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Policy interventions to address water security impacted by climate change: Adaptation strategies of three case studies across different geographic regions

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Water shortage in terms of both physical and economic water scarcity is still a major issue globally. The looming climate change threat has increased the adverse threats to water security in different regions. However, policy solutions to water security vary in different geographical regions and at different scales (local, regional, national, etc.). Understanding the successes and challenges of different policy solutions is critical to scaling-up successful policies and addressing water security holistically. This paper aims to explore the effects of implementing policies at different scales in three different case study contexts: 1. two Counties in California in the USA, 2. the City of Cape Town in South Africa and 3. the Country of Bangladesh. These case studies highlight various implemented policies and their effectiveness in each context. We reviewed relevant research papers consisting of peer-reviewed journal articles, conference proceedings and gray literature using a content analysis approach based on keywords such as water scarcity, water shortage, climate change, policies, interventions and solutions. Based on this cross-case analysis, we present key strategies moving forward, including: reallocation of water based on different community and sector needs, the importance of stakeholders engagement and public awareness, and a need to implement both short and long-term management plans. There is no one-size fits all policy solution to water scarcity. Understanding the context, scale, and cultural environment will be a key to future water security-focused interventions and policies.

KEYWORDS

water security, climate change, water management, water scarcity, policy interventions

Introduction

Water is an integral part of the survival for life in terms of both direct consumption and maintaining the environment. The extent to which it is abundant or scarce, clean or polluted, beneficial or destructive, largely determines the quality of life for nearby and/or dependent populations (Visser-Quinn et al., 2021). Water scarcity refers to a lack of freshwater resources to meet a region's human and environmental needs (van Vliet et al., 2021). Water scarcity is intrinsically tied to human rights, and ensuring adequate access to safe drinking water is a global development issue (Grillos et al., 2021; Orimoloye et al., 2021). However, many countries and large cities around the world have experienced increasing water scarcity in recent years as a result of climate change patterns related to global warming, population increase, and demands exceeding supply (Orimoloye et al., 2019).

Physical and economic scarcity are the two main types of water scarcities. When water demand exceeds water supply in any given geographical area, it is a physical or absolute water scarcity. According to the United Nations Food and Agricultural Organization (FAO) (2018), around 1.2 billion people live in areas of physical scarcity (Petruzzello, 2021), with many of these people living in arid or semi-arid countries. Physical water scarcity can be seasonal; an estimated two-thirds of the world's population lives in locations where water scarcity occurs at least once a year. As the world's population grows and weather patterns become more unpredictable and intense, the number of people affected by physical water scarcity is likely to rise (Ismail and Go, 2021; Petruzzello, 2021).

Economic water scarcity, on the other hand, is caused by a lack of water infrastructure in general, or inadequate management of water resources where infrastructure exists (Zisopoulou and Panagoulia, 2021). According to the FAO, more than 1.6 billion people are affected by economic water scarcity (Alobireed, 2021; Petruzzello, 2021). There is often enough water to meet human and environmental demands in locations with economic water scarcity, but access is constrained. Large inefficiencies in water use can contribute to water scarcity, mainly due to an economic undervaluation of water as a finite natural resource. Water undervaluation could result from inappropriate water tariff and underpricing. Accessible water may also be polluted or unfit for human consumption due to mismanagement or under development (Egbueri and Agbasi, 2022).

Anthropogenic pollution has been identified in all parts of the world, leading to degradation of water quality through nutrient and pathogen loading, and chemical pollution (United Nations, 2021). Thus, not only are physical and economic water scarcity a concern for water security, but also water quality. A recent study (Persson et al., 2022) submits that the safe operating space for the novel entities planetary boundary, which includes chemicals of concern (e.g., per- and polyfluoroalkyl substances and other forever chemicals) has been exceeded, and the United Nations estimates that 80% of global wastewater is discharged to the environment without treatment [WWAP (United Nations World Water Assessment Programme), 2017]. Such unrestricted water use for agriculture or industry, frequently at the expense of the public especially in countries where regulations are not well implemented, can also lead to economic water scarcity. However, some forms of water degradation can occur naturally, such as the leaching of geogenic elements, like arsenic and fluoride, from rocks. Water quality contributes to economic water scarcity. Reduction in water quality status results from a variety of sources including point source and non-point source pollution. These pollution sources could be attributed to anthropogenic and natural (geogenic) causes. Anthropogenics could result from inappropriate monitoring policies such as untreated wastewater discharge, unregulated chemicals discharged into water bodies by industries and farmland, among others (Baba and Gündüz, 2017).

Climate change leads to the disruption of weather patterns, resulting in extreme weather events, unpredictable availability of water, contaminated water supplies, and ultimately water scarcity (Kisakye and Van der Bruggen, 2018; Migdall et al., 2022). Climate change has also been demonstrated to have an impact on ecosystems, by altering the ecosystem water balance both directly and indirectly (Nosetto et al., 2012; Bradford et al., 2020). Extreme droughts alter the local hydrology and results in decreased plant productivity and increased tree mortality, as well as a reduction in the delivery of water-derived ecosystem services such as nutrient cycling, and flood management (Schwärzel et al., 2020; Stringer et al., 2021). These have dire consequences on the quantity and quality of water that humans have access to. In many regions, especially water-stressed areas, water availability is becoming less predictable and unsustainable due to increased flooding, drought, and contamination of water sources (Dasgupta and Sen, 2021; Nolte et al., 2021). Hence, in this paper, we define water sustainability as when a water resource is readily available and useful for an intended purpose. For example, enough water available for agricultural irrigation or water that is available and of high enough quality for human drinking water.

Developing nations and disadvantaged populations in developed countries, which are already sensitive to water supply risks, are likely to be the hardest hit, as noted in previous studies (Oki and Quiocho, 2020; Zhang et al., 2020) with more floods and severe droughts expected in the near future. Changes in water availability will impact human health and food security, thereby affecting population dynamics and political stability even in geographic areas not directly impacted by water scarcity, especially in low-income nations (Pawlak and Kołodziejczak, 2020).

Understanding policy solutions that address water security and sustainability in the face of all of these environmental stressors, including climate change, is critical. This helps in strengthening the understanding of the sensitivity of agricultural and water-management practices, especially in relation to irrigation. Given that crops and livestock consume a large percentage of irrigated water at local or regional levels, lack of water security could significantly affect agricultural production (Fader et al., 2013; Mancosu et al., 2015). The knowledge of improved policies and management practices can also aid in determining the best irrigation methods, taking into account water availability and sustainability (Young et al., 2021). Advancing water security policy solutions cuts across the water-energy-food sectors through building and sustaining strong coordination among the key stakeholders responsible for governance in each sector (Young et al., 2021).

