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Physically-based modelling of UK river flows under climate change

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This study presents the model setup and results from the first calibrated, physically-based, spatially-distributed hydrological modelling of combined land cover and climate change impacts on a large sample of UK river catchments. The SHETRAN hydrological model was automatically calibrated for 698 UK catchments then driven by the 12 regional climate model projections from UKCP18, combined with urban development and natural flood management scenarios. The automatic calibration of SHETRAN produces a median Nash-Sutcliffe efficiency value of 0.82 with 581 catchments having a value greater than 0.7. 24 summary metrics were calculated to capture changes to important aspects of the flow regime. The UKCP18 realisations in SHETRAN indicate that a warming climate will cause river flows, on average, to decrease. These decreases are simulated to be greatest in the south and east of the UK, with droughts becoming longer and more severe. While high flows also decrease on average, an increased number of extremes are exhibited, implying a greater number of extreme flood events in the future, particularly in the north and west of the UK. In the urban development scenarios, for flood events there is an increase in flow with the increased urbanization, with the 1 in 3-year peak flow event showing the greatest increase. The natural flood management scenarios consider the effect of increasing woodland and adding surface water storage ponds. The inclusion of these features produces a complex response but overall, the modelling shows a reduction in low, median, and high flows, although the more extreme the flow event the smaller the percentage change in flow. Simulated timeseries and summary metric datasets are freely available on the CEDA archive.

KEYWORDS

SHETRAN, UKCP18, flood, drought, climate change, river flow

1 Introduction

Hydrological modelling is an essential tool in understanding and predicting how river catchments respond to a changing climate or land use (Peel and Blöschl, 2011). A variety of hydrological models are available for simulating river flows (Peel and McMahon, 2020; Kumar et al., 2023), broadly falling into the categories of data-driven models, conceptual models, and physically based models. In this study, we use a physically-based, spatially-distributed hydrological model (SHETRAN) to explore how climate change will affect future floods and droughts. This is the first time a physically-based spatially-distributed hydrological model has been calibrated for such a large set of UK catchments, including Northern Ireland. Furthermore, this is the first time that a physically based hydrological model has been applied at this scale in the UK for assessing future climate change and land-use scenarios.

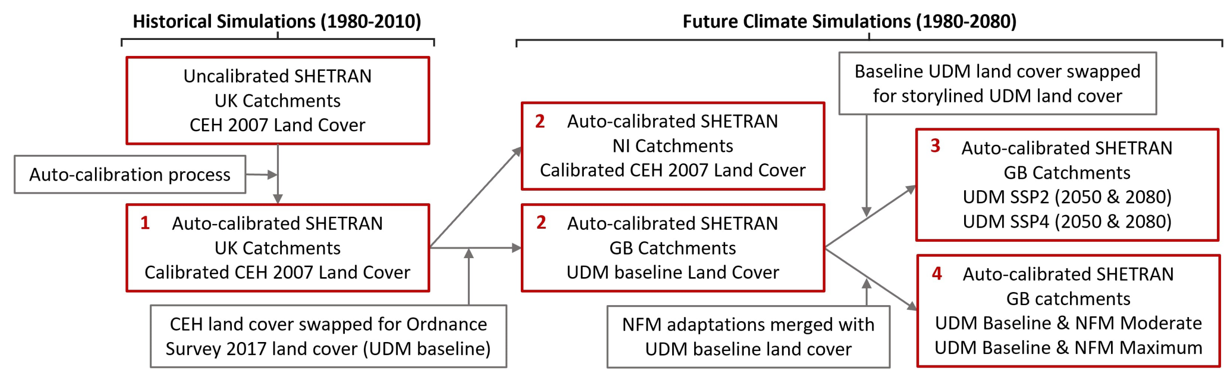

FIGURE 1
A flow chart showing the iterative setup of the four modelling scenarios (red numbers, as listed in Section 2), their regions (UK, GB, or NI), and the autocalibration and land cover alteration steps.

Data-driven models, e.g., long short-term memory models (LSTMs), are calibrated using the long-term dependencies between the meteorological data and the outlet discharge, without explicit characterization of the physical processes (Nearing et al., 2021). Conceptual models simulate hydrological processes by considering linked storage units with empirical relationships defining fluxes in and out of them. A large number of this type of model have been developed over the last 50 years (Peel and McMahon, 2020) and many have been applied to large scale studies of many catchments (e.g., Knoben et al., 2020; Lees et al., 2021). Data-driven and conceptual models are quick to run, often simple to understand, and can produce very accurate simulations (e.g., Kratzert et al., 2019). However, data-driven relationships and conceptual model parameters often do not have a direct physical interpretation and rely heavily on calibration to obtain a good fit between the measured and modelled discharge data.

Several studies examine the national scale impact of climate change on UK hydrology using conceptual models and the latest UKCP18 climate projections. These typically find climate change to cause an increase in the frequency and or magnitude of floods and high flows, particularly in the north west of Great Britain (e.g., Lane and Kay, 2021; Lane et al., 2022) and that we are likely to be seeing the effects of this already (Kay et al., 2021b), as well as decreases in median and low flows across, especially in the east of England (e.g., Lane and Kay, 2021; Lane et al., 2022; Parry et al., 2023; Arnell et al., 2021; Hannaford et al., 2022, Hannaford et al. 2023). These studies tend to report changes to only either high or low flows, overlooking the need for consistent projections across the whole flow regime (Kay et al., 2021a).

In contrast, this study reports changes to the full hydrological flow regime simulated by a physically-based hydrological model. Physically-based models simulate hydrological processes using well established physical laws described by discretised systems of partial differential equations (Freeze and Harlan, 1969). This should ensure that models capture catchment processes and makes them more suitable for modelling time periods and conditions beyond their calibration datasets. However, there are issues related to their use (Beven, 2001) including the large number of parameters and the slower run times compared to other types of models. Commonly used physically-based hydrological models include HydroGeoSphere (Brunner and Simmons, 2012), ParFlow (Kollet and Maxwell, 2008), MIKE SHE (Ma et al., 2016) and SHETRAN (Ewen et al., 2000); further examples can be found in Maxwell et al. (2014) and Kollet et al. (2017). Several of these have also been applied at large scales, such as Maxwell and Condon (2016) and Naz et al. (2022), as well as for climate change investigations (Condon et al., 2020).

This work forms part of the OpenCLIM project[1] designed to increase understanding of climate risk and adaptation needs in the UK. OpenCLIM brings together multiple teams from different fields relating to climate risk and harmonises their work to produce risk and adaptation metrics. It is designed to support future Climate Change Risk Assessments and National Adaptation Plans. The hydrological modelling in the OpenCLIM project considered here is focused on how climate change will affect future floods and droughts in the UK, with previous work showing that both are expected to get worse due to increase in extreme high and low flows (Sayers et al., 2020; Kay, 2021; Arnell et al., 2021). Within the OpenCLIM project the distributed conceptual HBV model (Seibert and Bergström, 2021) has been run for the same catchments using the same 1 km grid and the same meteorological drivers and discharge (calibration) data, so that direct comparisons between the results of the two models are possible.

2 Materials and methods

This study conducts the following hydrological modelling scenarios, shown in Figure 1:

1 Historical simulations using recorded data (1980–2010) for 698 UK catchments.
2 "Baseline" climate change scenarios (driven by UKCP18 future climate datasets 1980–2080) using current land use for the 698 UK catchments above.
3 Four scenarios (1980–2080) exploring the impact of realistic changes in urban coverage with the changing climate for 668 catchments in Great Britain.

1 https://tyndall.ac.uk/projects/openclim/

4 Two scenarios (1980–2080) exploring the impact of implementing national scale natural flood management strategies with a changing climate for 668 catchments in Great Britain.

2.1 SHETRAN-UK

All hydrological modelling is conducted using SHETRAN, a physically-based, spatially-distributed hydrological model (Abbott et al., 1986; Ewen et al., 2000). The model simulates fully integrated surface and subsurface flows, represented by the St. Venant equations (Abbott et al., 1986) and the three-dimensional extended Richard's equation (Parkin, 1996) respectively. It accommodates above-ground processes such as surface runoff and river flows, as well as subsurface flows through soils and rocks.

SHETRAN has been chosen as it has a proven history of accurate surface water and groundwater simulations (e.g., Escobar-Ruiz et al., 2019; Sreedevi and Eldho, 2019), has already been applied at a national scale (Lewis et al., 2018) and can be easily adapted to different modelling scenarios with changing climate and land use inputs. Furthermore, its ability to model groundwater flows make it well placed for simulating hydrology in the complex permeable catchments of the south and east of England, an area likely to be significantly affected by climate change. Using a physically based model, rather than lumped or conceptual models, as in previous studies, also increases the model's applicability beyond its calibration and validation periods (i.e., when simulating future climate scenarios).

In this study, SHETRAN predominantly adopts a 1 km-by-1 km gridded domain with a 20 m thick subsurface, split into 14 horizontal layers of variable thickness. The largest 16 catchments (catchments with areas greater than 2,000 km^2) use a coarser 5 km-by-5 km grid to reduce the computational demands.

Meteorological inputs and hydrological outputs are considered on a daily scale, though SHETRAN uses internal, higher resolution, adaptive timesteps for calculations. Static datasets (elevation, land use, vegetation) and meteorological drivers (rainfall, temperature, potential evaporation) are used to simulate hydrological processes in river catchments (e.g., evaporation and transpiration from vegetation and the land surface, surface runoff, snow melt, infiltration, 3D soil and groundwater flows, and river flows). River flows are the primary focus of this work, but other variables are simulated, such as soil moisture and groundwater levels.

