interface between hydrometric monitoring systems, and data users and decision-makers. Such systems should provide a seamless pipeline from raw data captured by sensing technologies through to actionable information provided with the latency needed by users. Crucially, the development of such systems should be an iterative process of co-design and co-development engaging both data providers and data users to ensure they are fit for purpose and support management systems (Hannaford et al., 2019; Grainger et al., 2021).

To this end, monitoring and early warning (MEW) systems are a particularly important pillar of effective water resources and hazard management (e.g. Wilhite, 2014). A recent World Meteorological Organization (WMO) report on the state of climate services internationally (World Meteorological Organization, 2020) notes that "*As climate change continues to threaten human lives, ecosystems and economies, risk information and early warning systems are increasingly seen as key for reducing these impacts*". The report goes on to say that in many parts of the world, such systems are deficient and require significant investment to make them fit-for-purpose. MEW systems enable timely provision of hydrological datasets to users, who need hydrological status to be characterised and put into historical context (e.g. by comparing the severity of the current flood or drought compared to past events). Quantifying and characterising current water resources status is a necessary prerequisite for applying appropriate and timely mitigation measures (e.g. those identified in drought or flood risk management plans) to avoid impacts. MEW systems are thus a vital part of our response to hydrological hazards–they are essential for proactive flood and drought management and a key part of disaster preparedness. This has led to a proliferation of MEW systems relevant for hydrological hazards, at a range of scales from river catchment through national to continental and even global (see for example the reviews of Pulwarty and Sivakumar, 2014 and Hao et al., 2017).

However, MEW is not just relevant for extreme hydrological events–water managers need to track water resources status across the entire hydrological spectrum from floods to droughts and all points in between, on a range of timescales from sub-daily through to annual and beyond. Knowledge of current water resources status is vital for a wide range of purposes including, for example: water allocation and abstraction licensing; appraising potential impacts on aquatic ecology; water quality assessment and so on. Many of these aspects are crucial to the day-to-day operations of 'statutory' stakeholders like water service providers, government agencies and regulators, etc. However, such information is also of fundamental importance to a very wide range of water users, including, but not limited to: farmers and growers; water dependent industrial or commercial businesses; power generation agencies; navigation; recreational users (e.g. canoeing, angling); conservation groups; catchment management partnerships; and more widely, citizens and communities with concerns about their local environment/ watercourse.

The United Kingdom (UK) has a very well established hydrological monitoring programme and is very densely monitored by international standards. The UK also has very well established MEW systems and other tools for tracking water resources status. The National Hydrological Monitoring Programme (NHMP)[1], operated by the UK Centre for Ecology & Hydrology (UKCEH) and the British Geological Survey (BGS), has provided an accessible, independent monthly "Hydrological Summary for the UK" since 1988 that reports on rainfall, river flows, groundwater and reservoir stocks, as well as notable temperatures and soil moisture deficits. Similarly, the UK regulatory agencies provide similar "Water Situation Reports" that are comparable in scope and appearance to the Hydrological Summary for the UK. UKCEH, BGS, the UK Met Office and these agencies also produce the "Hydrological Outlook UK" (Prudhomme et al., 2017), a monthly hydrological seasonal forecasting service, operational since 2013. There are also very sophisticated systems for flood warning run by the Great Britain regulators (i.e., Environment Agency in England, Scottish Environment Protection Agency and Natural Resources Wales)[2].

With the exception of the latter real-time, web-based flood warning services, a common thread of all these MEW products is that they are static pre-formatted reports prepared on a monthly basis. Until recently, there were no national UK-scale real-time, dynamic tools available for water resources status assessment. There has long been a need for improved MEW systems (Hannaford et al., 2019), especially in the context of climate change and an evolving policy landscape (Robins et al., 2017). This paper describes the development of a novel, high-resolution interactive system for hydrological status monitoring for the UK, the UK Water Resources Portal (UKWRP)[3], which aims to address these gaps in UK MEW.

The UKWRP was launched in spring 2020 following a long period of iterative co-design and co-development with a range of stakeholders. This paper sets out to:

i) Describe the process of development, particularly the stakeholder engagement process,
ii) Present the Portal itself, including the datasets it includes, the informatics systems on which it is based, and the visualisations it offers,
iii) Provide examples of the potential applications of the Portal, and
iv) Describe potential future development of the Portal, much of which is already underway.

We present the UKWRP as an operational system delivering a step-change in hydrological status assessment and data integration more generally for the UK, and as an exemplar

[1]https://nrfa.ceh.ac.uk/nhmp.
[2]For example: https://flood-warning-information.service.gov.uk/warnings.
[3]https://eip.ceh.ac.uk/hydrology/water-resources/.

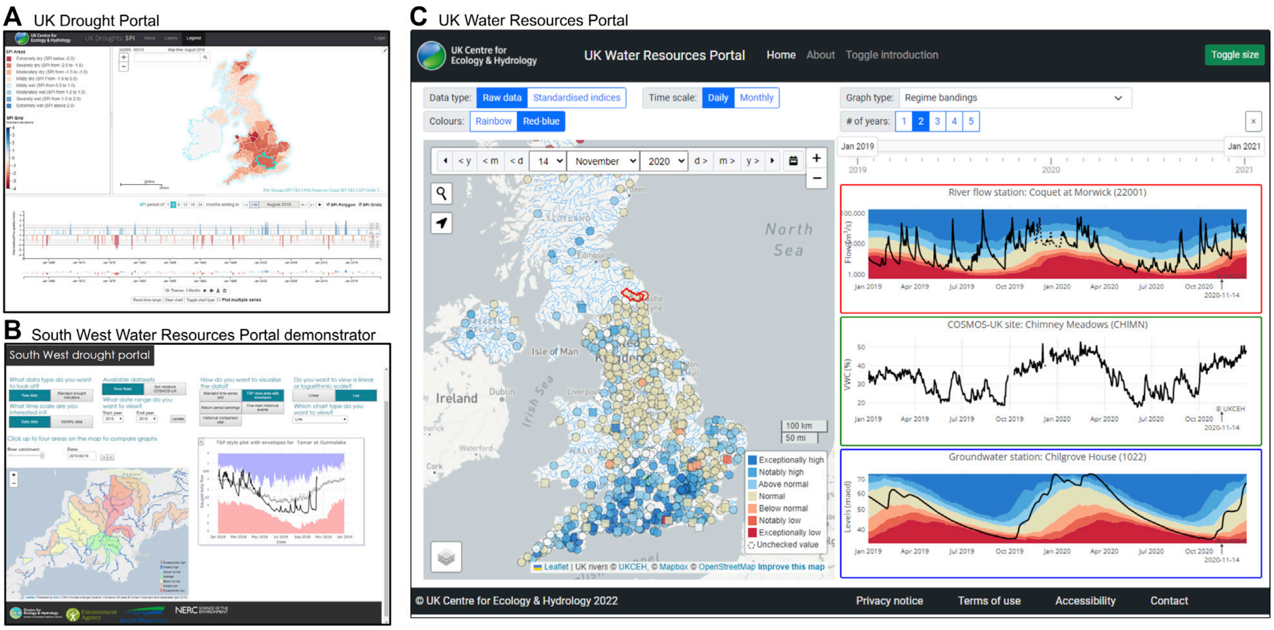


FIGURE 1 | Evolution of the UK Water Resources Portal: **(A)** screen shot of the UK Drought Portal showing the SPI-3 for the UK, **(B)** screen short of the South West Water Resources Demonstrator Portal showing river flow data from the south west of England; **(C)** screen shot of the UK Water Resources Portal showing map and time series data for the 14 November 2020 for river flows, soil moisture and groundwater levels at sites across England showing the default graph types in the red-blue colour scheme.

case study that we hope can provide important lessons for other hydrological data management and early warning systems in other contexts. While the UK is a particular case study, and a data rich environment at that, many of the challenges will resonate with other countries and settings, and the underlying principles (in terms of the design and stakeholder engagement process as well as particular data/informatics solutions) could be transferable elsewhere.