Water scarcity assessments provide valuable information on current and future water availability, with the purpose to provide suitable water management preparedness and implement successful adaptation plans based on conditions specific to the region (Brauman et al., 2016). Once the data on the state of water availability is collected, then local and regional managers must consider if the policies and management practices available to mitigate water scarcity are successful in that region, while highlighting the importance of community and cultural awareness. Just as scale is a necessary variable when attempting to provide reliable estimates of water scarcity, scale should also be considered in the adaptation and response measures employed.

Identifying who the key stakeholders are and how to design an inter-sectoral governance structure at international, national, and local levels can be enhanced or aided with the understanding of water security and successful policy solutions. Understanding the successes and challenges of different water security policy solutions needs to be well-explored at various scales. It is particularly critical because steady water supply, access, and use are intrinsically valuable human rights that should be pursued as a goal. As a result, more emphasis on practices and policies that can ensure water security is required to address water security issues. As the importance of water security is increasingly recognized as a serious concern given changes in climate, economics, and society, water will be prioritized in research, programs, funding, and policies.

In this paper, we use a case study approach to discuss different types of policy interventions employed in three different geographic locations and three different scales (City, County, and Country) to address issues of water security that span both surface and groundwater resources. We draw from examples spanning three continents: Imperial and Kern Counties, USA; Cape Town, South Africa; and Bangladesh. Relevant research papers consisting of peer-reviewed journal articles, conference proceedings and gray literature were reviewed using a content analysis approach based on keywords such as water scarcity, water shortage, climate change, policies, interventions and solutions. Each case study differs in scale and population served, from two rural agricultural counties (USA), an urban city (South Africa), and the country-wide problems facing Bangladesh. In each case study, we describe the intervention and discuss challenges and successes. At the end of this paper, we provide lessons learned and opportunities to improve. This paper takes the novel approach of exploring policy solutions at multiple case study geographies at various scales. This approach is important and novel as water security issues at one scale will likely impact other scales, as do policy solutions. Thus, our case studies draw from various examples and types of solutions to develop recommendations and best practices. While each intervention discussed is context-specific, our goal is to use a cross-case analysis to highlight possible solutions and policy mechanisms that may be scaled-up and/or applied elsewhere to help address issues of water scarcity in contexts similar to those of our case studies.

Selected case studies

In this section, we focus on outlining case studies from selected geographic regions: California, USA; Cape Town, South Africa; and Bangladesh. These three case studies were selected because they represent policy interventions for water scarcity arising from different environmental conditions and also to address water scarcity at various scales (county, city, country), including both groundwater and surface water. Additionally, they provide examples of context-specific interventions in different climatic, hydrological, and socio-economic systems.

Case study 1-Two counties in California, USA: Policy mechanisms to address groundwater and surface water scarcities in agricultural regions

Introduction to California

Croplands are critical to global food production, yet the people, ecosystems, and landscapes where they are located are increasingly under stress from climate change (Rosenzweig et al., 2014; Hanak et al., 2017). One example is the state of California in the western USA; where in 2020 the $50 billion dollar agricultural industry produced 1/3rd of the vegetables and 2/3^{rds} of the fruits consumed in the USA. California contains 1/6th of all irrigated land in the USA, and in 2015, 80% of total water consumption was allocated for agriculture (Berbel and Esteban, 2019). In arid and semi-arid regions of California, scarce surface water has led to the depletion of groundwater (Konikow and Kendy, 2005). In dry years in California, groundwater accounts for up to 60% of the irrigation water and has led to widespread over drafting of groundwater supplies (Hanak et al., 2017). There are also tensions for water between agricultural regions and the densely populated urban centers of San Francisco, Los Angeles, and San Diego.

Unlike other parts of the world, water management in California is decentralized, into local, municipal, and regional water agencies and organizations in addition to federal and state government entities (Berbel and Esteban, 2019). Indeed, recent droughts have catalyzed the creation of new institutions and sophisticated long-term policies and measures to mitigate the impacts of future drought (Berbel and Esteban, 2019). Two recent policies in California include the Quantification Settlement Agreement of 2003 (QSA), and the Sustainable Groundwater Management Act (SGMA) of 2014. Below, we present the case studies of the QSA in Imperial County and SGMA in Kern County and discuss highlights of the successes and challenges. The scale of analysis is the County, and how these two counties are addressing their water scarcity challenges in the agricultural sector.

Imperial County: Surface water and the quantification settlement agreement

Located on the US-Mexico border, Imperial County is a hub of wintertime agricultural production as farmers produce 2/3^{rds} of the wintertime vegetables eaten in the USA (Imperial County Farm Bureau). Imperial County is the hottest and driest region in California (Hopkins, 2018), and agriculture in the County is only possible with irrigation water from the Colorado River. Water from the Colorado River, which lies on the California-Arizona state border, is brought to the area through the 82-mile All-American Canal, and in 2017 the canal provided irrigation water for about 456,089 acres of land [United States Department of Agriculture (USDA), 2017]. Since Colorado River water first reached the area in 1901, policy has played a critical role in securing water rights and access. For example, the Colorado River Compact of 1922 established allocations of river water to Imperial County, which is allocated 77% of California's total surface water from the Colorado River (Carter, 1966; Finley, 1974; Munguia and Ganster, 2006; Butler, 2015).

San Diego County lies just to the west of Imperial County and is the home of the urban city of San Diego and ∼3.4 million people. With only a few local sources of water, San Diego County is forced to import water to meet the County's needs. In 2003, the Quantification Settlement Agreement (QSA) was reached, in which the local water district in Imperial County, called the Imperial Irrigation District, agreed to sell and transfer water to the San Diego County Water Authority (SDCWA) to meet the water needs of the city of San Diego. The Imperial Irrigation District could then use these payments from SDCWA to implement water conservation and agricultural fallowing programs to promote water-use efficiency on Imperial County farms (Cohen and Hyun, 2006; Butler, 2015; Rosenberg, 2021). This would then free up the surface water previously used for irrigated agriculture to send to San Diego County.

The QSA however was not without controversy, as agricultural stakeholders in Imperial County feared that the QSA might threaten their well-established water rights and allocations (Butler, 2015). Leveraging QSA funds, Imperial Irrigation District was also able to build a concrete lining for the All-American canal that brings water to the area from the Colorado River and lies just north of the Mexico-US border to reduce seepage and water loss (Munguia and Ganster, 2006; Butler, 2015; Hughes, 2020). This action faced resistance from the Mexican government, social and environmental justice groups, as Mexico had benefited from the water seepage in the maintenance of wetlands and agricultural land on the Mexican side of the border. Importantly, the water conservation measures implemented have led to less agricultural runoff reaching the Salton Sea–a large inland lake with no outlet that relies on irrigation runoff as a source of water. This has caused the Salton Sea to shrink, exposing the lakebed and leading to wind erosion and severe air quality issues resulting in health problems like increased rates of childhood asthma (Aguilera, 2019; Rosenberg, 2021).