SHETRAN-UK refers to the national scale SHETRAN setup for 698 UK river catchments. 671 of these catchments (namely their boundaries and recorded flow datasets) were taken from the CAMELS-GB dataset (Catchment Attributes and MEteorology for Large-sample Studies, Coxon et al., 2020), which covers England, Scotland, and Wales, with catchment areas ranging from 3 km^2 to 9,900 km^2. An additional 30 catchments were modelled in Northern Ireland using data from the National River Flow Archive (NRFA, 2023)—these represent all available gauged catchments that did not have headwaters in the Republic of Ireland, as the driving meteorological and climate data for the Republic of Ireland was not available in this study. Three catchments (National River Flow Archive station numbers: 76011, 80005, and 3906) were too small to be satisfactorily modelled using the 1 km^2 cell size so a total of 698 catchments are considered and published in this work. Details of the input datasets used in the modelling can be seen in Table A1.

2.2 Historical simulations and autocalibration

The historical simulations were run for a 30-year period from 1980 to 2010 for the 698 catchments as two different setups: uncalibrated and autocalibrated. The uncalibrated version used spatially variable soil and aquifer properties and seven land use classes and is based on the work in Lewis et al. (2018), which was shown to simulate river flows with reasonable accuracy (Seibert et al., 2018). These simulations provide the skeleton for the autocalibrated setup, discussed below. A comparison of the results between these two approaches is shown in Section 3.1.

For the autocalibration, the model was calibrated against daily flow data using the period 1990–2000 and then validated using the period 2000–2010. The period 1980–1990 was not used, so that models had ample time to "spin-up". The standard SCE-UA global optimization method (Duan et al., 1994) was selected as the optimisation algorithm with Nash–Sutcliffe efficiency (NSE) used as the objective function. Other objective functions such as the Kling-Gupta efficiency (KGE) and Percentage Bias (PBias) were also calculated (Moriasi et al., 2007), but NSE is presented here to benchmark against other studies using the CAMELS-GB catchments (e.g., Lane et al., 2019; Lees et al., 2021). KGE and PBias values can be found in Table E1. All three objective functions were calculated using the *hydroeval* Python package.[2]

Autocalibration used a single soil and aquifer type for each catchment together with two land use types (urban and rural). Taking into account previous sensitivity studies (Op de Hipt et al., 2017; Sreedevi et al., 2019), five parameters were selected for calibration: the aquifer conductivity, soil conductivity, soil depth, ratio of actual evapotranspiration to potential evapotranspiration (AE/PE), and an urban precipitation fraction. Details of these parameters, their physically plausible ranges during the calibration, and the effect they have on the simulation are given in Table A2. Physically realistic library values were used for the remaining parameters, details of which can be seen in Table A3. The optimal simulation from the autocalibration process is presented as the historical autocalibration scenario.

For most catchments the optimisation algorithm required around 460 simulations to produce consistent, high NSE simulations (although reduced parameter constraints were introduced for the larger catchments, which required only around 120 simulations). Simulations were run on two local, high-performance Windows computers: Intel(R) Zeon(R) Gold 6,134 CPU, 3.2 GHz processor, 512 GB of RAM, where a single machine could run 30 processes. Overall, the autocalibration for all 698 catchments took around

2 https://pypi.org/project/hydroeval/

TABLE 1 Changes in the 668 catchments under the four urban development scenarios relative to the 2017 baseline.

	SSP2 2050	SSP2 2080	SSP4 2050	SSP4 2080
Number of catchments with a change in urban area	86	106	131	134
Mean change in urban area (%)	0.8	0.9	0.9	1
Median change in urban area (%)	0.5	0.2	0.7	0.7
Maximum change in urban area (%)	12.5	12.5	6.5	6.5

300 days to complete. All model set up files are available, see Section 3.5 for details.

2.3 Future climate scenarios

Following the historical autocalibration process, the 698 catchment models were then driven using UKCP18 climate data to explore a variety of future climate, urban development, and Natural Flood Management (NFM) adaptation scenarios.

UKCP18 is the flagship climate projection dataset for the UK. As part of UKCP18, continuous daily timeseries for meteorological variables are provided at a 12 km spatial resolution for a 100-year period (1980–2080) from 12 realisations of regional climate models (RCMs) of the high emissions (RCP8.5) scenario. Potential evapotranspiration (PET) was calculated using the Penman-Monteith method, as has been done in other analogous studies (e.g., Kay et al., 2021a; Lane et al., 2022). The 12 km gridded dataset was regridded (without alteration) to a 1 km grid and (along with PET) then bias-corrected against the 1 km historical meteorological data (1980–2010). Similar downscaled and bias corrected datasets are now available for four RCMs via the recent CHESS-SCAPE project (Robinson et al., 2023).

For the bias-correction, an empirical quantile mapping approach was taken based on the OpenEarth Hydro Toolbox python package (Hydro Toolbox—OpenEarth—Deltares Public Wiki). Quantile mapping is commonly applied for hydrological applications and is useful when trying to capture extreme values (Fung, 2018). This is the same approach as was taken in Lane et al. (2022) and in the eFLaG project (Hannaford et al., 2022), with quantile mapping applied to monthly means. The quantiles were mapped at 1 km using daily data and a baseline period of 1980–2010 in both of the historical datasets (CHESS in GB and HadUK in Northern Ireland) and UKCP18 datasets. A brief discussion of the bias-correction process and results can be found in Appendix B.

2.4 Urban development scenarios

Realistic changes in urban coverage have been modelled for different Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017) as part of the OpenCLIM project (UK Climate Resilience Programme, 2022). These have been produced using the Urban Development Model (UDM) (Ford et al., 2019). Two SSPs (2 and 4) were considered for two future time snapshots (2050 and 2080), giving four development scenarios (Table 1). In the UDM framework, SSP2 represents the "Middle of the road" (with integrated and optimised land use) and SSP4 represents "Inequality (A Road Divided)" (with high urbanisation and flood plain developments).

For each 1 km-by-1 km grid square the land use is considered to be urban when urban coverage exceeds 40% (see below for details of why 40% was selected). If proposed urban coverage increases across this threshold then the SHETRAN cell changes from rural to new urban (as opposed to existing urban, which was parameterised differently—see Section A.5). Only catchments with changes to the land-use were simulated, with each simulation running for the entire period (1980–2080) regardless of the year that the development snapshot was taken. Note that each urban development scenario is static during a simulation with the results showing what effect a particular urban development scenario has on river flows compared to a "no adaptation scenario".

The Urban Development Model uses the 2017 Ordnance Survey (OS) MasterMap dataset as a baseline development state upon which future urban development scenarios are based. This clashed with SHETRAN-UK, which uses the Centre for Ecology and Hydrology (CEH) 2007 land cover maps. As such, to align the model land use data sources, and to correspond with the other research streams in the OpenCLIM project, the CEH land cover maps used in the SHETRAN-UK calibration phase were replaced in GB catchments with land cover data from the 2017 OS MasterMap dataset (Ordnance Survey, 2021). These OS MasterMap datasets were then used in the subsequent climate change simulations. To ensure the best match between the two land use datasets, cells with an urban fraction above 40% were classed as urban. This gave the resultant rural–urban classification very similar urban fractions in each catchment to that of the CEH dataset, albeit with slightly different spatial distributions, resulting in no meaningful changes to the flow projections. UDM data was not available for Northern Ireland, therefore results are reported for GB only (the default CEH land cover datasets were used for the historical and 'no adaptation' climate change scenarios for Northern Irish catchments).

Note that UDM constructs each plausible development from the 2017 baseline, this means that a simulated development late in the century has no "memory" of a development that may have been modelled for an earlier year. As such, land use developments in 2080 do not always match those that may have occurred in 2050.

2.5 Natural flood management scenarios

Natural flood management uses natural processes to restore or mimic the natural functions of rivers with the aim of reducing the flooding risk together with a broad range of additional benefits for nature and people (Quinn et al., 2022). Two of the most commonly used techniques are the addition of storage (through ponds or slowing the flow on floodplain) and afforestation, both of which were considered here. Two NFM strategies were implemented: a notional "maximum" scenario, where all locations identified within the national opportunity mapping are assumed to be implemented, and a "balanced" NFM scenario where a more a realistic perspective is adopted, balancing agricultural yield projections, changing conservation and restoration priority areas and urban development pressures are considered. For both scenarios a 1 km raster map was produced for both woodland and storage showing the fraction of each grid square where the strategies were implemented. As with the urban development scenarios the simulations were run for each RCM for the entire period from 1980–2080 and compared to the "no adaptation" scenarios. Details on how these adaptations are implemented within the model can be found in Section A.4.

2.6 Representation of climate and land use change scenarios

The UKCP18 future climate scenarios were run in SHETRAN for each of the 668 catchments for the period 1980–2080 using the autocalibrated model setups with a slightly different rural–urban classification based on the 2017 OS MasterMap dataset (Ordnance Survey, 2021) (Section 2.4). For each RCM scenario, all 668 catchments could be run for their 100-year duration in about 5 days using the computing system specified above.

The UDM scenarios were simulated by changing the urban fraction in the land-use map (Section 2.4) in accordance with modelled storylined development. For the NFM scenarios (Section 2.5), woodland was applied by increasing the intercepted evaporation (Birkinshaw et al., 2014) in proportion to the fraction of increased woodland cover specified for each 1 km grid cell. Storage was applied by allowing surface water to be stored in a cell up to a threshold volume, similar to the approach of Metcalfe et al. (2018). The threshold volume was defined according to the fraction of additional storage specified for the 1 km grid cell, up to a maximum storage volume of 100,000 m^3 (roughly the size of a large storage pond). Stored water is released slowly via surface runoff (which corresponds to a pipe or a leaky barrier) or via infiltration. Excess water flows through/out of the cell as if the pond was not there.