2 CO-DESIGN AND CO-DEVELOPMENT OF THE UKWRP

The UKWRP is the culmination of an iterative development programme that extends back to several workshops held in 2015 and 2016 as part of the DrIVER (Drought Impacts: Vulnerability thresholds in monitoring and Early-warning Research) project[4]. This stakeholder engagement exercise, summarised in detail in Hannaford et al. (2019), was focused on understanding the specific drought MEW needs in the UK, and scoping out potential enhanced MEW systems for the future. Although the broad spectrum of responses reflected the diversity of sectors represented (including government, regulators, water supply companies, agriculture, the environment and public health), there were some similarities. Users wanted a drought MEW system that:

- Provided information about different types of drought, from meteorological, to hydrological, to agricultural,
- Showed information at a range of spatial scales, from the local, field scale, to the regional and national scale,
- Showed information for a range of time scales, from droughts at the 1 month scale, to the annual or multi-year scale,
- Compared current conditions with those from historic drought events, and
- Was open and accessible for all, enabling consistent messaging between government departments, regulators, water companies and other organisations.

Crucially, around the time of the first workshop we developed a prototype drought-focused MEW system, the UK Drought Portal[5] (UKDP, shown in **Figure 1A**), a demonstrator developed as a showcase of "what's possible" for drought MEW in the UK. Although the UKDP at the time was not strictly a MEW system as it was not updated monthly (this was added in 2017, as discussed below), it demonstrated the potential of a web-based system to allow interactive mapping and time series visualisation of the current drought situation compared to historical conditions.

There are many drought indicators and indices that have been developed and applied in the academic literature (Lloyd-Hughes, 2014), but the UKDP adopted the Standardised Precipitation Index (SPI; McKee et al., 1993). The SPI was selected because: 1) it

[4]https://www.ceh.ac.uk/our-science/projects/driver.

[5]https://eip.ceh.ac.uk/apps/droughts/.

can be compared across both space and time; 2) it can be calculated for different, user-defined accumulation periods (McKee et al., 1993); and 3) comparable standardised indices for other variables such as river flows and groundwater are available (e.g. Standardised Streamflow Index (SSI), Vicente-Serrano et al., 2012; Standardised Groundwater Index (SGI), Bloomfield and Marchant, 2013). These three characteristics directly address some of the requirements stated by stakeholders listed above and discussed in Hannaford et al. (2019). The SPI is also recommended by the WMO for meteorological drought monitoring (Hayes et al., 2011).

Prior to its use in the UKDP, the SPI and other standardised indices had not been widely used in the UK, particularly in operational settings for water and drought management (Barker et al., 2016). As such, in parallel with the stakeholder engagement process and the development of the UKDP, a number of scientific studies were undertaken using the SPI and related standardised indices. Firstly, investigating the most appropriate probability distributions to fit to UK rainfall and river flow data when calculating the SPI and SSI, respectively (Svensson et al., 2017); and secondly, assessing what the SPI and SSI showed in terms of drought characteristics and drought propagation from meteorological to hydrological drought in near-natural UK catchments (Barker et al., 2016).

The UKDP provided interactive access to SPI data at the gridded scale (5 km; Tanguy et al., 2015) as well as river basins (specifically, "Integrated Hydrological Units", IHUs; National River Flow Archive, 2014; Tanguy et al., 2017b, Tanguy et al., 2017c)—meeting stakeholder criteria for data and information at the local and national scale. Users were able to view maps and time series graphs of SPI for individual grid cells or river basins enabling a comparison with historic events; as well as downloading timeseries of SPI for their selected location (catchment or grid cell). The UKDP was made operational as a true MEW system, with monthly updates of SPI from June 2017. Although the UKDP provided open access to the SPI at a range of spatial and temporal scales, it only offered SPI data, meaning users were only able to directly monitor meteorological droughts. At the second DrIVER workshop (held in November 2016) mock-ups were made of the UKDP to include river flows and groundwater levels shown as SSI and SGI data (see Hannaford et al., 2019). Positive feedback was received from a wide range of stakeholders, which emphasised the benefit of advancing the UKDP concept and expanding it to include other variables and indices.

In late 2017, a further phase of development commenced, funded through the ENDOWS (Engaging diverse stakeholders and publics with outputs from the UK Drought and Water Scarcity Programme) project[6], which aimed to expand the UKDP by including monthly updates of river flows and groundwater levels. At the time however, a major limitation was the difficulty of obtaining timely up-to-date river flow and groundwater level data at the national scale. The UK regulators (the Environment Agency (EA; England), the Scottish Environment Protection Agency (SEPA), Natural Resources Wales (NRW) and the Department for Infrastructure Rivers (DfIR; Northern Ireland) operate independent archives, and even within each organisation with a centralised hydrometric archive there were significant challenges in data provision. Consequently, static MEW efforts (e.g., the NHMP monthly Hydrological Summary for the UK) relied on a number of manual data transfers. Fortunately, in late 2017 the EA commenced a programme of releasing its daily river flow data through the Hydrology Data API[7] in near real-time, as part of a wider Open Data initiative. This offered up the prospect of building the next generation of the UKDP in a way that could exploit such live data feeds.

The EA Hydrology Data API was released in stages, with an initial pilot in Devon and Cornwall in southwest England released in 2018. To accommodate this, we developed a demonstrator portal for this region, as a collaboration with the EA and a private water company, South West Water - the South West Water Resources Demonstrator Portal (shown in **Figure 1B**). As well as building on the concepts of the UKDP to incorporate additional variables to rainfall indices, this demonstrator explored how we could access and visualise the new live river flow data from the API. Crucially, the South West Water Resources Demonstrator Portal was co-developed with stakeholders, facilitated through a series of meetings and exchanges. This allowed us to accommodate the stakeholder feedback on functionality and suggestions of potential new approaches to visualisation–for example, ensuring we presented graphs in manner that resonated with water industry and regulatory users (the "regime bandings", and historical analogue comparisons, see **Section 4**).

The South West Portal Water Resources Demonstrator Portal was developed throughout 2019. While it was focused on one region, it provided an example proof-of-concept that enabled engagement and testing with other users and sectors around the UK. An accelerated programme of software development and user engagement then commenced through 2018 and 2019, and the EA Hydrology Data API was rolled out to other parts of England throughout 2019. The demonstrator concept was expanded to cover the whole country, before the eventual release of the UKWRP as an operational product in March 2020 (shown in **Figure 1C**). Importantly, the UKWRP scope set out, right from the start, to include a range of hydrological variables, so in addition to accommodating river flows, it was designed to exploit soil moisture (made possible by the advent of real-time data from the COSMOS-UK network, described further in **Section 3.4**) and eventually groundwater levels from BGS.

The change of name from the UK "Drought" to "Water Resources" Portal reflected the shift away from simply characterising the drought hazard using standardised climate indices (such as the SPI). While still containing all the functionality of the original UKDP, users felt the UKWRP supported management and monitoring across the whole flow regime. An important caveat to note is that the UKWRP does

[6]www.aboutdrought.info.

[7]https://environment.data.gov.uk/hydrology/doc/reference.