Kern County: Groundwater and the sustainable groundwater management act

Kern County, located in the southern area of the Central Valley, California, is one of the most agriculturally productive landscapes in the world. In 2018, the almost 3.3 million acres of farmland produced over $7.4 billion dollars in agricultural commodities (Kern County, 2019). The major crops include grapes, almonds, pistachios, and citrus (Kern County, 2019; Wartenberg et al., 2021). Agriculture in Kern County is acutely dependent on both surface and groundwater (Elias et al., 2015), with prolonged and recurring drought affecting water availability. Drought and extensive groundwater pumping has not only led to over drafting and unsustainable water management, but during the 2012–2016 drought, water shortages were reported for domestic and household use as well (Greene, 2021; State of California, 2019). As a result, Kern County is one of 21 critically over drafted groundwater basins in California, which over the past 30 years the average overdraft has been about 2 million acre feet of water each year (Pitzer, 2019).

In order to remedy this issue, achieve long-term groundwater balance, and recharge sub-basins by 2040, in 2014 California passed the Sustainable Groundwater Management Act (SGMA). SGMA calls for the establishment of local Groundwater Sustainability Agencies who are tasked with creating Groundwater Sustainability Plans (Hanak et al., 2017; Kelsey et al., 2018). SGMA is the first state-wide groundwater management legislation and is overseen by the State Water Resource Control Board. SGMA allows for discretion in institutional design, and each basin has developed different governing systems. In the 2,834 square mile Kern sub basin are a total of 21 Groundwater Sustainability Agencies, including the Kern River Groundwater Sustainability Agency (KRGSA) (2020) and the Kern Groundwater Authority (Mknelly, 2021).

These agencies have collaborated to create 11 Groundwater Sustainability Plans (Mknelly, 2021). While activities vary in each Groundwater Sustainability Plan, the KRGSA plan includes increased water banking, use of recycled water, converting agricultural lands to urban areas and housing developments among others [Kern River Groundwater Sustainability Agency (KRGSA), 2020].

While this mix of approaches will help meet the objectives of SGMA, it is forecasted that Kern County will have to retire approximately 800,0000 acres out of production due to water scarcity (Kelsey et al., 2018; Hanak, 2019). While many farmers have thus far absorbed cuts in water deliveries through improved on-farm efficiency, this strategy will only go so far before land must be fallowed (Pitzer, 2019). Importantly, research has found that the groundwater minimums established in Groundwater Sustainability Plans are not enough to recharge shallow groundwater wells used by households and communities for domestic consumption (Bostic, 2021). This could result in over 100,000 people having their household wells dry up by 2040 (Bostic, 2021). Research has also suggested that the variance in institutional design, composition, and management across Groundwater Management Agencies in Kern County may decrease transparency, stakeholder accessibility, and community engagement (Mknelly, 2021).

Challenges and successes

The QSA and SGMA have been successful at promoting both on-farm and system-wide water efficiencies in order to reallocate water resources-urban water use in the case of the QSA and recharging groundwater basins in the case of SGMA. SGMA has led to the creation of new institutions, groundwater sustainability plans, and initiated activities and actions to sustainably manage historically over drafted groundwater basins. The QSA has secured water for the growing urban area of San Diego, which has few local water resources to rely on.

The increased water efficiencies promoted by both SGMA and QSA policies have contributed to a statewide increase in the economic productivity of water, with increases also in Imperial and Kern Counties (Cooley et al., 2014). Essentially, farmers are increasing their incomes, while decreasing their water use. For example, statewide, farm production generated 38% more income in 2015 than in 1980, even though on-farm water use was 14% lower (Mount and Hanak, 2018). For example, in Imperial Valley, funds from the QSA have helped farmers replace flood irrigation technology with micro-sprinklers and drip irrigation, significantly reducing water use (Tindula et al., 2013; Berbel and Esteban, 2019).

However, these changes in water-use efficiency and water availability are not without consequences. For example, as discussed, increased on-farm efficiency has decreased water flows into the Salton Sea, leading to local health issues from toxic dust exposure as the lake bed dries up. In Kern County, on-farm water efficiency can only go so far before a significant amount of land is fallowed due to water scarcity, with significant economic and environmental consequences.

Importantly, the focus of both policies is on water scarcity and sustainability, and not on water quality or access (Mknelly, 2021), which may result in less access to shallow wells for household water consumption (Bostic, 2021) and degraded water quality (Ayres et al., 2021). Furthermore, balancing California's consumptive uses of water with protection of its aquatic species and ecosystems continues to be a challenge. For example, California's native fishes are undergoing rapid decline, with 80% of species on paths toward extinction (Pinter et al., 2019). Lastly, it has been noted that despite the policy advances of the QSA and SGMA, water policy in California, including Imperial and Kern Counties, may remain ill-suited to face the severe drought, flood, wildfire, and sea-level rise risks posed by climate change (Hedden-Nicely, 2021).

Case study 2-Cape Town, South Africa: Policy mechanisms in place to avoid "day zero" water crises

Introduction to Cape Town, South Africa

The Western Cape Province, which includes the city of Cape Town as its capital, is situated on South Africa's southernmost coast. Cape Town is a growing, coastal city of 4.8 million people (Rogerson and Visser, 2020) characterized by a number of natural and man-made tourist attractions. The varying topography and effect of the surrounding ocean currents have formed several distinct micro- and macroclimates in the Western Cape. These are the warm Agulhas current, which flows south along South Africa's east coast, and the cold Benguela current, which flows west along South Africa's west coast and is an upwelling current from the depths of the South Atlantic Ocean (Branch and Branch, 1981; Tyson and Preston-Whyte, 2000). As a result, climatic conditions can differ dramatically across short distances. The city of Cape Town and the majority of the province has a Mediterranean climate, with cold, rainy winters and hot, dry summers. Cape Town has an average mean yearly rainfall of 515 mm and a mean temperature of 16.7°C. The Cape Metropolitan Areas are regarded as a winter rainfall area. However, the meteorological depressions that normally bring rain to this area in winter move past to the south of the area and the land mass during summer which leads to a long dry spell.