2.7 Flow regime summary metrics

Twenty-four high and low flow metrics were produced; a subset of these are discussed in this paper. The online dataset includes all metrics: Q1 and Q5 (high flows, exceeded 1% and 5% of the time), GTQ1 and GTQ5 (the number of days the flow is greater than the historical Q1 and Q5 flows), Q95 and Q99 (low flows, exceeded 95% and 99% of the time), LTQ95 and LTQ99 (the number of days the flow is less than the historical Q95 and Q99 flows), drought duration, drought length, drought deficit, and return period flows for the 1 in 2, 3, 5, 10, 25, 50 and 100-year flow events. The 1 in 25, 50 and 100-year flows are not discussed in the paper due to the significant uncertainty associated with using 30-year calculation periods. Appendix C shows basic regional results for most metrics at 2°C and 4°C with percentile changes for the different RCMs. Metric definitions, caveats, and calculation steps are described in Appendix D.

3 Results

3.1 Model performance

The autocalibration process greatly enhanced the performance of the simulations for the historical period (1980–2010) when compared to the uncalibrated simulations for the measured daily river flows (Figure 2, left). For the 698 UK catchments the median NSE values for the validation period increased from 0.69 to 0.82. Catchments where the autocalibration yielded a lower performance than using the measured parameters generally had large spatial variations in soils and aquifer properties meaning that the simplified autocalibration setup (with the same soil and aquifer throughout) was unable to reproduce the complex response.

Figure 2 (right) shows that good simulations were achieved using the autocalibration through the whole of the UK. Catchments with lower NSE values were generally in the north of Scotland or in the south-east of England. In the north of Scotland, the issue was generally caused by complex snow process that were simulated within SHETRAN using a simple uncalibrated degree day factor. A more sophisticated snow module exists (the "Energy Budget Method") and could be used to address these issues in future research (Bathurst and Cooley, 1996). This module was not used here as it requires grided datasets that were not available when the model simulations were carried out (net radiation, windspeed, air temperature, slope of the saturation vapour pressure/temperature curve and vapour pressure deficit of the air). In the south-east of England, and particularly in East Anglia, the combination of patchy glacial till on top of a chalk aquifer was difficult to model satisfactorily using the simplified autocalibration setup. Overall, 581 of the 698 historical autocalibration catchments had a validation NSE of 0.7 or above and were considered in the future climate scenarios.

Calibrating models using NSE focuses the models on producing accurate high flows, rather than objective functions such as logNSE, which targets lower flows (Krause et al., 2005). Multiobjective optimisation was beyond the scope of this project but will be considered in future work. Catchments returned KGE scores for the validation period with a median of 0.82 and a mean of 0.79; all 698 catchments performed better than taking simply the mean flow, with all KGE values above −0.41 (Knoben et al., 2019).

Comparisons of the autocalibrated SHETRAN model with other (non-physically based) models shows that SHETRAN performs well. Direct comparisons are difficult because of the different catchments and years selected, the different objective functions used and whether a split sample calibration/validation is applied or just a calibration. The eFLaG project (Hannaford et al., 2023) used 200 catchments with median NSE values quoted of between 0.85 and 0.86 for the GR4J and GR6J and PDM models and slightly lower for the G2G model, SHETRAN has a similar validated NSE value of 0.85 for these 200 catchments. Lane et al. (2019) simulated over 1,000 catchments. The median NSE values for the subset of these which were CAMELS-GB catchments were between 0.76 and 0.79 for the four conceptual models, which is slightly lower than the SHETRAN value of 0.82. Coxon et al. (2019) simulated 1,366 catchments across the

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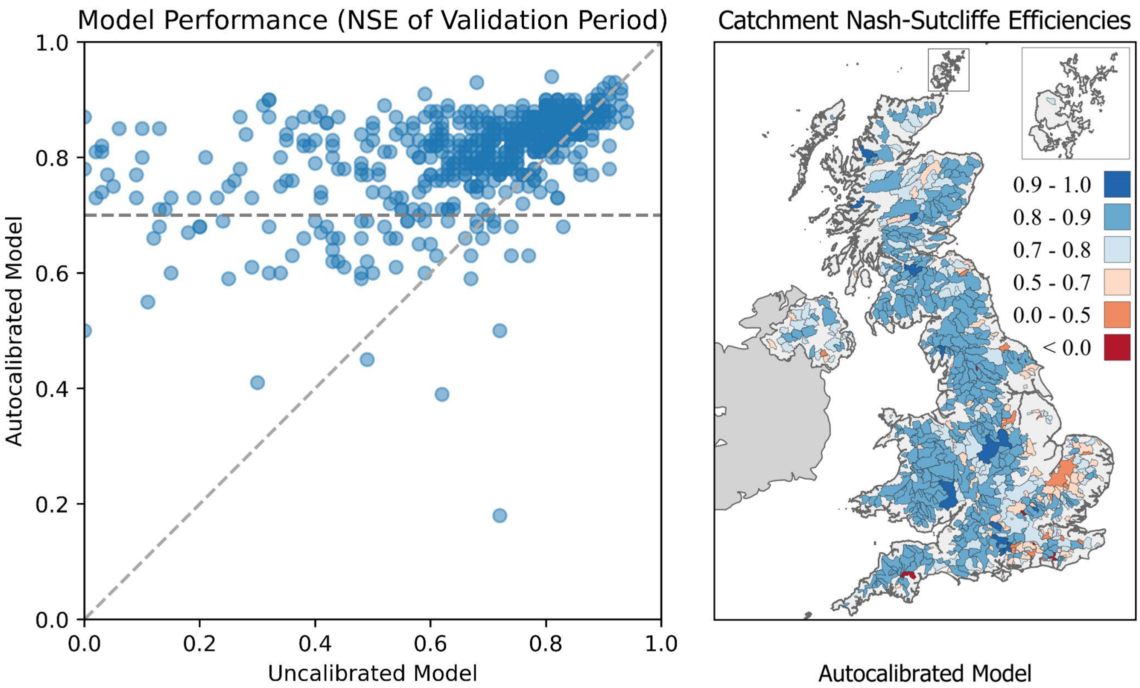

FIGURE 2
SHETRAN model performance. (Left) The change in performance between the uncalibrated SHETRAN simulations using measured parameter values and the autocalibrated SHETRAN-UK, the horizontal dashed line shows the performance threshold of 0.7 required for modelling the future climate scenarios and the diagonal dashed line shows the expected correlation between the models if both performed equally. (Right) The national distribution of model performance for the autocalibrated simulations—see the results maps for a view of those catchments with NSEs of 0.7 and above.

UK as part of the DECIPHeR framework producing slightly lower NSE values. Lees et al. (2021) simulated the CAMELS-GB catchments using two data-driven LSTM models producing median NSE values of 0.86 and 0.88, which are slightly higher than the SHETRAN value of 0.82.

3.2 Future climate scenarios results

Simulation results are presented in terms of changes from the baseline period of each respective RCM. A baseline period of 1980–2010 is used, with the first 5 years removed to allow for model spin up. This period corresponds to approximately 0.6°C warming compared to pre-industrial levels. Following the method of (Arnell et al., 2021), results are given for 30-year long “warming periods”. These are 15 years either side of the year when the respective warming threshold was reached relative to the pre-industrial period. These periods differ between each of the 12 RCMs. In instances where the 30-year warming period extends beyond the end of the 100-year simulation, the period ends in 2080 and the metrics are, if necessary, adjusted to account for the shorter period. The warming thresholds used can be found in Table B1.

Boxplots visualise data at either national or regional levels. Aggregated national boxplots are coloured blue or red according to whether the metric is aimed at exploring high and median flows or low flows, respectively. Regional boxplots were created by assigning catchments into hydrological regions according to the region that the

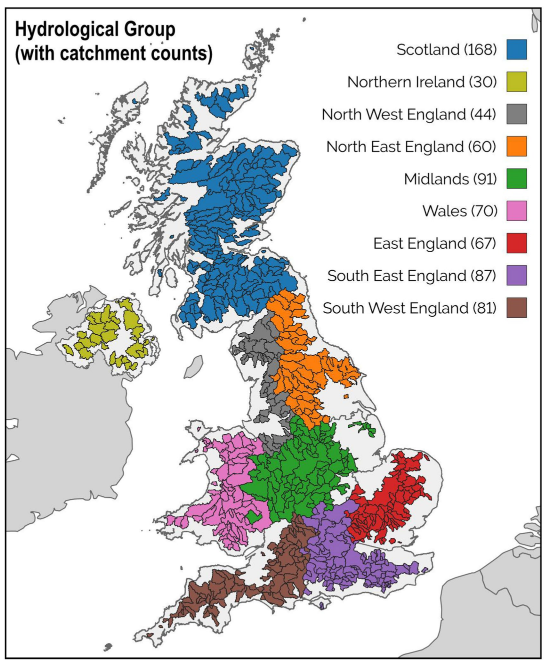

FIGURE 3
The 698 catchments modelled in the study and their hydrological groups. Regional colours correspond to boxplot colours in subsequent figures. Numbers in brackets denote the number of catchments in each region.

majority of their area is within. Regions with similar hydrological characterises and results were combined, such as in Scotland, which has similar results across its catchments, the colour key for which can be seen in Figure 3.

Maps categorise catchments based on the greatest decrease (or in cases where all values increase, the smallest increase), mean change, and greatest increase in metrics across the 12 Regional Climate Models (RCMs), offering a comprehensive view of potential flow changes. Maps are color-coded in blue and red, with blue indicating wetter conditions and red indicating drier conditions. Catchments with NSE performance values less than 0.7 are not show on maps or included in the boxplots. Boxplots show the 25th, 50th and 75th quartiles of the data, with 'whiskers' stretching to the data point that is greatest or smallest but still within 1.5 times the interquartile range from its respective upper or lower quartiles, and points representing values beyond this range.