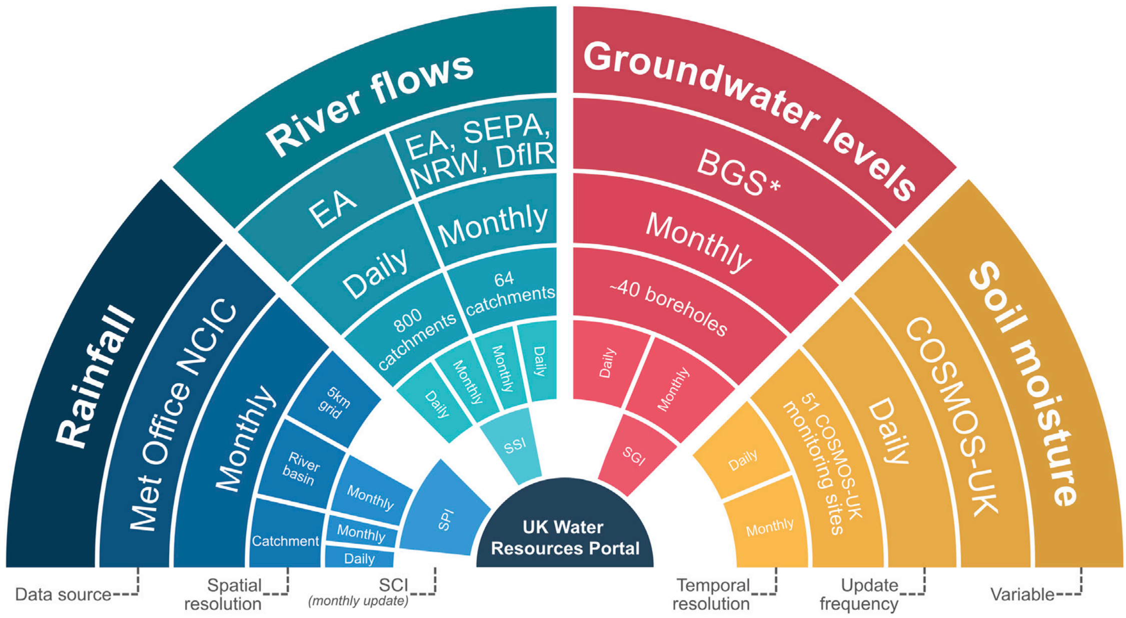


FIGURE 2 | Summary of the variables and associated metadata of data available in the UK Water Resources Portal, *Note that BGS collate data in the National Groundwater Level Archive collected by the UK environmental regulators.

not intend to provide flood status or warning information, as compared with the current national flood warning services mentioned above. It does, however, provide useful information during flood episodes, as illustrated in the case study below in **Section 6**.

Given the wide range of hydrological variables included, and the variety of presentation styles, early user engagement suggested that it offered the potential to be used for a wide range of water resources management purposes by a wide range of users. In addition to the early co-development in south-west England, extensive engagement and hands-on user testing was undertaken with a wide range of audiences, including (for example) workshops with the water industry (in April 2018 October 2018 and July 2019) and farmers and growers (November 2019), as well as with mixed audiences (e.g. at multi-sectoral stakeholder events in March 2018 and November 2019). Since the release of the UKWRP, bilateral discussions (e.g. with the Canal and River Trust, power companies and water companies), virtual engagements and webinars have also been undertaken (notably with conservation and catchment groups, e.g. the Rivers Trusts and Catchment Based Approach partnerships in April 2020). Some applications and feedback from this process are discussed in **Section 6**.

3 DATA

The UKWRP displays a range of variables and drought indices following feedback from stakeholders on the need to be able to monitor different types of drought as discussed above and in Hannaford et al. (2019). It provides access to rainfall, river flow, groundwater level and soil moisture data, in their raw, observed, form, but also as standardised climate indices (with the exception of soil moisture). Data can be viewed at a range of scales, enabling national and regional overviews, as well as catchment or field scale status assessments. The data available in the UKWRP is summarised in **Figure 2**.

3.1 Rainfall

Gridded rainfall data is provided and updated once a month by the National Climate Information Centre (NCIC) at the UK Met Office, from which additional products are derived; **Table 1** summarises the rainfall data available in the UKWRP. Portal users can view cumulative daily and monthly rainfall for gauged catchments, and monthly rainfall for generalised river basins (as represented by Integrated Hydrological Units (IHUs); National River Flow Archive, 2014). SPI data are available at the gridded (5 km resolution), gauged catchment or river basin scale, with historic data to 2015 available to download in Tanguy et al. (2017a), Tanguy et al. (2017b), Tanguy et al. (2017c). The SPI is calculated each month as described in McKee et al. (1993) using a reference period of 1961–2010 and the gamma distribution as set out in Tanguy et al. (2017a). The SPI is derived for different accumulation periods (1, 3, 6, 12, 18 and 24 months), providing precipitation anomalies over a range timescales from the monthly, to the seasonal and annual scale.

3.2 River Flows

River flow data for the UKWRP is provided by the UK regulators (i.e. EA, SEPA, NRW and DfIR). Historic river flow data are taken from the National River Flow Archive (NRFA) which are validated each year by a team of NRFA regional representatives and the corresponding UK regulator

TABLE 1 | Summary of rainfall data available in the UK Water Resources Portal.

Rainfall Data	Temporal Resolution	Period of Record	Raw Data (mm)	Standardised Precipitation Index (SPI)
5 km grid	Monthly	1862-present		✓
Catchments	Daily	1891-present	✓	
	Monthly	1891-present		✓
IHUs	Monthly	1862-present	✓	✓

(Dixon et al., 2013) which are published with a delay of one water year. In England, data for over 800 gauges are available via the EA Hydrology Data API[8], which is updated in near real-time, with data available within a couple of days of being recorded. A further 64 stations across Scotland, Wales, England and Northern Ireland are available with monthly updates (within the first 2 weeks of the month) provided by the regulators as part of the NHMP Hydrological Summary for the UK. All 864 river flow records are then processed each month to calculate the SSI using a reference period of 1961–2010 (in line with that used to derive the SPI) and fitted using the Tweedie distribution, found by Svensson et al. (2017) to have the best fit for UK river flow records.

3.3 Groundwater Levels

Groundwater levels are shown for ~40 boreholes across the UK from a range of aquifers and are updated within the first 2 weeks of the month. UK regulators provide data each month to the National Groundwater Level Archive at BGS as part of the NHMP Hydrological Summary for the UK. Where groundwater levels are automatically monitored each day, daily data are available; in some cases levels are manually measured each month and therefore data are not available for each day of the month. The SGI is provided each month by BGS and calculated using the methods set out in Bloomfield and Marchant (2013).

3.4 Soil Moisture

The UKWRP shows volumetric water content recorded at 51 COSMOS-UK (COsmic-ray Soil Moisture Observing System for the United Kingdom)[9] observation sites across the UK located on a range of soil and vegetation types (Cooper et al., 2021; Stanley et al., 2021). The COSMOS-UK network provides field-scale (up to 200 m) soil moisture observations in real-time using a cosmic ray soil moisture sensor (CRS). The CRS counts the fast neutrons from cosmic rays reflected by the earth's surface; fast neutrons are absorbed by hydrogen atoms in the soil (predominately in water molecules). A lower neutron count indicates a higher water content and by comparing current counts to background readings, can provide a measure of soil moisture (Evans et al., 2016; Cooper et al., 2021). The UKWRP shows the volumetric water content (%; VWC) which provides an absolute measure of water content in the soil, which at the extremes is determined by the soil characteristics and status is determined by the weather (Boorman et al., 2020). Soil moisture records from COSMOS-UK sites are relatively short, with the earliest records starting in 2013 and the shortest in 2019 (Stanley et al., 2021). COSMOS-UK data are transferred from each site by telemetry and daily data are available in real-time on the UKWRP, i.e. for the previous full 24 h (Evans et al., 2016; Boorman et al., 2020).