Physical and economic scarcity are the two main types of water scarcity in the Western Cape. Following a sustained rainfall in 2013 and 2014, the City of Cape Town and some parts of the Western Cape experienced drought in 2015, the first of 3 years of dry winters caused by the El Niño weather pattern. The City's dams' water levels dropped from 71.9 percent in 2014 to 50.1 percent in 2015 (Visser, 2018; Dube et al., 2020). Droughts and water scarcity in other parts of South Africa ceased in August 2016 but the Western Cape drought persisted. In March 2018, the City of Cape Town and its surroundings adopted major water restrictions in an effort to alleviate water scarcity and were able to cut daily water consumption by more than half, to roughly 500 million liters (130,000,000 US gal) per day (Narrandes, 2018). Furthermore, the city introduced the catchphrase *Day Zero*. This phrase was a warning that its decreasing water source would shortly be unable to supply water to its inhabitants, tourists, and various industries including agriculture (LaVanchy et al., 2021). However, the City postponed its *Day Zero* prediction due to a drop in water demand, and a significant amount of rainfall that began in June 2018 thereby helping dam levels to recover. At present, the city has moved beyond the intimidations of lack of water supply, but its water supply structures remain fragile mainly because climate change and sea surface temperature warming threaten to further disturb the timing and position of wintertime storm fronts necessary for reservoir replenishment. Furthermore, it is convincing that multi-year droughts comparable to or worse than the *Day Zero* drought, will affect Cape Town again (LaVanchy et al., 2019, 2021) which emphasizes the need for policy mechanisms to be in place for achieving water sustainability in Cape Town, Western Cape Province of South Africa.

Policy mechanisms for water sustainability in Cape Town

Water demand is high during the dry season as a result of higher temperatures and a custom of watering gardens among the residents. This contrast complicates the management of a bulk water supply system, as sufficient run-off needs to be stored during winter in order to meet the increased water demand in hot and dry summer months. Inadequate condition of the existing water resources and the scarcity of raw water storage capacity have evidently amplified the threat of water scarcities happening in the Cape Metropolitan Areas from the year 2001 and onwards [City of Cape Town (CCT), 2007]. Therefore, a multidisciplinary strategy was adopted to address both surface and groundwater scarcity. Water resources are managed in a way that maximizes economic and social wellbeing while not jeopardizing ecological functions, to manage and protect water resources in order to prevent a repeat of the drought or other climate and human events. This section highlights the policies implemented to avert Day Zero. No new policy is suggested, instead we aim to provide a review of what was done, what worked, and how it worked. These policies implemented in Cape Town as strategies to provide solutions to the water crisis in the area are discussed below.

Water conservation and water demand management strategy

The City of Cape Town adopted a water conservation and water demand strategy to reduce loss or waste of water; protect water resources; and promote efficient and effective use of water [Department of Water Affairs and Forestry (DWAF), 2004]. Furthermore, this was also adopted to endorse actions that promote sustainable use of water resources (Savenije and Van der Zaag, 2002). This policy backs the strategic aims drawn in the council's vision, goals and priorities statement for 2003 and beyond. Its development began in 2004 after the department of water affairs had approached the city of Cape Town and demanded that it intensify its commitment to water conservation and water demand management [City of Cape Town (CCT), 2007]. Water conservation and water demand management strategy aims to achieve water savings from all consumer categories including industrial, target reticulation losses, and exploring alternative water resources to reduce abstraction from the current surface water resources. It also aims to educate, capacitate and provide direct support to consumers so that they achieve savings with no negative effect on economic activities or lifestyles [City of Cape Town (CCT), 2007]. Furthermore, it plays a crucial role in rehabilitation of wetlands, removal of invasive vegetation, prevention of pollution to rivers, and the decrease of usage of water from water resources [City of Cape Town (CCT), 2007].

Water sensitive urban design

The City of Cape Town's new water policy was issued in 2019, aimed precisely to turn Cape Town into a water-sensitive city to complement the old existing policies. This strategy intends to unite the engineering concept of integrated urban water management (IUWM) with the planning concept of urban design in order to build a water sensitive city where the most well-organized and operative utilization of water is well thought out. This strategy embraces all facets of integrated urban water cycle management, including water supply, sewerage, and storm water management (Madonsela et al., 2019). The IUWM was designed to address the poorly coordinated management of water resources that led to the water scarcity crisis. The IUWM combined all facets of water sources and resources into a tool for a holistic common approach in solving Cape Town water management problems. The principles of water sensitive urban design are to protect and enhance natural water systems; improve the quality of water draining from urban area; use storm water treatment systems in the landscape for multiple uses and with multiple benefits such as water quality treatment, wildlife habitat, public open space, recreational and visual amenity; reduce peak flows by on-site temporary storage measures with potential for reuse and reduce impermeable areas; and reduce the drainage infrastructure cost of development and use storm water as a resource through retention and reuse for non-potable purposes [City of Cape Town (CCT), 2019].

Challenges and successes in averting "day zero"

The re-visitation of water rights and allocations played a dominant role in the successes of averting "Day Zero." To determine a fairer process of water allocation between competing users and sectors, a set of water resource management decisions were made to reallocate water. For example, the amount of water consumption by commercial farmers in South Africa, including Cape Town, was not evenly coordinated or distributed. The need for an equal right to water usage by consumers, small and large scale farmers, therefore necessitated merging the concept of right over water (such as access to the amount of groundwater abstracted) and availability of water for the needs of other consumers. To ensure equitable distribution of water, water management and rights decisions were made based on water allocation and the needs of other users (Dugard, 2021) leading to a reallocation, with the primary intention of achieving equity for farm size (smallholder and large-scale farmers), race and gender equity, as well as meeting international obligations and the requirements for water rights (City of Cape Town, 2020). Equity in this context means equal access to water that is readily available and fit for the intended purposes.

The city implemented a series of water restriction policies to avert day zero. The water restriction policies ranged on a scale of one to six. One was less severe and six was the most severe restriction. All the implemented policies can be grouped into short and long term intervention. Specific successful policies undertaken are: the declaration of a water disaster area, the creation of a water resilience task team, and the release of a water resilience plan to accommodate Day Zero. Others are the approval by the finance minister allowing the city to alter the budget mid-year, the launching of a provincial disaster management plan, the launching of the city online water management dashboard and the transfer of water from nearby dams to augment Cape Town water supply (Joubert and Ziervogel, 2019).

Shorter-term and less successful long-term interventions to avert "Day Zero" included failed plans to augment the municipal water supplies with groundwater, greywater usage, and desalination. Desalination plants were constructed to provide water during the intense drought. The plant is now abandoned due to the high cost of treatment (Joubert and Ziervogel, 2019), sewage in water sources (from the city's pipe, especially along the coast of the commercial areas) and an algal bloom in the plant. In addition, the plants were only given a 3 year license by the Department of Water Affairs. In search of longer-term solutions like the water rights and reallocation decision-making described previously, the national and regional government also embarked on intensive exploration and exploitation of existing aquifer systems. The inability to tap groundwater sources extensively was due to the poor water quality across the Cape Flat aquifers, hence limited boreholes were eventually drilled.