As we simulate future periods, we see a greater range in values across all of the metrics discussed here. This widening range is due to a combination of some or all of the following factors: (1) increases in extreme flows with changing climate, (2) regional divergence as some regions dry and others get wetter, (3) and national scale divergence as some RCMs generate drier hydrology while others make catchments wetter. Figure C3 shows several of the metrics split into their respective RCMs and demonstrates that, while some of the range we see is from diverging RCMs, there is typically an increasing range in the catchment metrics as we look into the future. The same is also generally seen in the regional breakdowns (e.g., Figure 4, bottom-left).

3.2.1 Future climate scenarios—floods

The change in the return period flows for the different warming levels increases have been calculated. Return period flows are available for the 1 in 3, 5 and 10-year events in the on-line dataset; larger flow events are also included for comparison with other work, but as these are less statistically robust, they are not included in the text. Return periods were calculated by extracting the annual maximum daily flows for the baseline and warming periods and using l-moments and a GEV distribution to calculate the return period flows (calculations were performed using the Python lmoments3 and SciPy packages). For more information see Appendix D.

The change in the 10-year return period flows is shown in Figure 4 for all 698 catchments and the 12 RCMs. Although the national median 10-year flow remains relatively constant, the range of 10-year return period flows increases with warming. Figure 4 (bottom-left) shows clear regional variation (the regions are defined in Figure 3), typically showing reductions in the 10-year return period discharge for catchments in the south and east, with the greatest decreases in the East England catchments, where median flood flows decrease by around 15% at 2°C and by 50% with 4°C. There are typically increases in the 10-year return period flow in the Scotland, Wales, North West England, and Northern Ireland regions, with median values increasing on the order of 10–20%. While the RCMs show similar spatial patterns of change (Figure C4), Figure 4 (right) shows that at 2°C there is potential for both increases and decreases in flow for almost all catchments across the simulation ensembles. At 4°C of warming the regional variations

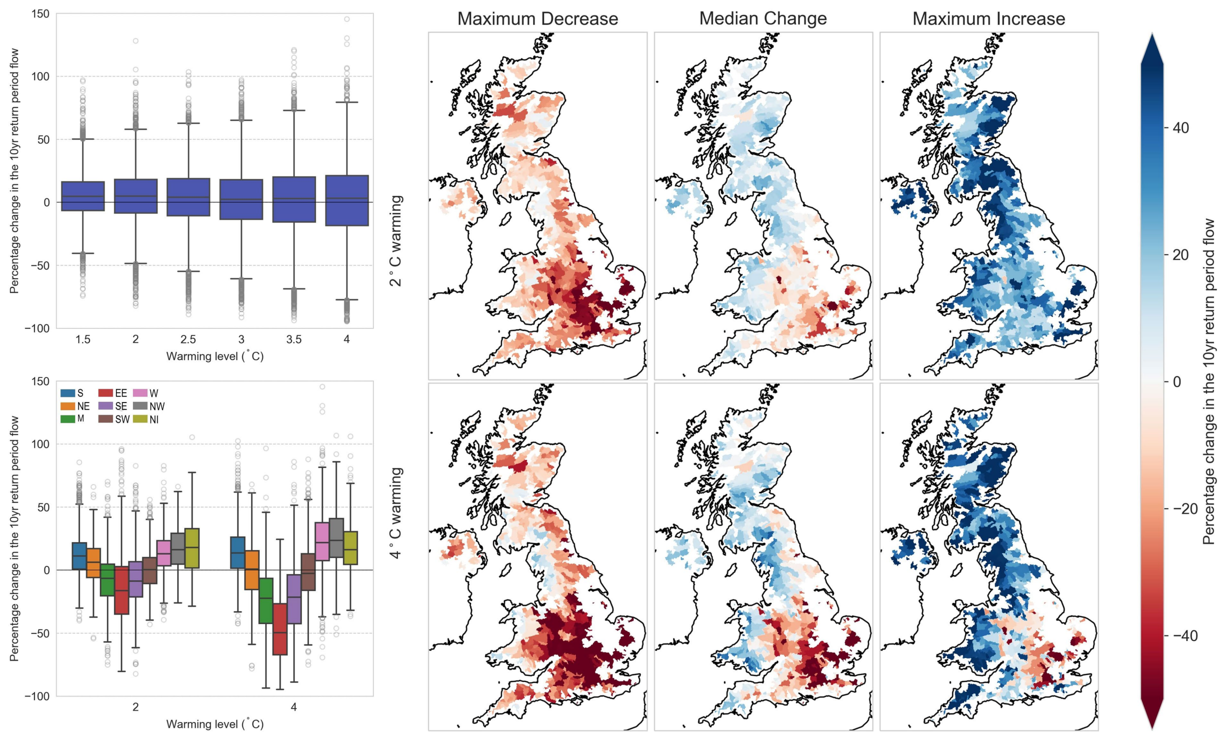

FIGURE 4
Change to the 10-year return period flows for future warming levels across all 12 RCMs. Boxplots of (top-left) all catchments, (bottom-left) catchments split by region, and (right) maps showing the maximum decrease, median change, and maximum increase for each catchment across all RCMs.

become more extreme, and every RCM shows a decrease in the 10-year flow in most East England and South East England catchments. A similar pattern can be seen for other return period floods in the online dataset. The overall pattern suggests an increase in flood discharges in the north and west of the UK, and a decrease in the south and east. However, this is for daily rainfall and the effect of using sub-daily rainfall is considered in the discussion (Section 4).

3.2.2 Future climate scenarios—median flows

Figure 5 (top-left) shows that median flows (Q50) typically decrease as the warming level increases, with median national values dropping from a 12% decrease for 2°C of warming to 26% decrease for 4°C of warming. Variability increases into the future with a wider range of flows in the plots at 4°C (typically approx. −35 to 10%) compared to 2°C (typically approx. −65 to 10%). The bottom-left and right panels of Figure 5 show significant spatial variation across the UK. Scotland, Northern Ireland, and Northwest England show small reductions in Q50 flow for most catchments but in some catchments for some RCMs there is an increase in Q50 flow at both 2°C and 4°C warming (this can be seen in the blue catchments for the maximum increase in Figure 5, right panel). In contrast, catchments in East England and South East England typically show large reductions in Q50 flows with a median reduction in Q50 flows in East England of 24% at 2°C and 42% at 4°C.

3.2.3 Future climate scenarios—droughts

The change in river flows for the different warming levels have been calculated for eight different drought metrics: the mean drought duration, mean severe drought duration, the number of months of drought, the number of months of severe drought, the total drought deficit, the maximum drought deficit, the mean drought deficit, and the mean drought deficit for severe droughts (full details in Appendix D). In this section the mean drought duration is considered, i.e., the average duration (in months) of each instance of drought in the period under consideration (Rudd et al., 2019).

Of all the metrics presented here, drought duration (Figure 6) shows the most distinct regional variation, with dramatic increases in the number of months of drought in the East of England and the surrounding regions, with potential increases of several years' worth of drought per 30-year period (Figure 6, bottom-left and right panels). Figure C2 shows that all regions have an increase in the number of months classed as being in drought. More northern and western regions see increases of 20 to 50 additional drought months in some catchments by 2°C, while the East of England is more extreme and sees an upward shift in all catchments, with many catchments being in drought for the entire 4°C period. Total water deficits also increase across all catchments with normalised deficits increasing in the region of 30 m^3 in more northern and western catchments and by up to several 100 m^3 in the East of England. Plots show that all areas are shown to be more frequently in drought, with droughts lasting longer, and yielding greater water deficits.

3.3 Urban development scenarios

The results of the SSP4 2050 urban development scenario (Table 1) for the 12 RCMs can be seen in Figure 7, these results are

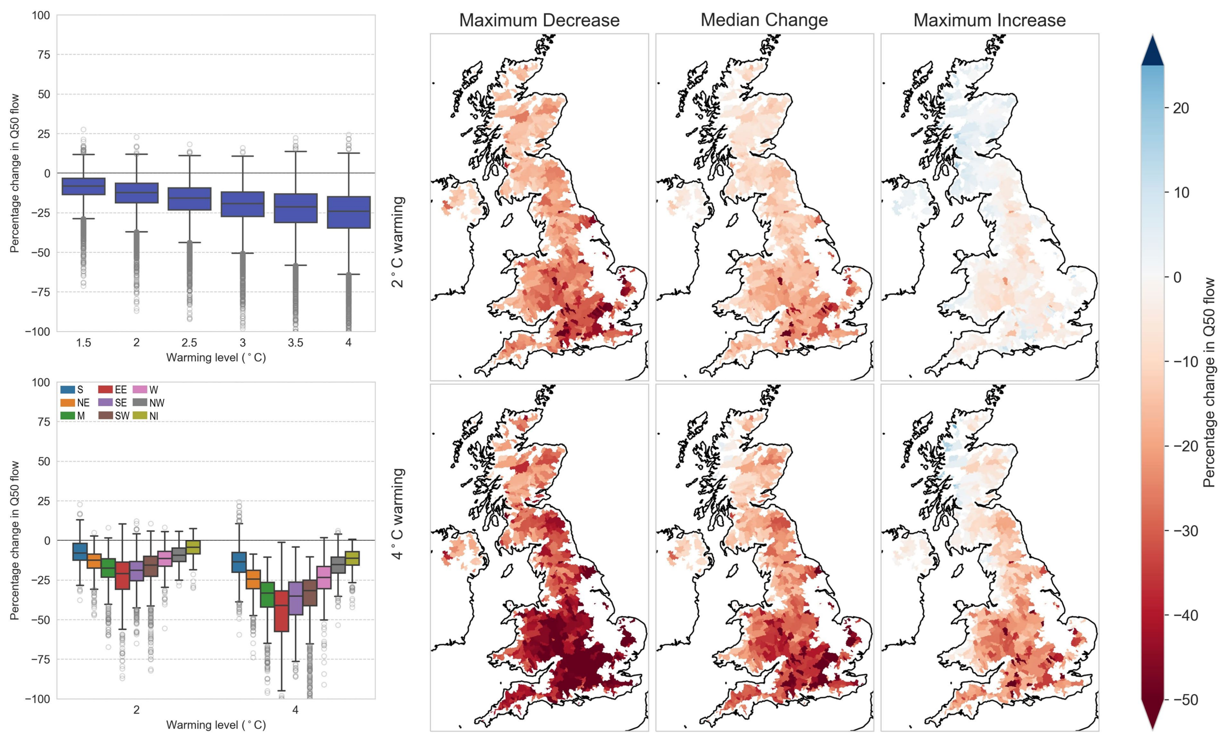

FIGURE 5
Change in the median (Q50) flows for future warming levels across all 12 RCMs. Boxplots of (top-left) all catchments, (bottom-right) catchments split by region, and (right) maps showing the maximum decrease, median change, and maximum increase for each catchment across all RCMs.