4 VIEWING DATA IN THE UKWRP

The data in the UKWRP can be viewed on a map for individual days or months for data points (i.e. river flow gauges, boreholes or COSMOS-UK sites) or spatial areas (gauged catchment or river basin rainfall in addition to grid cells for the SPI). These are coloured according to the status for the given day or month as characterised by the raw data or standardised climate indices. The main functions and tools within the UKWRP are summarised in **Figure 3**.

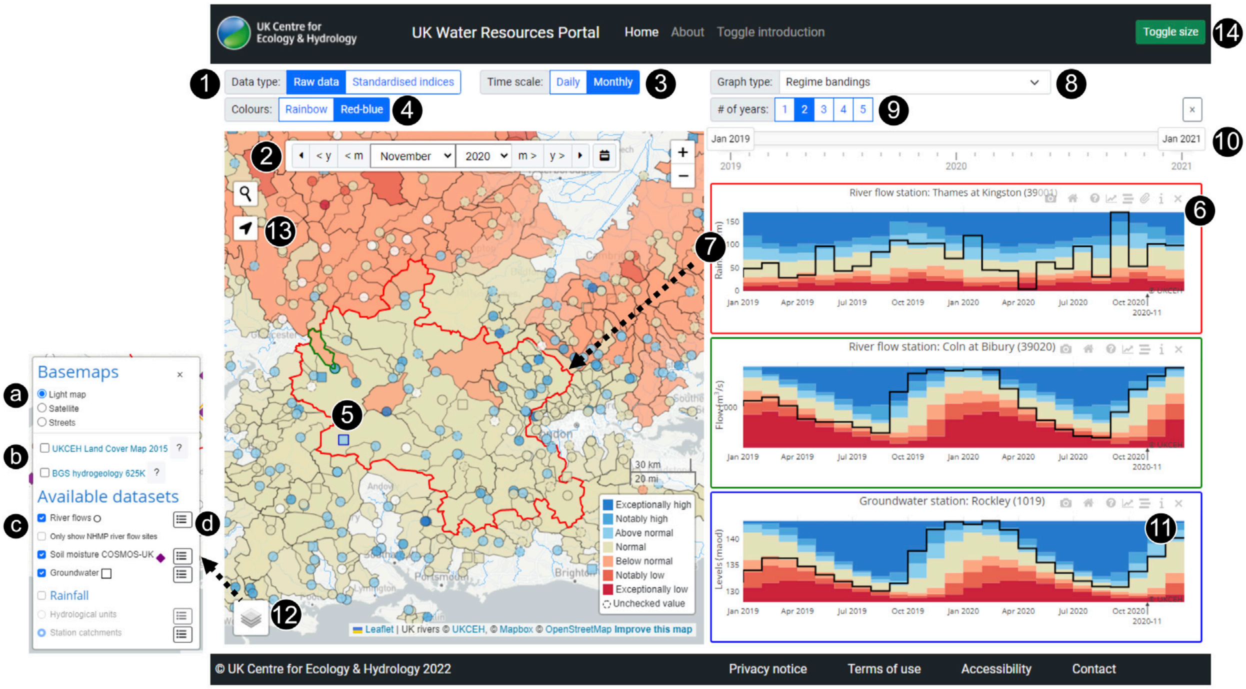
In the default view when the Portal is loaded the hydrological status is summarised using regime bandings, which assess whether data for the given day or month is in the normal range, above or below normal (e.g. as shown in **Figures 1C**, **3**). These regime bandings or categories are calculated by normalising the data for each site against its historic data, using a minimum of 20 years from start of the record to the end of December 2017 (currently). For each day, the values are ranked and the percentiles calculated (in the case of river flows, pooling all values in a 30-day period to reduce the influence of extreme daily values). The percentile values are then categorised to identify conditions that are: the normal range (28–72%), above/below normal (72–87%/13–28%), notably high/low (87–95%/5–13%) or exceptionally high/low (>95%/<5%). These bands correspond to those used in the Hydrological Summary for the UK.

For catchment rainfall this process is applied to the cumulative daily total from the start of the month, as this generally provides a more useful measure of the recent rainfall than a single daily value. For monthly data, monthly mean data (river flows and groundwater levels) or monthly total (rainfall) are used to calculate the bandings.

The date selector on the map allows users to step forwards and backwards in time to view how the hydrological status changes through time, and the temporal resolution of the map data and time series plots can switched from daily to monthly.

[8]https://environment.data.gov.uk/hydrology.

[9]https://cosmos.ceh.ac.uk/.



1. View either raw observed data or standardised climate indices

2. Use the date selector to change the date of the map data

3. View either daily or monthly data

4. View map and graphs in the default colour scheme (Rainbow) or the red-blue colour scheme

5. Click features to select locations to view data on a graph

6. View graphs for the selected features

7. Graph outlined in same colour as selected feature

8. Change the graph type for selected locations

9. Change the number of years shown in the time series graphs

10. Use the slider to change the date range of the graphs

11. View metadata for selected feature

12. a) Change base map, b) Add additional map layers, c) Show/ hide variables and d) Search for specific sites to view and download data

13. Search for a specific location or zoom to your location

14. Change the window layout and make map full screen width with graphs underneath

FIGURE 3 | Summary of UK Water Resources Portal functionality and features.

By clicking on individual features (e.g. catchments, boreholes, grid cells etc.), users can view time series data for up to four selected features (as shown in **Figures 1C**, **3**). The selected feature is highlighted with a red, green, blue or yellow outline and the corresponding time series plot is outlined in the same colour. With the exception of soil moisture, by default the raw data are plotted against regime bandings which show whether flows, groundwater levels, soil moisture or rainfall totals for the given day or month are in the normal range, above or below normal.

Stakeholder engagement with the EA and South West Water particularly noted the importance of a range of plotting styles which enable users to view data within the UKWRP in a way that means they can use it in conjunction with existing products, tools and processes as well as enabling comparisons to previous years or drought events. **Figure 4** shows the different types of time series plots available in the UKWRP for both raw data and the standardised climate indices. These include: 1) a simple time series plot, 2) a time series plot with the day/month recorded maximum and minimum and the long-term average as used in the NRFA/Hydrological Summary for the UK (raw data only), 3) regime bandings as described above which are used in the EA's Water Situation Reports regularly used by the water supply sector as well as other users (raw data only), 4) comparisons to five pre-selected major drought events, and 5) the option for the use to select up to 3 years of their choice. The latter two options were