In summary, community and stakeholder decision-making based on equity and water allocation were most successful in providing immediate and long-term solutions to water challenges in Cape Town (Ziervogel, 2019). Shorter-term opportunities such as desalination and other alternative water supplies may have provided some initial relief but do not appear to be viable long term options for providing water security in a region where climate change is predicted to further stress water supply by reducing the amount of rainfall available to recharge water reservoir storage. The subsequent (post "Day Zero") development of policies that move Cape Town toward a water-sensitive city through integrated urban water management may pose opportunities for long-term improvements to water access under climate change. It is obvious that if Cape Town continues with the IUWM policies it would lead Cape Town toward a circular economy, water sustainable city, and climate resilient environment based on water reuse and recycling.

Case study 3-Bangladesh: Policy mechanisms to address geogenic groundwater quality

Introduction to geogenically-influenced water quality in Bangladesh

Degradation of water quality can also present a significant water security challenge. Some water sources are naturally elevated in elements of concern to human health, such as fluoride that leaches from volcanic deposits (Onipe et al., 2020; Parrone et al., 2020) and arsenic (As) present in some aquifers (Mukherjee et al., 2009). Podgorski and Berg (2020) predict that up to 220 million people (94% in Asia) are potentially exposed to geogenic arsenic concentrations greater than the World Health Organisation (WHO) drinking water guideline of 10 ug/L As. Such geogenic contamination of water sources thus presents a great threat to water security globally and the case in Bangladesh illustrates an example where access to clean, safe water defines a country's challenges regarding water security under increasing threats of climate change. The challenge for Bangladesh is not lack of water but lack of access to *clean* water. Climate change is contributing to sea level rise and salinization of coastal aquifers (Islam et al., 2020) as well as contributing to more intense floods and storms (Khan et al., 2011), which have increased the incidence of waterborne diseases. Abeden et al. (2019) report that residents of coastal areas under climate threats identify diarrhea, dysentery, and skin diseases as the dominant health risks from climate-related safe water scarcity in Bangladesh. Thus, access to arsenic-free groundwater is an important component of the country's ability to provide continuous safe drinking water under the increasing threat of climate change.

Bangladesh geogenic arsenic water: History and context

Historically, surface waters in Bangladesh have been prone to microbial contamination leading to acute gastrointestinal disease (particularly in infants and children) causing a significant burden of disease and mortality (Smith et al., 2000). In the 1970's the United Nations Children's Fund (UNICEF) and the Bangladesh Department of Public Health Engineering (DPEH) worked to install tube wells to tap aquifers, providing a safer supply of drinking water. At the time, arsenic was not routinely tested during water quality reporting. By 1987, however, patients in neighboring West Bengal began to present with skin lesions and pigmentation characteristic of arsenicosis (Saha, 1995) and by the late 1990's a comprehensive DPEH report produced in combination with the British Geological Survey estimated 55 million people in Bangladesh may be exposed to drinking water with elevated arsenic concentrations above the WHO 10 ug/L limit (Kinniburgh and Smedley, 2001).

Geochemical investigations ensued to understand the mobilization and transport of arsenic, which was found to be primarily controlled by reductive dissolution of iron oxyhydroxides and release of sorbed arsenic (Nickson et al., 2000), a geochemical process commonly observed in other global sedimentary aquifers impacted by elevated geogenic arsenic (O'Shea et al., 2007; Berg et al., 2008; Mukherjee and Fryar, 2008). Chronic exposure to arsenic *via* drinking water has been linked to diabetes, several types of cancer, high blood pressure and skin disorders (CDC, 2013) and for more than 20 years the Bangladesh arsenic crisis has been referred to as the largest mass poisoning, beyond the scale of the Chernobyl nuclear environmental disaster (Smith et al., 2000).

Bangladesh geogenic arsenic water: Policy and practices

Much work has been done to understand the health, geochemical, and sociological aspects of Bangladesh water security challenge. Ahmad et al. (2018) provides a comprehensive review of activities undertaken by the Bangladeshi government and non-governmental agencies to identify the extent of arsenic in groundwater, identify arsenicosis patients, and implement mass awareness programs to prevent exposure. Initially, a nationwide water testing campaign tested close to 5 million tube wells and painted those exceeding the Bangladeshi arsenic standard (50 ug/L) in red, while those wells which tested below 50 ug/L were painted green. Based on detailed studies in one *upazila* of 55,000 people and almost 5,000 tube wells, the spatial distribution of arsenic was found to be highly variable, with red-painted wells located close to green-painted wells, meaning that 90% of the population in the study upazila lived within 100 m of a "safe" well. As such, the researchers recommended switching wells to reduce arsenic exposure (Van Geen et al., 2002). Further investigation of the geologic controls on arsenic spatial heterogeneity (e.g., Radloff et al., 2011) indicated that deep groundwater could be used with low risk of arsenic contamination. Hence the installation of tube wells beyond shallow depths (potentially > 150 m depth) was recommended as a viable safe water source. Treating pond or river water by sand filtration raised concerns over microbial contamination, particularly since ponds are often located close to latrines (Ahmed et al., 2006). Household and community filtration systems were listed as one option in the National Policy for Arsenic Mitigation but a study analyzing 18 arsenic removal plants cited maintenance, clogging, and a lack of user friendliness as challenges to success, resulting in 15 of the 18 plants not working by the end of the 2 year study period (Hossain et al., 2005). Piped water supplies are least used and most expensive. Overall, the cost of testing a well with a field kit (and potentially promoting well switching) is only $1 per person compared to $143 to drill a well that targets deeper As-free aquifer sediments, or $158 per person for a piped water supply (Jamil et al., 2019). Given that the costs associated with arsenic-related mortality are estimated up to $12.5 billion over the coming two decades (Flanagan et al., 2012) reducing population exposure is important for public health, water security, and economic reasons.