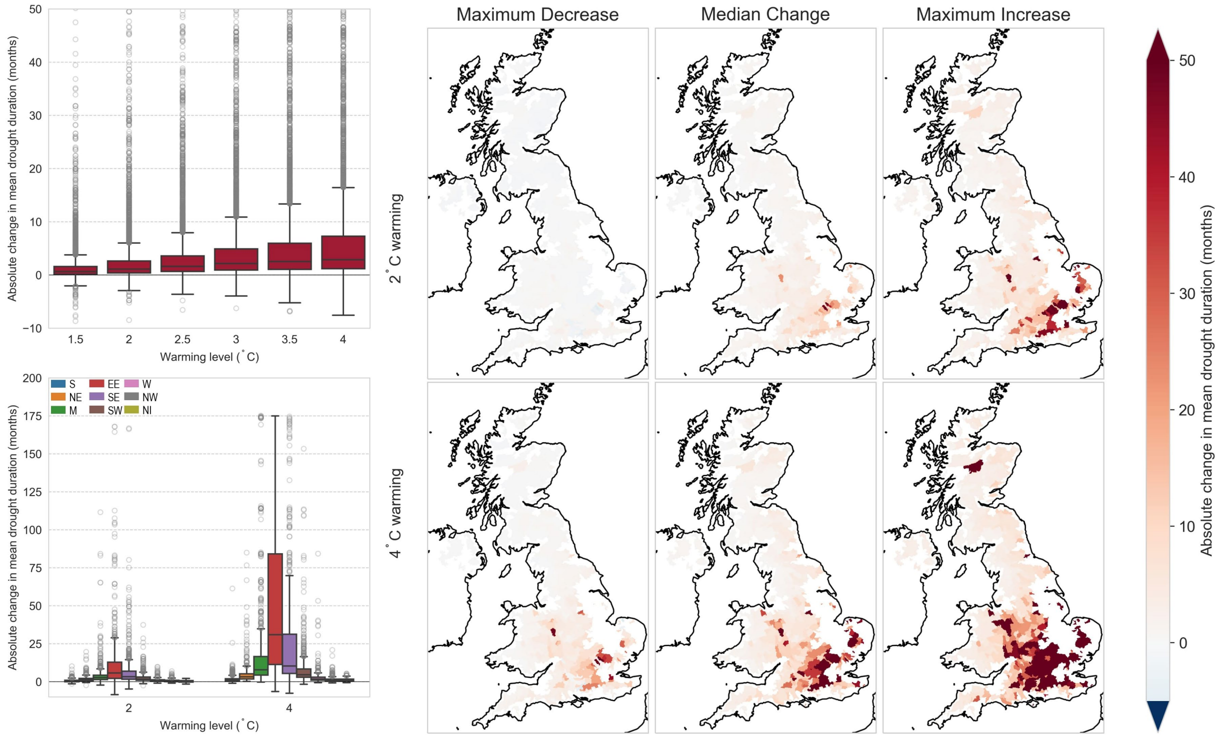

FIGURE 6
Absolute change in the mean drought duration for future warming levels across all 12 RCMs. Boxplots of (top-left) all catchments, (bottom-right) catchments split by region, and (right) maps showing the maximum decrease, median change, and maximum increase for each catchment across all RCMs. Note the different boxplot y-axis scales.

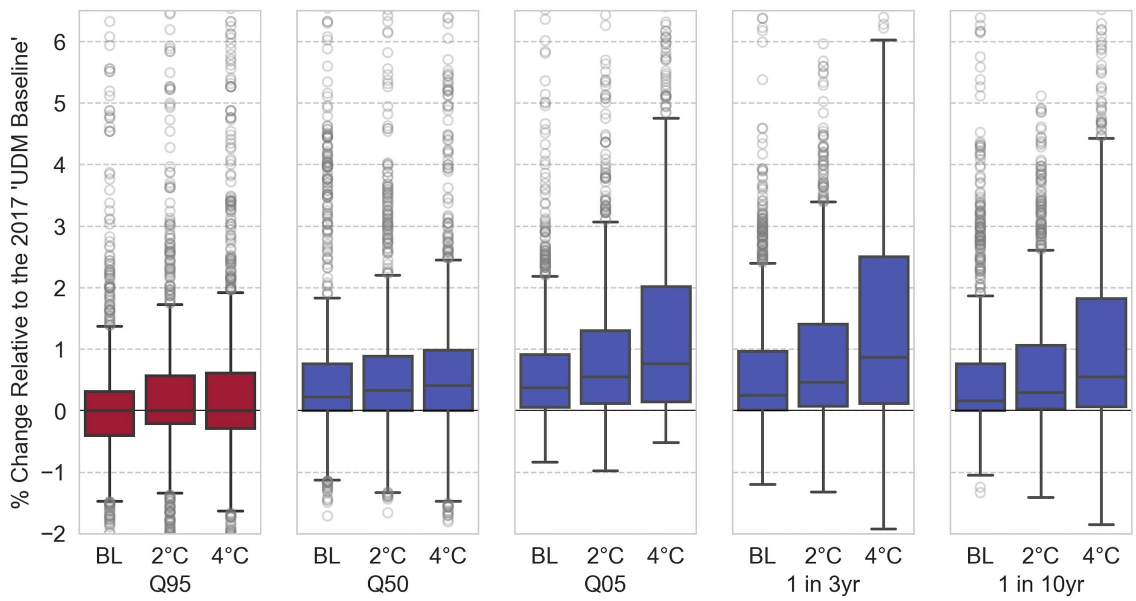

FIGURE 7
Percentage change in flow for five metrics for the SSP4 2050 urban development scenario compared to the "no adaptation" scenario. Q95 is shown in red as it is a low flow metric the others are shown in blue as they are median or high flow metrics. The change is shown for the baseline (BL) period (1985–2010), 2°C and, 4°C of warming.

representative of all four UDM scenarios considered in this work. The boxplots show the percentage change compared to the "no adaptation" scenario (i.e., the same warming period as on the x-axis, but without UDM changes). For high flow (Q5) and peak flow events (1 in 3-year and 1 in 10-year) there is generally an increase in flow with the increased urbanization. Q5 shows median increases of around 0.4, 0.5, and 0.7% in the baseline, 2°C, and 4°C periods respectively, although some catchments show much larger changes, with an upper quartile change of around 3% at 2°C and nearly 5% at 4°C of warming. Of the high flow statistics presented, the 1 in 3-year event shows the largest percentage flow increase from to urbanisation, with a median increase of around 0.9% at 4°C of warming. For the median flow event (Q50) there are typically smaller increases in flow with increased urbanization and less sensitivity to the warming period; flow changes are typically up to 1%. Low flows (Q95) show a more varied picture, with over half of the catchments showing lower flows with increased urban development in the baseline period, though this change becomes dominated by slightly increased flows later in the simulations as the climate warms. Change relative to the non-UDM scenarios tends to increase as the warming level increases, although the range of flows also increases, showing that some catchments get increasingly dry while others get increasingly wet.

Overall, the changes in flow resulting from urbanization are smaller than the changes shown in Section 3.2 that are a result of a changing climate. However, UDM projects relatively small changes in urban fraction in most catchments. Figure 8 shows the relationship between the 1 in 10-year flow and the percentage change in urban area (relative to the catchment's total area) for catchments in two of the urban development scenarios. As expected, the larger percentage changes in urban fraction takes place in the smaller catchments. The important thing to note in Figure 8 is the correlation between the 10-year return period flow and increasing urban fraction. However, there is a lot of variation within this relationship, depending on the location of the new urban area within a catchment and the RCM. In a few cases the new urban areas cause a reduction in the 10-year return period flow; this occurs if the new urban area is close to the outlet. This is because the new urban area can route overland flow into the river channel near the outlet before the main flood wave goes through thus decreasing the peak flow (Birkinshaw and Krivtsov, 2022).

3.4 Natural flood management scenarios

The results for the NFM "maximum" scenario for the 12 RCMs can be seen in Figure 9. This shows the percentage change in flow compared to the 'no adaptation' scenario (i.e., the standard 1985–2080 future climate scenarios considered in Section 3.2) at different warming levels. This shows that the larger the flow event the smaller the percentage change in flow compared to the 'no adaptation scenario'. So, for the 1 in 10-year return period at 4°C of warming the median reduction in flow compared to the no adaptation scenario is only around 4%, whereas the reduction for median flows it is around 9%. The warming level makes little difference to the percentage change in flow, apart from for the low flows (Q95), where the 4°C warming level causes a typical reduction in flow in the order of 2–6% when compared to the baseline (1985–2010) scenario.

The changes produced in Figure 9 are the result of a complex set of factors that can be seen in Figure 10. This shows four metrics for a single climate scenario (RCM 4) at 4°C warming. In these runs the storage and woodland adaptations were modelled separately to explore the effects of each. Note that storage produces much smaller changes in flow than woodland as it was applied to a smaller percentage of the catchment. Woodland always reduces the flows as it is modelled as an increase to the intercepted evaporation, whereas storage has the potential to increase the flows, as, although it has been set up in the model to slow down the overland flow, nearly the same volume of water eventually reaches the outlet (increased surface storage slightly increases the evaporation).