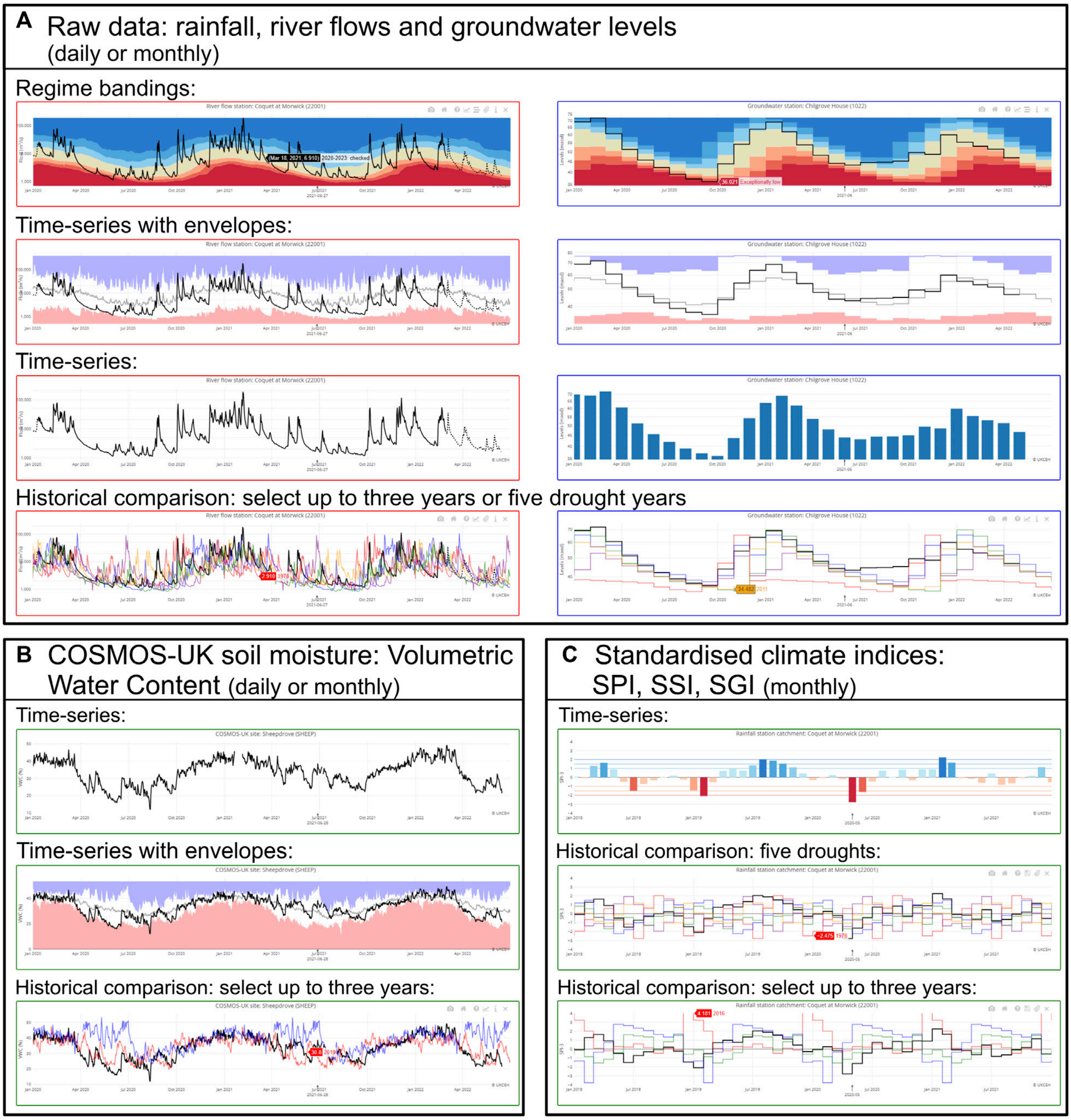


FIGURE 4 | Examples of plot types in the UK Water Resources Portal showing **(A)** daily river flow data for the River Coquet at Morwick and monthly groundwater levels at Chilgrove House, **(B)** soil moisture data for the COSMOS-UK site at Sheepdrove, and **(C)** SPI-3 for the Coquet catchment.

highlighted as being of particular importance by users. In practice, water managers routinely assess the current situation (especially in droughts) through comparison with past events–whether recent droughts known from lived experience, or 'droughts of record', i.e. severe historical droughts used in drought plans to test the resilience of water supply systems.

Figure 3 also highlights features which allow users to change the base map, add additional layers such as UKCEH Land Cover Map 2015 (Rowland et al., 2017a; Rowland et al., 2017b) or the BGS Hydrogeology 625 k map[10], as well as change the colour palette from the rainbow palette (used in existing products like the EA Water Situation Reports) to a red-blue palette which is accessible for (most) colour blind users. Individual graphs can be

[10]https://www.bgs.ac.uk/datasets/hydrogeology-625k/.

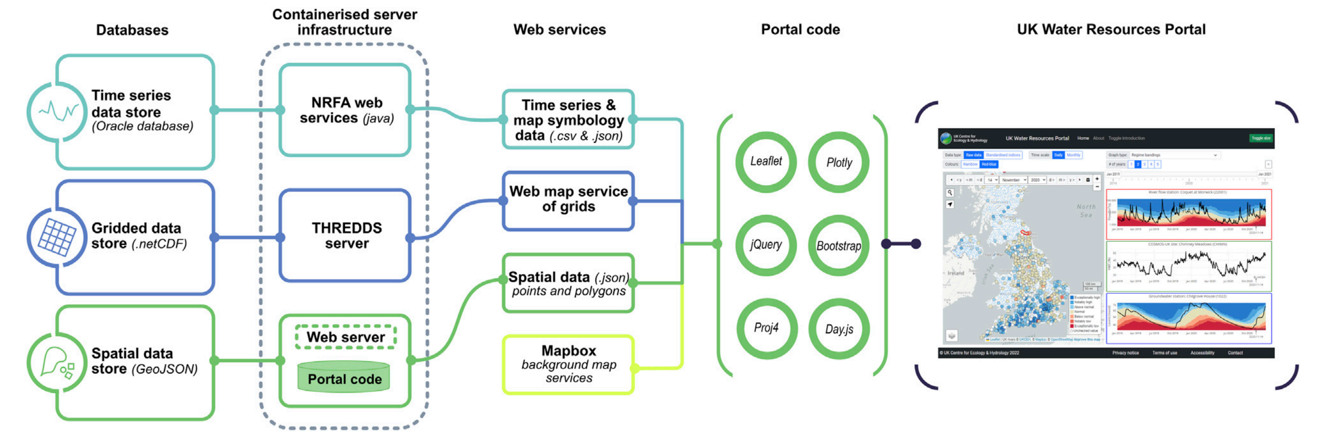


FIGURE 5 | Infrastructure, processes and libraries used to build the UK Water Resources Portal.

downloaded for use in reports, *y*-axes changed to from a log to a linear scale, and for river flows, the units changed from m^3/s to mega litres per day (Ml/d).

5 UKWRP INFRASTRUCTURE

The UKWRP is delivered through a combination of technologies to provide the functionality described in the section above. A summary of how these technologies are brought together is shown in **Figure 5**.

5.1 Database

The majority of the underlying data for the UKWRP is stored within UKCEH's Oracle database. River flow and rainfall for gauged catchments is stored within a database for the NRFA, and is also used to populate the NRFA website[11]. Historic river flow data within the archive is merged with real-time data downloaded from the EA Hydrology Data API, and updated on a daily basis. Rainfall series are derived and updated on a monthly basis from data provided by the NCIC. Data for COSMOS-UK stations is stored within a database for the wider COSMOS-UK monitoring project and is updated in near real-time from telemetry systems (Cooper et al., 2021), this database is also used to populate the COSMOS-UK website[12]. A specific database was created for additional data required specifically for the UKWRP such as the SPI and the other standardised climate indices. Each database is comprised of tables for the various spatial features displayed (i.e. river flow stations, groundwater boreholes, catchments, etc.) and their metadata, with separate time series tables for each type of feature. Monthly data series are pre-calculated and stored to improve the speed of delivery to the UKWRP.

Spatial datasets used within the UKWRP are largely static and as such as are accessed as files in GeoJSON format from a web server. These include boundaries for gauging station catchments relating to the locations at which flow data is displayed, and a more generic set of UK-wide river basins at two scales appropriate for different map zoom-levels (IHUs; hydrological areas—105 across the UK, and catchment groups—405 across the UK). Point locations for gauging stations, boreholes and COSMOS-UK soil moisture sites are available via web-services directly from the database.