Successes, challenges, and current threat under climate change

Of the more recent initiatives to alleviate the arsenic problem, public awareness of the issue has seen some success with the use of inexpensive field test kits alerting users to concentrations above the Bangladesh arsenic standard. An analysis in the Araihazar *upazila* of Bangladesh suggests that arsenic exposure for more than 85% of the population there can be reduced below the 50 ug/L Bangladeshi standard by using imprecise field test kits (Jameel et al., 2021). Educating well users on the awareness of the arsenic problem remains a challenge though, with a 2022 study indicating only 21% of the studied population knew about the elevated arsenic in their drinking water, however, 64% were willing to pay for a technological intervention or treatment to provide clean drinking water (Dasgupta et al., 2022). However, more than two decades after the discovery of the arsenic problem, exposure remains high across the country and access to a nation-wide arsenic-safe water supply in Bangladesh is lacking (Ahmad et al., 2018). The past success of well testing to promote well-switching and subsequently reduce arsenic exposure may be good news for the Bangladesh government who are about to embark on a blanket testing campaign of millions of wells using field test kits, producing a possible short-term, effective, and inexpensive arsenic-exposure reduction option for additional tube well users across the region. With the reliance on groundwater to provide drinking supplies and irrigation increasing under climate change

(Podgorski and Berg, 2020), coastal aquifers in Bangladesh is at risk of salinization due to sea level rise (Islam et al., 2020) and access to safe groundwater is an important public health challenge in a region where switching from groundwater to surface or rain waters can increase the likelihood of water borne disease (Islam et al., 2013).

Case study synthesis and potential future pathways

Major findings of the three case studies are presented in Table 1, including the successes and challenges of each policy solution.

Using a case study approach, we discuss different strategies to improve water security and water quality for household consumption, agricultural irrigation, and other important uses in the different contexts and at different scales (city, county, country). Securing access to clean, usable water will only continue to grow in importance as the impacts of climate change and continued population growth challenge current water systems. Finding policy solutions at different scales will be a critical piece of securing clean water for all. Policies implemented in one context may not be appropriate for other contexts, just as policies implemented at one scale, may not be appropriate for other scales.

For example, Brunner et al. (2019) notes there is agreement that focusing water scarcity assessments at the national scale, such as Bangladesh, neglects within country variability, while Liu et al. (2017) suggest that regional scales, like the city of Cape Town, are the most policy-relevant scales of assessment. In our assessment of three case studies of different spatial scales, this variability in scale is well highlighted in the proposed policy measures, mostly in the uniqueness of measures required for each locale. In Kern County, USA, localized groundwater management plans are moving to conserve water based on stakeholder feedback and the specific agricultural context, and in Imperial County, USA, policies to allow water transfers have resulted in newly funded water infrastructure projects that benefit specific stakeholders, namely urban and agricultural users. Alternatively, in the city of Cape Town, the focus of policy solutions and interventions is on surface water reservoir storage and the challenges in managing water allocations equitably for the city's 4 million residents. In contrast, at the national scale in Bangladesh, water is abundant but the efforts to have a nation-wide supply of safe water is lacking despite members of the community being aware of–and often willing to contribute to –new policy measures to access clean water.

Arguably then, two important factors in successful implementation of policy interventions to address water security must include (1) an understanding of the spatial (and temporal) scale of the water security challenge, and then (2) a solid grasp of how the affected community will respond to proposed mitigation measures at that specific scale. To address the first point, recent hydrologic studies are working to improve scale-based estimates of water scarcity. For example, Brunner et al. (2019) argue that the choice of scale used in water scarcity assessments may affect the outcome and conclusions drawn from those assessments. However, understanding how the affected communities may perceive and be impacted by water policies is equally importantly. There is a growing movement for interdisciplinary collaboration between natural, physical, and social scientists in order to understand issues of water security, the potential policy solutions, and the impacts of both on local populations from all lenses (Quandt, 2022).

Key learning's from the cross-case analysis

While our case studies do provide some key lessons learned, it is also critical to implement solutions to water security that are context-specific, politically feasible, and culturally-appropriate. Below we synthesize three lessons learned from our case studies and provide potential future pathways to greater water globally.

Ensuring effective policies are in place is critical

As seen in the case studies from the USA, the early establishment of water policy regulations in Imperial County have allowed for the growth of a flourishing agricultural sector, while a lack of water policy in Kern County led to the unsustainable over drafting of groundwater resources. In Imperial County, the introduction of the QSA in 2003 has helped to promote improvements in off and on-farm water efficiencies, allowing water to move to growing urban areas while maintaining agricultural production (Rosenberg, 2021). Alternatively, in Kern County, the late establishment of groundwater management policies through the SGMA of 2014 has now created a situation where the agricultural sector will have to significantly reduce its water use through land fallowing, which may have negative consequences on the local economy and agricultural production (Pitzer, 2019). If such regulations had been put in place decades ago, the agricultural sector would have grown in Kern County in a more sustainable manner without depleting critical groundwater resources. Additionally, the South Africa case study also highlights this point. The implementation of water efficiency and conservation policies help to reduce demand in and around Cape Town and extend the timeline for *Day Zero*. Further, in Bangladesh, implementation of a cheap, efficient well testing program is critical to avoid the serious public health implications of arsenic exposure, and earlier implementation would have improved the health and social wellbeing of many.

TABLE 1 Synthesis and comparison of three water-challenged regions.

Case study	Scale	Approximate 2022 population	Climate (Koppen classification)	Water availability	Climate-related impacts to water supply	Successful interventions employed	Challenges remaining
Imperial County, USA Kern County, USA	County County	179,850 917,670	Hot desert climate (Bwh) Mostly hot summer Mediterranean climate (Csa)	Access to sufficient quantities of water for agriculture competes with drinking water and ecosystem needs As above, with overreliance on groundwater withdrawal	Increased warming and drought in the American southwest will continue to stress water allocation and supply	Policies to allow water transfers to urban areas have helped fund water infrastructure projects that conserve water for irrigation Groundwater sustainability management plans are localized and targeted	Lack of water allocation to surrounding ecosystem (Salton Sea) negatively impacts community health Moves to conserve groundwater are not yet sufficient to allow recharge and will require land fallowing
Cape Town, South Africa	City	4.8 million	Warm and temperate Mediterranean climate (Csa, Csb)	Physical and economic water scarcity challenges surface water reservoir storage	Climate change and sea surface warming threaten disruption to the formation of storm fronts necessary for reservoir recharge	Stakeholder decision-making to re-think water rights and allocate water more equitably Implementation of a new policy focused on water sensitive urban design	Government mismanagement of some alternative water supplies (e.g., desalination) led to failure to fully implement these options
Bangladesh	Country	167.7 million	Monsoonal, sub-tropical, and tropical (Am, Aw, Cwa, Cwb)	Water is abundant but access to clean water is not	Floods, cyclones, droughts, sea level rise and saltwater intrusion each contribute to degradation of water quality	Implementation of a low-cost field test kit has led to well switching and a reduction in As exposure *via* drinking water	Arsenic groundwater exposure remains high despite knowledge of the problem for >2 decades and access to a nation-wide safe water supply is lacking

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Successful interventions integrate community stakeholders for decision-making, monitoring, and assessment

In Cape Town, South Africa, stakeholder engagement has been a crucial tool for establishing a common knowledge of the situation and facilitating effective dialogue in water sustainability in water-stressed regions. This common understanding was critical for making decisions that stakeholders accept in the case of sustainable water management. As indicated by (D'Agostino and Benichou, 2020) context is important for effective stakeholder engagement, and continued communication must take place throughout time.