Storage reduces the high flows (1 in 10-year flow event and Q5) by storing surface water and then releasing it gradually when the

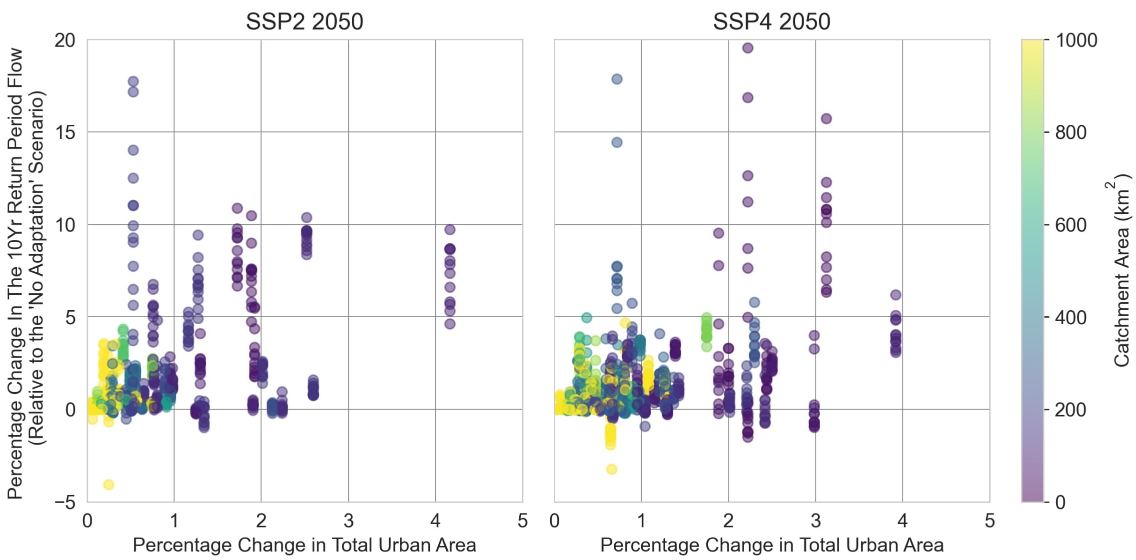

FIGURE 8
Percentage change in the 10-year return period flow compared to "no adaptation scenario" plotted against the percentage change in urban area within a catchment for two urban development scenarios. The colours show the catchment area. The analysis has been carried out for the 12 RCMs, which can be seen for each catchment as the 12 points along a vertical line.

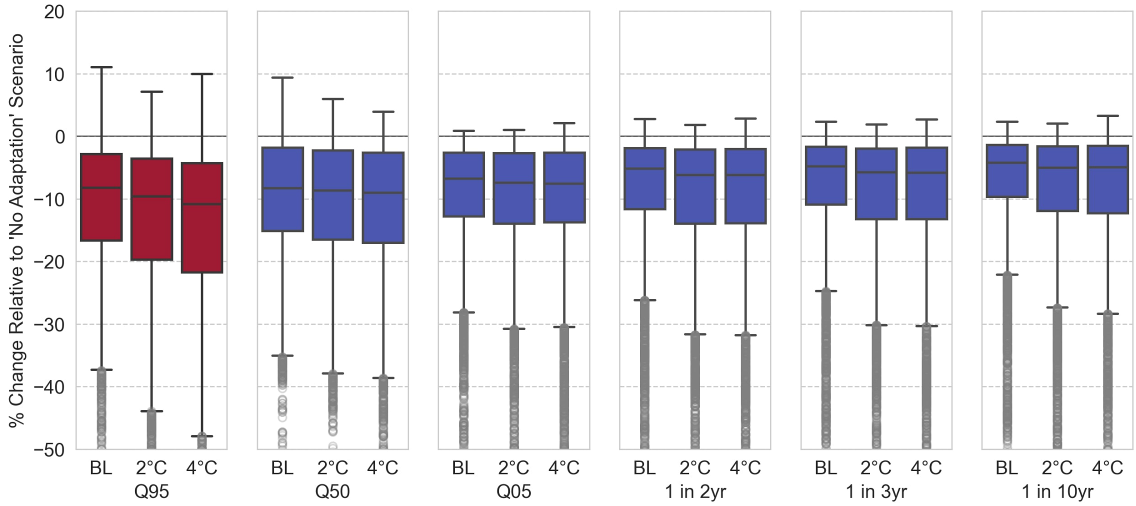

FIGURE 9
Percentage change in flow for six metrics for the NFM "maximum" scenarios compared to the "no adaptation" scenario (i.e., the 2017 UDM Baseline). Q95 is shown in red as it is a low flow metric the others are shown in blue as they are median or high flow metrics. The change is shown for the baseline (BL) period, 2°C and 4°C of warming.

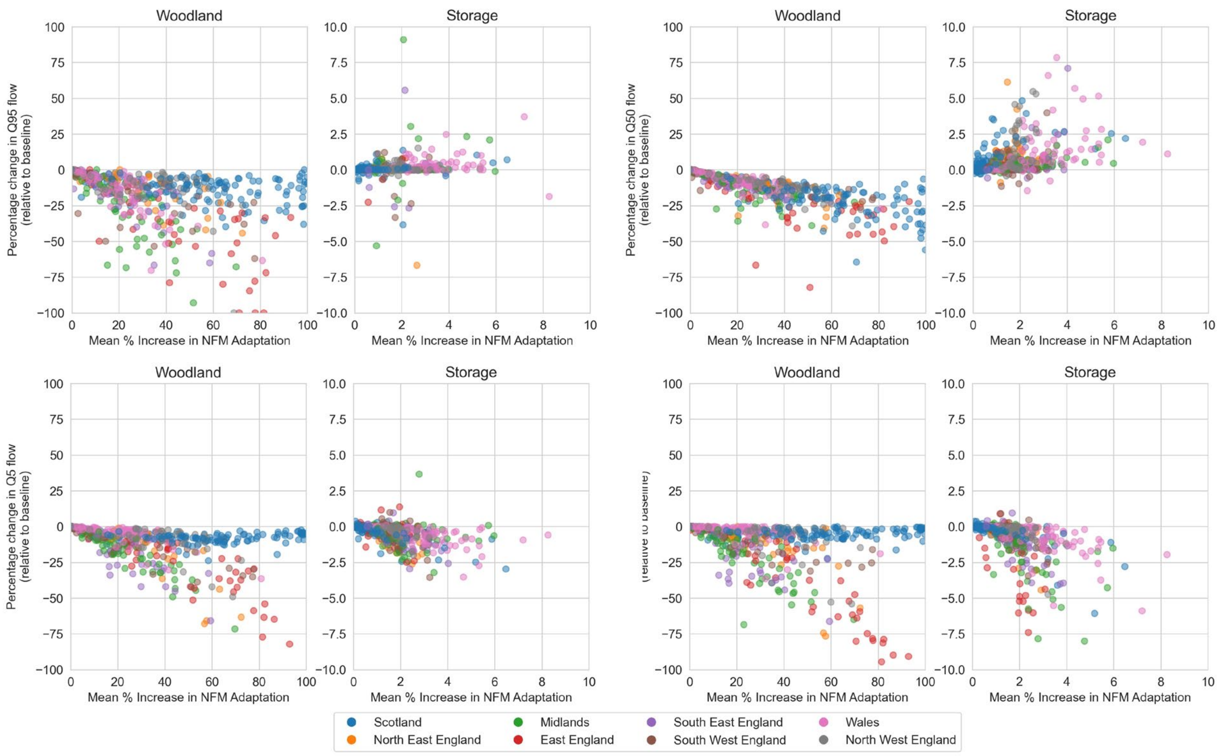

FIGURE 10
Scatter plots of percentage change for four flow metrics for each catchment in the NFM "maximum" scenario relative to the "no adaption" simulations. These results are from simulations exploring the effect of increased woodland and increased storage applied separately. (Top-left) Q95, (top-right) Q50, (bottom-left) Q05, (bottom-right) 1 in 10-year return period. The figures shown use the RCM 4 scenario at 4°C of warming, with catchments coloured by hydrological region. Note the different scales between the woodland and storage plots.

peak flows have passed. This has the effect of increasing the median flows (Q50), as is seen in the figures. Low flows (Q95) occur when there is little overland flow and so the additional storage has little effect.

The effect of woodland varies depending on the location of the catchment. In Scotland, with high rainfall and little groundwater flow, the woodland only makes a small difference for the high flows (1 in 10-year flow event and Q05), whereas in East England, with low

TABLE 2 Mass balance changes for two contrasting catchments comparing the "no adaptation" scenario and the NFM maximum scenario.

	Catchment 89007			Catchment 36010		
	No adaptation	NFM "maximum"	Change (%)	No adaptation	NFM "maximum"	Change (%)
Precipitation (mm)	2,992	2,992	0	589	589	0
Actual evapotranspiration (mm)	394	697	77	413	517	25
Discharge (mm)	2,600	2,298	−12	176	73	−59
Runoff ratio (−)	0.87	0.77	−11	0.30	0.12	−60

Simulations use RCM 4 at 4°C of warming. Catchments have the same precipitation as they are driven by the same climate data.

rainfall and predominantly groundwater flow the woodland makes a big difference for all the flow metrics where the change in river flows is proportional to the extent of afforestation.

Table 2 shows the water balance for two catchments in detail. Catchment 89007 (Abhainn a'Bhealaich at Braevallich) is in western Scotland with an annual precipitation of 2,992 mm and catchment 36010 (Bumpstead Brook at Broad Green) is in eastern England with annual precipitation of 589 mm. In the NFM "maximum" scenario there is a 100% increase in woodland cover in catchment 89007 and 93% in catchment 36010. The difference in annual precipitation means that despite a 77% increase in actual evapotranspiration in catchment 89007 there is only a 12% reduction in annual discharge, whereas a 25% increase in actual evapotranspiration in catchment 36010 produces a much higher 59% reduction in annual discharge.