The gridded SPI data is produced as monthly files in netCDF format and is managed using Unidata's Thematic Real-time Environmental Distributed Data Services (THREDDS) data server (TDS)[13]. TDS is an open source web server that supports netCDF formats and provides metadata and data access for scientific datasets using a variety of remote data access protocols. TDS also supports several dataset collection services including aggregation capabilities, which are used by the UKWRP to link all files in the whole time series by creating a single virtual dataset, thereby simplifying the access to the data collection, and the monthly update process.

5.2 Web-Services

With the exception of static catchment boundary datasets, most data within the UKWRP is delivered to the application via web services. RESTful-style services (REpresentational State Transfer; an approach to providing simple, lightweight and responsive access to information over the web using URLs) deliver time series data of river flow, rainfall, soil moisture and groundwater levels in JSON format from the Oracle database and are implemented in the Java programming language. Whilst these services are bespoke, they are effectively extensions of the NRFA API[14],

[11]https://nrfa.ceh.ac.uk/.

[12]https://cosmos.ceh.ac.uk/.

[13]https://www.unidata.ucar.edu/software/tds/.

[14]https://nrfaapps.ceh.ac.uk/nrfa/nrfa-api.html.

supplemented with additional information required for use within the Portal. Three separate web service concepts deliver this data for each data type:

1 A JSON metadata service containing site location data for mapping as well as site name, and related information,
2 A site-time series service providing a csv format time series for plotting data within graphs and delivering downloads, and
3 A date-specific service providing data for all sites for a requested date (day or month) used for defining the colour and value of the sites on the map.

Gridded SPI data are delivered from the TDS using its standard Web Map Services (WMS) functionality that provides images of the data over the selected area. Time series for the gridded data are also accessed via WMS for a selected grid cell. Web services are also used to deliver contextual background mapping (from a commercial provider) as well as hydrologically-specific layers of rivers (from UKCEH 1:50 k river network), land cover (UKCEH Land Cover Map 2015, 1 km dominant class) and hydrogeology (British Geological Survey 1:625 k hydrogeology) from an ArcGIS server instance.

5.3 Web Application

The Portal interface is a bespoke JavaScript application, using Leaflet for mapping (with the PROJ library for handling projections), Plotly for graphing, and other widely used libraries including jQuery and Bootstrap. Catchment boundary geometries are simplified for faster rendering within the map. Graphing functionality is tailored specifically for this application (e.g. adding log/linear options for *y*-axes) and limiting some of the available Plotly options. In particular, the Plotly graph zooming is disabled and instead the graph *x*-axes are linked to a custom slider control which synchronises the graphs and means data for the selected features can be compared. Each graph can be exported as an image file by the user; and data downloads for selected sites are also enabled, using a simple csv format that includes full site metadata.

6 BENEFITS AND APPLICATIONS OF THE UKWRP

The UKWRP enables (near) real-time access to rainfall, river flow, groundwater level and soil moisture data for the UK at a range of spatial and temporal scales. This means that hydrological status monitoring information are freely and easily accessible to all, whether a water manager or water user (from farmers, business owners to members of the general public). The data availability and the Portal functionality deliver key MEW information for a range of users and applications in the context of water and drought monitoring and management. Quotes from users in **Table 2** highlight some of the benefits and practical applications of the UKWRP that are discussed below. Some of these quotes pertain to the UKDP, the predecessor to the UKWRP described in **Section 2**—however, this functionality has been entirely subsumed into the UKWRP. The UKDP has been operational for longer, and was available during the significant drought in 2018. The UKDP has had a total of 11,750 page views since its operational release in June 2017 to the end of July 2021. In contrast the UKWRP, with the addition of real-time data and more variables, was viewed 16,647 times between March 2020 and July 2021—an average of over 1,000 users per month.

Live river flow data in England enables abstractors to view the same local scale data that is being used by the EA to monitor abstraction license conditions, meaning they can have greater confidence in when they are able to abstract water as well as help to plan ahead for potential abstraction restrictions. The real-time data available in the UKWRP provides much greater granularity and information at the local scale–this is beneficial for the agricultural sector, for example, where conditions can rapidly change in both time and space (as highlighted in **Table 2**). In addition to specific applications such as these, live river flow data in England on the UKWRP provide easy access to the real-time data, for all water, or river, users–for example, for assessing when conditions are suitable for canoeing, kayaking or angling etc.

The standardised climate indices included in the UKWRP, such as the SPI and SSI, form part of operational drought monitoring undertaken by water companies (e.g. Anglian Water where these indices form part of the drought management triggers set out in their drought plan; Anglian Water, 2021), and where the SPI is routinely used to prove exceptional shortage of rain supporting statutory drought permit applications (as highlighted in **Table 2**). The national coverage of the data means that even though the UKWRP datasets do not currently meet the statutory regulations for inclusion in drought permit applications (Environment Agency, 2021) those preparing applications can rapidly check local and regional figures against those seen at the larger scale and assess the severity of the rainfall deficits in the wider spatial context. The data used in these cases can be viewed in the local or regional context to support local scale decision making, but the availability of national scale data mean these data, and local scale situations can be viewed in the broader context. This 'big picture' view can be particularly beneficial when considering large-scale management options, such as bulk water transfers, or for supply chains affected by drought in one or more parts of the country.

The UKWRP not only provides access to an integrated assessment of current water resources at a range of spatial scales, but also allows the user to: compare current conditions to those of the past as highlighted in **Table 2**–whether by using the different graphing options (described in **Section 4**) to compare to previous high flow or drought events; explore the severity and spatial extent of past hydrological extremes; or view the full time series of the standardised climate indices (which are available for the period of record for the individual sites for SSI and SGI, or each rainfall dataset as shown in **Table 1**). The functionality and visualisation of the standardised climate indices is very similar to that used in the UKDP to ensure that established users of the UKDP could switch to the UKWRP without any loss of functionality. The benefits of national scale data, live data, a range of variables and historical comparisons available in the UKWRP are well demonstrated using case studies

TABLE 2 | User quotes on the UK Drought Portal and UK Water Resources Portal from AboutDrought (2021).

a) "*The way he can be helped in the future will be by having more information on what the flow is like in his river and what might happen at an earlier stage—just knowing that a week in advance could have avoided this situation. We would like to see more value added to the research programme to give users that extra granularity in information. If they know something is going to happen, even just 1 week's warning will be helpful. The challenge for us all is that water availability is so localised—but it is also a great opportunity for people to understand that the power of some of About Drought's research outputs is such that it can go down to a reasonably local level and that's exactly where we need to get.*" National Water Resources Specialist, National Farmers Union
b) "*I used the Drought Portal during the 2018 drought to illustrate aspects of the unfolding hydrological situation. The Drought Portal was useful in showing how serious the situation was compared to other time periods and highlighting the spatial extent of the drought. Data from the Drought Portal was used alongside other evidence on drought permit applications to the Environmental Agency in the winter of 2018/2019*." Senior Hydrologist, Yorkshire Water
c) "*We use the Portal, mostly (perhaps obviously) when water resources are tight. We manage a network of 2,000 miles of waterway, so in a drought event we need to balance resource use very carefully across multiple sources on each canal system. In a more severe event we manage increasing restrictions and then the closure of canals, and justifying that to internal and external stakeholders is often backed up by summary stats from the Portal. Just knowing the severity of an event is really useful for placing our own datasets in the correct context, for example when comparing against other drought years. Knowing the data are robust and reliable is really important and helpful*." Principal Hydrologist, Canal & River Trust
d) "*I found the tool both easy to use and understand. I thought it was an ideal tool (that was very timely too for the 2018 dry weather) that presented the data clearly in a pictorial way. This was very useful in showing the stark differences between the 2018 event and the benchmark 1976 drought once this information had been gathered*." Hydrologist, Natural Resources Wales

including the 2018 drought and the change from wet to dry conditions in 2019/2020.