Cape Town averted Day Zero by working across governmental levels, and with local stakeholders. The participation of the national, provincial and local government was enhanced with a lessened bureaucratic process in order to fast track decision making. The result was an advertisement, approval, construction and commissioning of a wastewater plant within the shortest possible time. The transfer of water from other dams to augment the city supply was another success. The Day Zero provided the city with future water management policy and strategy, as well as emergency augmentation policies that can be replicated elsewhere if such a similar occurrence ever happens.

A similar success of community involvement employed in Bangladesh has been educating local drillers to identify specific colored-aquifer sands where arsenic poor ground waters are more likely to occur (Hossain et al., 2014). Additionally, in Kern County, USA, the diverse institutional arrangements for sustainable groundwater management agencies (GSMA) have so far proven to hinder community engagement through a lack of transparency. Improved community involvement in Kern County will help ensure that water needs are met for all water uses and not just agriculture, including shallow household wells and fish habitat conservation.

The most expensive option is not necessarily the most effective

In Cape Town, the use of desalination to provide an alternative source of fresh water was short-lived due to operating expenses and other challenges, both technical (algal blooms) and bureaucratic (limited operating licenses). Cost of desalination treatment is beyond municipal financial capacity and consumers' spending power for water. Both the Strandfontein and Monwabisi desalination treatment plants were decommissioned in 2020 (Simpson, 2020). This has led to wastage of meager resources in the construction of desalination treatment plants and eventual abandonment. Similarly in Bangladesh, expensive testing of water need not be achieved by rigorously precise and large-scale laboratory testing programs, nor the installation of large-scale infrastructure like desalination plants. Rather, the widespread use of inexpensive field test kits to determine water quality within a safe or unsafe range has proven an effective method for (1) enhancing awareness of a regional water quality issue, and (2) providing a first-step toward identifying alternative safe water sources. This approach also allows community involvement and investment thereby including locals in water security and public health measures which, remarkably, has seen success at the country-level scale. Finally, as seen in Imperial County, USA, the costs of implementing on-farm and system-wide water conservation technologies and strategies can be offset from water sales to urban areas. Thus, farmers themselves can implement otherwise expensive water-efficient irrigation systems, and the Imperial Irrigation District has been able to use these funds to reduce water loss within the system through the lining of the All-American Canal.

Potential future pathways

The lessons learned above are important for highlighting examples (both negative and positive) of water scarcity and water policy solutions across the three case studies. They also speak to three different types of water security-agricultural, urban, water quality; and water policies employed to address the challenges. Policy solutions to improve these three types of water security were different, and as seen in our case studies, should be different because the context, issues, and stakeholders vary from case to case. The case studies covered in this paper have the additional advantage of being different in scale -from county to urban to city as well as in size and increasing population served. However, the specific interventions discussed in each case study are context-specific and may not be directly transferable or scalable. This means that the interventions should not be applied across the board but only on a scale as used in this study. Thus, below, we provide a few key points from the case studies that may be transferable across different types of water scarcity and policies used in addressing them. Importantly, we have identified these future pathways at key takeaways from our case studies.

Collaborative water governance

This will be key to ensure fair and equitable access to clean water. Ensuring that all stakeholders have a say in when and how water is used is critical to water security in the future for everyone–from farmers to local communities to ecosystems. Studies in Bangladesh indicate that when the community is involved in the search for clean water, through testing or educating well drillers on identifying aquifer sediments that are more likely to produce arsenic-free groundwater, the population exposure can be reduced. Climate change is a social and environmental justice issue, and it is important to ensure that the voices and needs of the most vulnerable people are included in a just transition to sustainable, equitable, and water management globally (Abimbola et al., 2021).

Continual re-assessment of water supply and allocation

The need for water allocation and reallocation may also be needed under new climate regimes globally. In order to ensure that allocation decisions are based on current water availability, and not past water availability, reassessments may need to be conducted. For example, the Colorado River, utilized by farmers in Imperial County, USA for irrigation, is currently so over allocated that water often does not reach the ocean. Indeed, river water allocations were determined during an unusually wet period, leading to the current water scarcity and over allocation. In Cape Town, 15 million liters of groundwater is added daily *via* the Table Mountain Aquifers. This was not an option before "Day Zero." Cape Town water demand and supply had been based on surface water designed based on past water projection. Thus, undertaking periodic assessments of water supply will help to fairly allocate water to all users, instead of constant states of scarcity and uneven water allocation.

Short-term and long-term water challenges may require different approaches

Some climate-induced water challenges may require immediate, short-term options to increase water availability that may not be viable for long-term sustainability of a region's water supply needs. For example, degradation of water quality due to floods or cyclones can require immediate attention to prevent public health impacts like outbreaks of water-borne disease. Increasing chlorination and other disinfectants in community water systems after wildfires can lead to an increased quantity of disinfection by-products suspected of impacting human health (Pennino et al., 2022). Switching to high-energy, high-cost technologies like desalination may only provide short-term relief but may be necessary to offset public health concerns. Managers thus should consider having different response plans for short-term challenges (e.g., a weekly or monthly timescale) and longer-term plans that address water security on a multi-year scale.

Conclusions

This paper has highlighted the effect of implementing innovations and policy solutions in a variety of different case studies, and at three different scales, to avert water scarcities amidst increasing looming climate change issues that will only compound the social, environmental, and economic issues already affecting water security. The use of different case studies consisting of two counties in California, USA, the city of Cape Town in South Africa, and the country of Bangladesh has highlighted that implementing policies according to context-specific socio-economic and environmental scales can bring about successful benefits to the communities impacted. Despite the cases considered here having some negative and some positive outcomes, in this paper we provide three key lessons learned: 1. It is important to ensure that effective policies are in place in the first place before reaching critical water shortages, 2. Successful policies are those that integrate community stakeholders in decision-making, water monitoring, and assessment, and 3. The most expensive options aren't necessarily the most effective or efficient.