3.5 Data availability

The catchment discharges and catchment metrics for each section of this study are freely available via the CEDA Archive (Newcastle University and University of East Anglia, 2024; Newcastle University, 2024). Available datasets include:

- Data for all 24 flow metrics, containing values for each catchment for all 12 RCMs for 30-year periods and for incremental 0.5°C warming periods (Table B1).
- Catchment outlet discharges for all 698 catchments for the historical period (1980–2010).
- Catchment outlet discharges for all 698 catchments for the baseline future climate simulations (1980–2080).
- Catchment outlet discharges for the future climate simulations with the two NFM scenarios (maximum and moderate) for all 668 catchments.
- Catchment outlet discharges for the climate simulations with the four UDM scenarios (SSPs 2 and 4 with development snapshots taken from 2050 and 2080) for those catchments that experience urban change.

The SHETRAN model can be downloaded from GitHub,[3] along with basic python code for setting up and running SHETRAN simulations (Smith, 2024a), and analysing the data (Smith, 2024b). Goodness of fit metrics for all catchments can be found in Appendix E.

4 Discussion

4.1 Comparison with other climate impact studies

A number of hydrological modelling studies have used the UKCP18 climate projections since they were released (e.g., Arnell et al., 2021; Hughes et al., 2021; Kay et al., 2021b; Kay, 2021; Lane et al., 2022; Parry et al., 2023). These take a variety of approaches, some using the UKCP18 data directly in models (e.g., Lane et al., 2022) and others using historical meteorological data scaled by the change factors derived from the future climate datasets—a "delta change" approach (e.g., Kay, 2021). See Kay et al. (2021a) for a review of studies using the older UKCP09 projection data. A comparison between results from the other research and this research is considered in this section divided into two groups of either drought and low flow metrics or floods and high flow metrics. High and low flow metrics are often considered separately but are both produced here as part of the same modelling framework, which Kay (2021) note is important for consistency.

Firstly, considering drought and other low metrics, there is a consensus between our work and others that there is likely to be an increased occurrence of low flows and droughts increasing into the future. Arnell et al. (2021) find that both agricultural and hydrological drought risk will increase across the UK and results in Kay (2021) indicate decreases in low flows with those to the south and east tending to show greater decreases in low flows. Parry et al. (2023) investigated the effect of climate change on groundwater levels and river flows in Great Britain using data from the eFLaG project and found that the increase in drought occurrence will be especially significant for the south-east of the UK.

While our research agrees with these findings, SHETRAN simulates a more severe decrease in low flows and drought in groundwater dominated catchments than in Parry et al. (2023), which appears to be driven by the different processes included within the models. Parry et al. (2023) note that the AquiMod groundwater model does not explicitly represent any upward flux from the water table to atmosphere and, therefore, their projections do not account for this process, whereas in SHETRAN there is an upward flux of water from the water table to the top soil layers as

3 https://github.com/nclwater/Shetran-public

evapotranspiration occurs near the ground surface. This is an advantage of using SHETRAN, as it is a physically-based model with a three-dimensional subsurface including the unsaturated and saturated zones.

This consequence of the changing climate in SHETRAN is well demonstrated in the Stringside chalk catchment (Stringside at Whitebridge, catchment number 33029) in East England. This catchment performs well in our simulations, with an autocalibrated NSE of 0.78 in the historical simulations. Annual mass balance totals for the 99 km^2 catchment are plotted in Figure 11 (top) for RCM 4 (discharge values are "specific discharge", i.e., discharge normalised by catchment area, so it represents the average discharge from 1 km^2 cell). Figure 11 shows a small reduction in precipitation over the 100-year simulation but a large increase in potential evapotranspiration (PET), which increases the actual evaporation and reduces the recharge. This causes the water table depth to drop (Figure 11, bottom), with the median water table depth in SHETRAN dropping from 8.4 m below ground in 2000 to 11.8 m below ground in 2080. This results in a decrease in the annual discharge over the 100-year simulation, leading to the more severe droughts.

Further investigations and comparison with measured groundwater levels in SHETRAN are required before firm conclusions can be made on which models are likely to be producing the most realistic predictions of the severity of the droughts in groundwater dominated catchments under a future climate. If the results presented here are correct, increased stress could be placed on groundwater and surface water resources in the south and east of the UK than estimated by other studies; these would be likely to require additional, regional management strategies.

Secondly, considering flood and other high flow metrics, Kay et al. (2021b) conclude that studies into flood risk in the UK generally show that flooding is likely to increase in the future and that we are likely to be seeing the effects of this already. This will produce an increase in the expected damages (Sayers et al., 2020; Bates et al., 2023). Lane et al. (2022) simulated 346 catchments across GB using 12 RCMs from UKCP18 as driving data for the DECIPHeR hydrological modelling framework and found increased flood flows in Wales, Scotland, and northern England. However, there was considerable uncertainty in the south and east of England depending on the RCM, with some producing an increase and some a decrease in flooding.

Similar results are seen here in the 4°C warming period with a majority of RCMs showing an increased in flood flows in Wales, Scotland and northern England and a majority show a reduction in peak flows in the south and east of England. 2°C warming shows catchments in the south east of the UK having reduced high flows in all but a few of the RCMs. While this may well be true for the daily flows considered here, other research shows that flooding from intense rainfall is likely to increase right across the UK (Kendon et al., 2014).

4.2 Comparison with other land cover impact studies

A review of the effect of urbanisation and climate change on urban flooding (Miller and Hutchins, 2017) found -high confidence that both pressures will result in an increase in pluvial and fluvial flood risk. A more recent study in the UK that considers the effect of urbanisation on river flows found increasing river flows with increasing urbanisation (Han et al., 2022) with low flows showing the biggest change. Our research agrees with consensus that both urbanisation and climate change increase the potential for fluvial flooding, although we found the maximum percentage change occurs

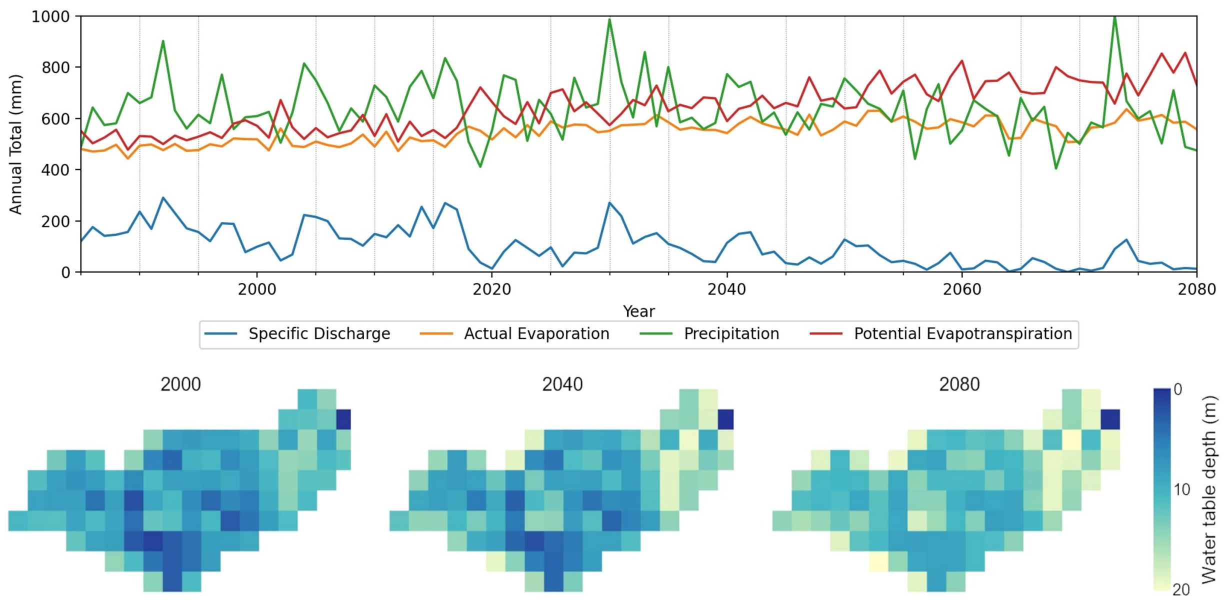

FIGURE 11
(Top) the area normalised SHETRAN long term water balance for catchment 33029 for RCM 4. The first 5 years of spin up period are not shown. (Bottom) SHETRAN simulated water table depths for catchment 33029 showing the 1 km grid resolution. The grid square in the north east with the water table close to the ground surface is location of the urban part of this catchment, which has an impermeable subsurface. This shows the water table dropping between 2000 and 2080.

for a 1 in 3-year events rather than for low flow found by Han et al. (2022).

The complexity of the hydrology within an urban environment makes predicting the effect of urbanisation on fluvial flooding difficult. It is significantly affected by a variety of features including the design of the sewage system and stormwater ponds, and the location of urbanisation within a catchment (Birkinshaw et al., 2021; Birkinshaw et al., 2021). Urbanisation is also expected to increase hourly extreme rainfall (Li et al., 2020), which will make urban areas increasingly vulnerable pluvial flooding (Miller and Hutchins, 2017), these effects will be explored in future work (Section 4.4).