The severity and impacts of the 2018 drought are well documented for the UK (Turner et al., 2021) and other parts of Europe (e.g. Bakke et al., 2020). Engagement with users (e.g. **Table 2**) demonstrated that the UKDP available at that time (now effectively replaced by the UKWRP) provided a useful tool to explore and compare conditions to those of the past. A key characteristic of 2018, was that although the summer was notably hot and dry, it was part of a longer term period of below normal precipitation, beginning in the winter of 2015/2016 (Turner et al., 2021). Long-term precipitation deficits (to varying degrees of severity) were evident in the 12–24 months accumulation periods of the SPI in the summer of 2018 (e.g. as shown for river basins in **Figure 6A**), with long-term deficits also evident in river flows and groundwater levels in the SSI and SGI, respectively).

The benefits of the live data capabilities of the UKWRP were also highlighted in February 2020, when intense rainfall brought by a sequence of frontal systems contributed to the wettest February on record (in a series from 1910; Parry et al., 2020; Sefton et al., 2021). River flow data for the ~500 gauges in England available at the time were updated within several days of the observation being recorded, and showed the rapid response of river flows to the intense rainfall. **Figure 6B** shows the UKWRP in late February 2020, showing exceptionally high rainfall and notably high river flows and groundwater levels in north-west England. This exceptionally wet start to 2020 was swiftly followed by an exceptionally dry spring (e.g. **Figure 6C**; Sefton et al., 2020; Turner et al., 2020), which in turn was followed by a wet start to the summer (Barker et al., 2020). Again, the dynamic features of the UKWRP demonstrated its utility in comparison to the static reports available at the time (such as the Hydrological Summary for the UK and EA Water Situation Reports), enabling users to step through time, view data for different variables and accumulation periods and in different formats and graphing styles.

The innovations and benefits of the UKWRP, and the functionality within, are also clear when compared to other status monitoring tools and products from around the world. Many hydrological data explorers and status assessment tools tend to show or visualise one dataset/time series at once (e.g. Australian Water Outlook[15]) and/or provide static maps or graphs. One exception is the USGS National Water Dashboard[16], which provides access to a range of data from meteorological and hydrological monitoring stations across the United States *via* an interactive portal. However, it uses only one plotting style with simple time series graphs, with categories and bandings shown on the maps not shown on the available graphs. There are a significant number of drought specific monitoring products around the world, as catalogued by the Integrated Drought Management Programme[17], including the US Drought Monitor (Svoboda et al., 2002), Czech Drought Monitor (Trnka et al., 2020), Drought Management Centre for Southeastern Europe[18] and the predecessor to the UKWRP, the UK Drought Portal. While their drought focus is intended by design, and confers some advantages for drought-specific applications (see below), it inhibits the use of such products for monitoring across the flood-drought continuum. Very often these are static products (e.g. the USDM which can be viewed at the national and state scale), with limited user choice or flexibility, and/or are reliant on modelled data (e.g. the SPEI Global Drought Monitor[19] and the German Drought Monitor[20], Zink et al., 2016). In the UKWRP we present a flexible tool, which allows users to select the data type, variable, spatial and temporal scale of interest as well as the option to select how to view the selected data. This

[15]https://awo.bom.gov.au/.
[16]https://dashboard.waterdata.usgs.gov/app/nwd/.
[17]https://www.droughtmanagement.info/pillars/monitoring-early-warning/.
[18]http://www.dmcsee.org/en/drought_monitor/.
[19]https://spei.csic.es/map/maps.html.
[20]https://www.ufz.de/index.php?en=37937.

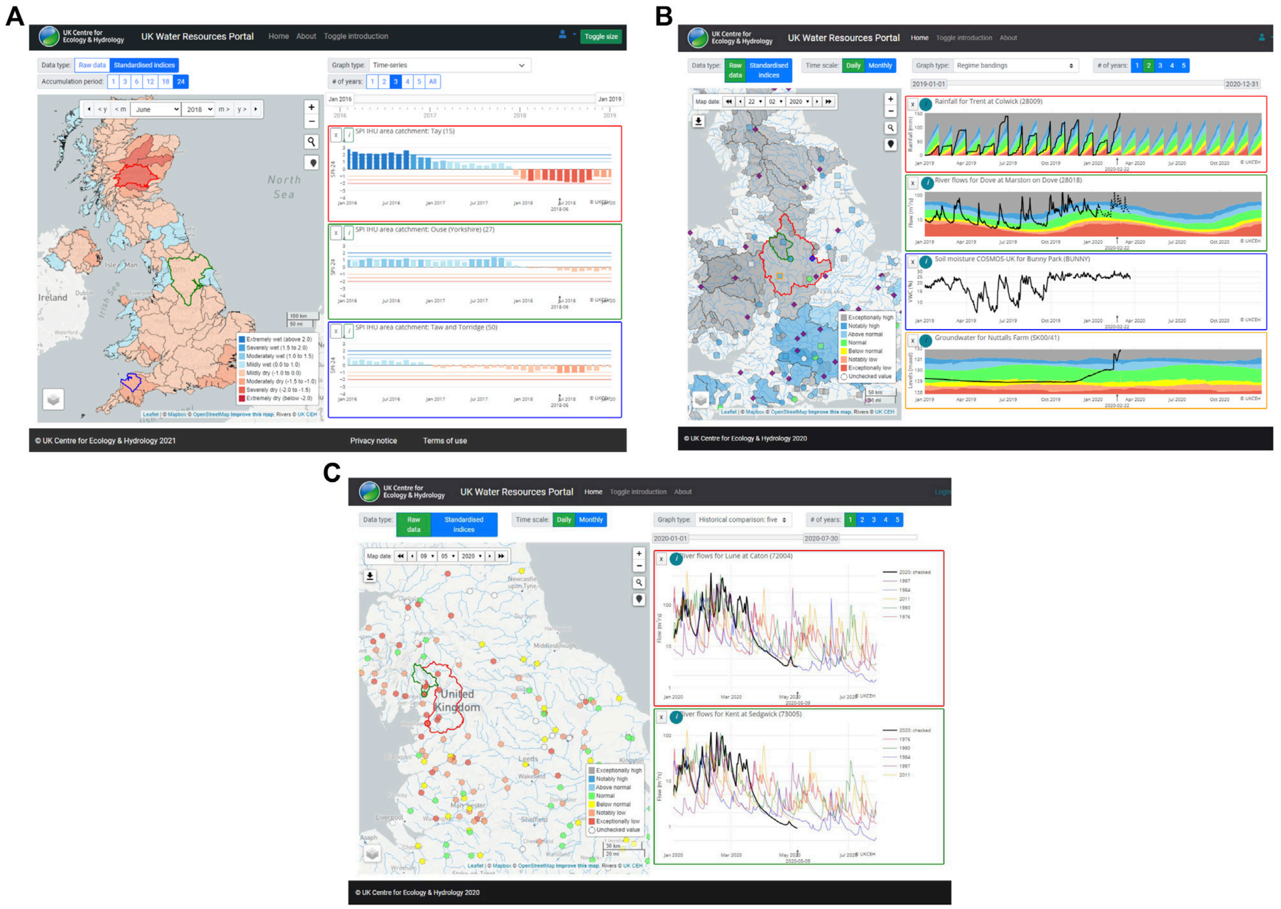


FIGURE 6 | Screenshots of the UK Water Resources Portal showing **(A)** SPI-24 data for June 2018 for river basins, **(B)** rainfall, river flow, soil moisture and groundwater level data for February 2020 and **(C)** river flows compared to past drought events in May 2020. *Note that the user interface has changed slightly since screen shots* **(B,C)** *were taken in 2020.*

means the information can be used by various sectors and for different applications, as discussed above. The generic, extensible informatics architecture (**Section 5**) also means that it is also straightforward for new variables/indicators to be added, as evidenced by the growth of the UKWRP until now and the prospects for future evolution (**Section 7**).

Unlike other tools, such as the USDM, the UKWRP is not embedded into a particular operational decision-making framework–for example, it does not link directly to drought triggers or assistance payments. Rather, it is aimed at, and used by a wide range of users as demonstrated in **Table 2** and noted above. The UKWRP is designed specifically to support decision-makers through the visualisations on offer (most notably the UK regulators and water industry by adopting flow regime bandings comparable to those used in decision-support and for example in the EA Water Situation Reports). The data and information within the portal is also referred to in water company drought plans (e.g. Southern Water, 2019a; Southern Water, 2019b; Anglian Water, 2021) and drought planning guidance provided by regulators in Wales (Natural Resources Wales, 2017).

7 FURTHER DEVELOPMENTS

The structure of the UKWRP and supporting databases mean that as more APIs become available from the UK environmental regulators there will be further developments to include more real-time data for river flows and groundwater levels, for example, real-time river flow data for Scotland via the SEPA time series data service[21]. Similar developments are in progress for adding real-time rainfall data in collaboration with the UK Met Office, whilst noting the additional challenges in updating the gridded products (from which catchment rainfall, for example, is derived) in real-time, which are currently updated at the monthly scale.

There are also opportunities for possible additions to the UKWRP to enhance its MEW capabilities. However, any future additions to the UKWRP will need to balance complexity of the user interface and usability whilst still meeting user needs, with options for developing specific services for individual user groups/sectors. There are a number of considerations to be borne in mind when

[21]https://timeseriesdoc.sepa.org.uk/.

making such decisions on further inclusion (e.g. including measured versus modelled data) so the following sections illustrate likely types of data that can be included, rather than any specific datasets. Furthermore, some of these developments are separate portals developed in parallel with the UKWRP (e.g. the Hydrological Outlook UK Portal) but using the same informatics systems, and which may be integrated in future or kept distinct–in effect this section provides a blueprint for further development of the UKWRP and related tools.

New variables from earth observation data: earth observation (EO) data provide the opportunity for consistent, national coverage of data–something that is not possible using ground observed data, particularly when considering variables such as vegetation condition indices (such as NDVI, VCI and VHI) that are not routinely monitored *in situ*. These indices are of particular interest for agricultural and environmental sectors, and the real-time nature and national coverage are advantageous for agricultural drought monitoring (which can start very quickly and have quite localised impacts) and associated impacts on crops and the terrestrial ecosystem (e.g. Bachmair et al., 2018).

Standardised Evapotranspiration Index (SPEI): the addition of the SPEI to the UKWRP would provide more comprehensive information on the water balance–this could be of particular use and interest in the south-east of England (e.g. Barker et al., 2016). Currently, data availability means that it is more challenging to calculate potential evapotranspiration in near-real-time based on observations. However, it is hoped that in the future, this would become possible, either through the use of remote sensing data or if the driving data necessary to calculate potential evapotranspiration (PET) becomes available in real-time.

Gridded datasets to "fill the gaps": as well as EO data, hydrological models can also provide continuous fields that show spatiotemporal variability in "ungauged" areas not captured by the *in-situ* monitoring networks that make up the UKWRP at present (only precipitation is currently included as a gridded dataset). This is especially important for soil moisture. While COSMOS-UK provides a step-change in soil moisture sensing, there are still only ~50 sites across the UK. However, COSMOS-UK can provide ground-truth for EO or model-based datasets that enable users to fill in the gaps. Several new soil moisture datasets are being developed within UKCEH, including a blended EO/model-based product (Peng et al., 2021) and a gridded model-based subsurface dryness map currently released as a static product within the Hydrological Outlook UK. Such products are being considered for inclusion on the UKWRP (and allied Hydrological Outlook UK Portal, see below) in the future–although as with EO data, uncertainty of model outputs is an important constraint.

Reservoir stocks: many parts of the UK are reliant on surface water stored in reservoirs for domestic and industrial water supplies. In the past, reservoir stocks were not shared publically, with the exception of data in static reports such as the Hydrological Summary for the UK or EA Water Situation Reports, however, in recent years, more data have been made available online. These data could be included in the UKWRP, again allowing users to compare current conditions to those of the past. However with the inclusion of reservoir data, it would be important to note changes in capacity, management or the impact of maintenance on available supplies.

Drought impact/incident data: stakeholder engagement on drought monitoring and early warning in the UK highlighted the need for a better understanding of when and where drought impacts occur (Hannaford et al., 2019). A range of impact and incident data and information are currently collected by, for example, the environmental regulators (e.g. water quality and macroinvertebrate monitoring data released via EA APIs), water companies and other organisations as well as via citizen science initiatives (such as CrowdWater[22] and the Bloomin' Algae app[23]). In the future, these could potentially be collated and shared via the UKWRP to provide water managers and decision makers additional information on the impact of the current conditions on society, the environment, agriculture, industry and so on.

Seasonal forecasts: in addition to better understanding of how severe the current conditions are, unsurprisingly stakeholders were interested in what was coming next (Hannaford et al., 2019). Correspondingly, a separate portal to view and explore outputs from the Hydrological Outlook UK[24] (Prudhomme et al., 2017) has now been released[25]. This portal includes seasonal river flow forecasts from each of the Hydrological Outlook UK methods. The two Portals (i.e. UKWRP and Hydrological Outlook UK) are separate entities by design as the UKWRP contains observations, while the Hydrological Outlook UK Portal necessarily employs a range of statistical and process-based models. However, the design of the Hydrological Outlook UK Portal is very similar to the UKWRP in terms of interactivity, mapping and time series visualistion. Many of the same catchments are available in both the UKWRP and the Hydrological Outlook UK Portal, and links between the two portals enable the forecasts to be visualised for the next 3 months (up to 12 months) in the context of the current conditions by toggling between the two.

The development of the UKWRP has fed into and supported the development of other tools, such as the Hydrological Outlook UK Portal mentioned above, but also a global Hydrological Status and Outlook System (HydroSOS) demonstration portal[26] within the World Meteorological Organization (WMO) HydroSOS initiative[27], the implementation phase of which was approved in 2021. Through this work HydroSOS is demonstrating how data on hydrological conditions from a range of scales, from global to national and regional, can be blended to provide the best information for monitoring global surface and groundwater status (Jenkins et al., 2020). The development of the UKWRP is helping to understand how information produced to meet national requirements can also deliver information through a federated "system of systems" to improve understanding of water resources at a global scale within a global system such as HydroSOS.

[22]https://crowdwater.ch/en/start/.
[23]https://www.ceh.ac.uk/our-science/projects/bloomin-algae.
[24]https://hydoutuk.net/.
[25]https://eip.ceh.ac.uk/hydrology/outlooks/.
[26]https://eip.ceh.ac.uk/hydrology/HydroSOS/.
[27]https://public.wmo.int/en/our-mandate/what-we-do/application-services/hydrosos.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

This paper was written by LB, JH, and MF, with contributions from GN, MT, and OS.

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