There are two NFM measures considered in this work: afforestation and increased storage. Afforestation has led to increased evapotranspiration and a reduction in river flow across Europe (Teuling et al., 2019). Recent modelling work (Buechel et al., 2023) that considers the effect realistic afforestation scenarios under current and future climates in Great Britain showed a reduction in low flows due to afforestation but no reduction in high flows and that modelled changes are minimal in comparison to those driven by climate change. In our work, although afforestation is shown to reduce both high and low flows to some degree, we also conclude that the effect of afforestation is minimal in comparison to that of climate change. Furthermore, potential reductions in low flows due to afforestation may be of additional concern in the south and east of England, as this work shows that under a future climate there is expected to be a reduction in river flows and increased droughts as the climate changes. Conversely, Meier et al. (2021) show from observations that afforestation can increase precipitation—this is not considered in this work but could potentially mitigate some of the afforestation effects.

Increased storage using NFM measures is achieved by the building of soft-engineered structures or runoff attenuation features (RAFs) that reduce the connectivity between fast overland flow pathways and the channel by temporarily storing water. Although well-designed RAFs reduce flooding at the local scale there is currently a lack of evidence for the effectiveness of RAFs at larger catchment scales (Quinn et al., 2022). Recent research (Beven et al., 2022) in the Kent catchment found that many RAF features reduce the flooding by only a small amount for large events but that they can be more effective locally. A similar reduction in peak flows can be seen in this research but with large variability depending on the catchment and the location of the measures within a catchment.

These results suggest that, in a scenario of unaddressed warming (as in the RCP 8.5 climate scenarios modelled here), with urban development in line with the UDM modelled storylines, daily river flows are controlled by the changing climate and not urban changes (although these do not consider increased water consumption). Furthermore, while the widescale NFM strategies modelled here are shown to decrease high daily river flows, these alone cannot mitigate the full impact of climate change and could, in some drier regions, intensify the effects climate change during periods of lower flow.

4.3 Model simplifications and improvements

This work has for the first-time produced results for the application of a physically-based spatially-distributed hydrological model for a large set of UK catchments, including simulating future climate scenario and land-use scenarios. Previously physically-based hydrological models have been criticised for being over parameterised (Beven, 2001). Here the aim was to use parameters values based as much as possible on measured or standard library values, leaving only five parameters to be optimised using an automatic calibration procedure. For the 698 catchments considered in this work the autocalibration has produced a similar or better model fit to historic observation than conceptual models.

However, a number of simplifications were necessary, and these are considered here.

1 Only two land uses were considered, a rural and an urban land-use.
2 For rural grid squares a single soil type and aquifer type was considered throughout the catchment and the aquifer was only considered down to a depth of 20 m (urban cells had a very shallow impermeable soil).
3 No groundwater or surface water abstractions were considered.
4 Flow out of the model is only possible at the river outlet as catchments did not have boundary conditions linking them to neighbouring catchments; as such, groundwater catchments are taken to match the surface water catchments.

These simplifications were introduced to reduce the number of parameters that needed to be calibrated but could be removed in further work. Certain catchments or groups of catchments have been identified where these simplifications have reduced the quality of the simulations and are discussed below.

There is a group of 12 catchments in East Anglia where there is a chalk aquifer overlain in parts with low conductivity glacial till, which were not well simulated with a NSE less than 0.7. Incorporating the correct spatial distribution of glacial till would likely significantly improve these simulations. Chalk aquifers are known to have complex spatial patterns of transmissivity which may also need to be represented in detail.

A large number of catchments have significant groundwater abstractions, and these are often implicitly taken into account in models through the calibration process (Rameshwaran et al., 2022). Similarly, in this work the abstractions are implicitly taken into account by increased evapotranspiration during the autocalibration of the ratio of actual evapotranspiration to potential evapotranspiration (AE/PE) (Table A2). This produces the correct water balance within the catchment but in some cases gives an AP/EP ratio that is very high. In SHETRAN, abstraction wells can easily be included within the model, but the locations and the amount of water abstracted are in many cases unknown making adding them to the model difficult, especially at a national scale. However, there is the potential to add abstractions in a physically realistic way taking into account uncertainties in their locations and abstraction rates, when data from studies such as Rameshwaran et al. (2022) becomes available. AE/PE ratio parameters are available in the published dataset and so results can be easily filtered by the used to exclude catchments with high values if desired.

4.4 Uncertainty

Hydrological modelling involves uncertainty at all stages of the modelling process whether this be from input flow and meteorological data during model setup and calibration, or the storylined approaches to climate change, urban development and natural flood management. The use of the quality-controlled CAMELS-GB dataset helps reduce uncertainty by providing standardized input data for comparison with other studies. Presenting results from all 12 climate RCMs, along with median values, serves to highlight the range of uncertainties in climate projections. The autocalibrated SHETRAN-UK model parameters generally fall within expected ranges, with subsurface conductivities correlating well with UK aquifer units. Ongoing research into parameter uncertainty, equifinality, and their effects on future climate projections will be published in future work.

4.5 Additional work

Additional work is either in progress or planned, with the intention either to improve the modelling for future studies or to develop our understanding of the modelling results.

1 Comparison of the results with the conceptual HBV and the data driven LSTM models. HBV and LSTM simulations have been set up and run for the same catchments using the same measured data.
2 The use of hourly precipitation and discharge data for autocalibration and hourly precipitation data for the long-term climate simulations using UKCP local. This will provide greater information on high flow events and the implications of increased urbanisation or NFM implementation, especially for intense hourly scale events that, here, are simulated as occurring uniformly over 24 h periods.
3 Examination of modelled and recorded groundwater levels and soil moisture data to further assess model performance and the effects of climate change on groundwater levels. This is especially relevant in the East of England to assess whether the modelling conducted here correctly portrays reduced groundwater levels in comparison to other studies.
4 The inclusion of abstraction data in future model calibration to enable improved model performance in non-natural catchments (as in Rameshwaran et al., 2022).

The historical and future climate simulations used in this research used daily measured and simulated discharge and were driven with daily meteorological data (precipitation, PET, temperature). For large catchments this satisfactorily captures the fluvial flooding that occurs. However, localised short duration (hourly or sub-hourly events) are expected to increase in frequency and intensify (Fowler et al., 2021; Kendon et al., 2023) potentially leading to an increase in flash flooding for small catchments (Dale, 2021). Hourly precipitation data should be included in future work together with calibrations carried out for hourly measured and simulated discharge data. This will improve the accuracy of the flood predictions for the short duration high intensity events. Furthermore, while SHETRAN can, at this scale, simulate overland flow on a 1 km grid, fine detailed hydro-dynamic models are necessary to capture the surface flooding that occurs in urban areas as a result of these high intensity events (Glenis et al., 2018).

One of the advantages of using a physically-based spatially-distributed model is that the soil moisture and water tables depth are produced by the model. This means the model outputs can be tested against measured soil moisture data (Bell et al., 2022; Gruber et al., 2019) and groundwater levels (British Geological Survey, 2023). So, as well as producing good simulated discharges at the catchment outlet, we can test that the model is producing realistic results within the catchment, which gives greater confidence that the processes included within the model are correct. This would create a fit-for-purpose model producing the right results for the right reasons (Beven, 2018; Naz et al., 2022). This internal validation of the results is currently in progress.

5 Conclusion

The physically-based spatially-distributed SHETRAN hydrological model was automatically calibrated for 698 UK catchments using daily measured data for the years 1980–2010. This consisted of 668 catchments from the Camels-GB dataset plus 30 catchments in Northern Ireland. The autocalibrated catchments were then run for 12 RCM realisations of the UKCP18 climate projections for the years 1980–2080 and as well as storylined urban development scenarios and natural flood management scenarios (incorporating woodland and storage ponds). This is the first time a physically-based hydrological model has been run for combined future climate and land cover scenarios for such a large range of UK catchments and the results are broadly similar to those produced using simpler conceptual models. The main points are:

1 An increase in the likelihood and severity of droughts particularly in the south and east of England with the situation worse at 4°C warming compared to 2°C of warming.
2 An overall reduction nationally in the median daily river flows with a 12% drop for a 2°C warming and 26% drop for a 4°C.
3 For the majority of the RCMs we see an increase in daily peak flows in floods in Wales, Scotland, northern England, and Northern Ireland and a reduction in peak flows in the south and east of England for the majority of the RCMs.
4 An increase in daily flows with increased urbanization and the with the 1 in 3-year event showing the biggest increase, though this is small in relation to the influence of climate change.
5 Overall, the natural flood management scenarios show a reduction in flows, although the more extreme the flow event the smaller the percentage change in flow. There is significant regional variation, with woodland in Scotland producing a small reduction in peak flow, whilst woodland in East England produces a large reduction.

The main difference between these results and the conceptual hydrological models is the more extreme droughts predicted here for the south east of England, and the related decrease in flood peaks for daily flows. It is clearly important to understand why these models are producing different results and so all the model setups and outputs data from this work, along with much of the analysis code, have been made freely available to enable comparisons and future model development.

There are potentially huge human, environmental, and financial costs associated with the changing climate and by producing realistic future hydrological predictions of droughts and flooding this work has increased our understanding of the consequences of this changing climate and so can be used to assess these costs. Indeed, if the hydrological changes modelled in this work transpire, there will likely be significant human and ecological impacts, with potential for major disruption to water supply and demand.

As such, decision makers require detailed projections of future river flows on a national and local scale. Information on not only climate impacts, but also future land cover change and potential adaptation options are required. This dataset allows users to explore future combinations of climate and land cover scenarios at both a detailed catchment scale and a national scale through a comprehensive, rigorous, physically-based modelling system.

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: OpenCLIM—Catchment Flow Metrics, https://catalogue.ceda.ac.uk/uuid/81567bfb789e4ec4ae30cdd3772f8242; OpenCLIM—Catchment Discharges, https://catalogue.ceda.ac.uk/uuid/a2e1601a29004c13849be5e84594f37a.

Author contributions

BS: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. SB: Investigation, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review & editing. EL: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. EM: Investigation, Writing – review & editing. PS: Funding acquisition, Methodology, Resources, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2024.1468855/full#supplementary-material

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