Drawing from our cross-case analysis we also highlight that ensuring water security in the future will require collaborative governance, continual reassessment of water supply and allocation, and different, context-specific approaches. Importantly, as shown in the Bangladeshi and Cape Town cases, expensive or highly sophisticated options in tackling climate impact are not synonymous to the most effective option. This is a key source of important knowledge to prevent, reduce and minimize the wastage of budgeted resources. Moreover, there is no one-size solution that fits all case scenarios. Understanding the context and cultural environment will be a key consideration in the local approach taken to address water security under the increasing threat of climate change. The cases considered here cover three different types of water scarcity-agricultural, urban, water quality-and have the additional advantage of being different in scale so their lessons provide possibilities for future considerations in many different locales. Such lessons include adjusting the reallocation of water based on different community and sector needs, clear stakeholder investment *via* engagement and public awareness, and finally, there is a need to implement both short-term and long-term management plans. Using these key findings from a synthesis of the case studies presented herein illustrates the complex nature of addressing water security in the face of climate change and highlights the need for continual assessment and evaluation of policy interventions to avoid water scarcity.

Author contributions

All authors contributed to conception and design of the study, the writing of the first draft of the manuscript, and revising and approving the submitted manuscript. AQ wrote the California, USA case study, and drafted the first draft of Section Case study synthesis and potential future pathways. BO' drafted the introduction, Bangladesh section, and design of Table 1. SO and OO drafted the Introduction, South Africa case study, and Conclusion.

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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.

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References

Abimbola, O., Aikin, J. K., Makhesi-Wilkinson, T., and Roberts, E. (2021). *Racism and Climate (In)Justice: How Racism and Colonialism Shape the Climate Crisis and Climate Action*. Washington, DC: Henrich Boll Stiftung.

Aguilera, E. (2019). *What Keeps Families in One of the Most Polluted Places in California?* Available online at: https://calmatters.org/health/2019/01/what-keeps-families-in-one-of-the-most-polluted-places-in-california/ (accessed January 24, 2019).

Ahmad, S. A., Khan, M. H., and Haque, M. (2018). Arsenic contamination in groundwater in Bangladesh: implications and challenges for healthcare policy. *Risk Manag. Healthc. Policy* 11, 251–261. doi: 10.2147/RMHP.S153188

Ahmed, M. F., Ahuja, S., Alauddin, M., Hug, S. J., Lloyd, J. R., Pfaff, A., et al. (2006). Ensuring safe drinking water in Bangladesh. *Science.* 314, 1687–1688. doi: 10.1126/science.1133146

Alobireed, A. (2021). *Global Water Desalination: A Comparison Between Saudi Arabia and The United States of America* (*Doctoral* dissertation, University of Pittsburgh).

Ayres, A., Hanak, E., Gray, B., Sencan, G., Bruno, E., Escriva-Bou, A., et al. (2021). *Improving California's Water Markets.* Public Policy Institute of California. Available online at: https://www.ppic.org/publication/policy-brief-improving-californias-water-market/ (accessed September 1, 2022).

Baba, A., and Gündüz, O. (2017). Effect of geogenic factors on water quality and its relation to human health around mount Ida, Turkey. *Water* 9, 66. doi: 10.3390/w9010066

Berbel, J., and Esteban, E. (2019). Droughts as a catalyst for water policy change. analysis of Spain, Australia (MDB), and California. *Global Environ. Change* 58, 101969. doi: 10.1016/j.gloenvcha.2019.101969

Berg, M., Trang, P. T. K., Stengel, C., Buschmann, J., Viet, P. H., Van Dan, N., et al. (2008). Hydrological and sedimentary controls leading to arsenic contamination of groundwater in the Hanoi area, Vietnam: the impact of iron-arsenic ratios, peat, river bank deposits, and excessive groundwater abstraction. *Chem. Geol.* 249, 91–112. doi: 10.1016/j.chemgeo.2007.12.007

Bostic, D. (2021). *At Risk: Public Supply Well Vulnerability Under California's Sustainable Groundwater Management Act*. Oakland, CA: Pacific Institute. Available online at: https://pacinst.org/publication/at_risk_wells_SGMA (accessed September 1, 2022).

Bradford, J. B., Schlaepfer, D. R., Lauenroth, W. K., and Palmquist, K. A. (2020). Robust ecological drought projections for drylands in the 21st century. *Glob. Chang. Biol.* 26, 3906–3919. doi: 10.1111/gcb.15075

Branch, G., and Branch, M. (1981). Living Shores: Interacting with Southern Africa's Marine Ecosystems, 1st Edn. *Cape Town: Struik Nature*. p. 272.

Brauman, K. A., Richter, B. D., Postel, S., Malsy, M., and Fl rke, M. (2016). Wa- ter depletion: an improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments. *Elem. Sci. Anth.* 4, 1–12. doi: 10.12952/journal.elementa.000083

Brunner, M. I., Zappa, M., and Stahli, M. (2019). Scale matters: effects of temporal and spatial data resolution on water scarcity assessments. *Adv. Water Resour.* 123, 134–144. doi: 10.1016/j.advwatres.2018.11.013

Butler, K. A. (2015). *Reconfiguring Spaces of Capital in Southern California: A Political Ecology of the Imperial Valley-San Diego County Water Transfer Agreement*. Available online at: https://digitallibrary.sdsu.edu/islandora/object/sdsu:2017 (accessed September 1, 2022).

Carter, J. P. (1966). Acreage limitation: imperial valley's new challenge. *Calif. West. Law Rev.* 2, 99–108.

City of Cape Town (CCT). (2007). *Long-Term Water Conservation and Water Demand Management Strategy*. Cape Town (2007). Available online at: https://www.greencape.co.za/assets/Water-Sector-Desk-Content/CoCT-Long-term-water-conservation-and-water-demand-management-strategy-2007.pdf (accessed April 29, 2022).

City of Cape Town (CCT). (2019). *Our Shared Water Future: Cape Town Water Strategy. Department of Water and Sanitation.* City of Cape Town (2019). Available online at: https://resource.capetown.gov.za/documentcentre/Documents/City%20strategies,%20plans%20and%20frameworks/Cape%20Town%20Water%20Strategy.pdf (accessed April 29, 2022).

City of Cape Town. (2020). Our Shared Water Future Cape Town's Water Strategy. Available onlineat: https://resource.capetown.gov.za/documentcentre/Documents/City%20strategies,%20plans%20and%20frameworks/Cape%20Town%20Water%20Strategy.pdf (accessed October 1, 2022).

Cohen, M. J., and Hyun, K. H. (2006). *Hazard: the Future of the Salton Sea With No Restoration Project*. Oakland, CA: Pacific Institute.

Cooley, H., Gleick, P., and Wilkinson, R. (2014). *Agricultural Water Conservation and Efficiency Potential in California.* Issue Brief, Pacific Institute.

D'Agostino, J. O., and Benichou, L. (2020). *Tracking Coronavirus Hospitalizations in California by County.* Available online at: https://calmatters.org/health/coronavirus/2020/04/california-coronavirus-covid-patient-hospitalization-data-icu/ (accessed September 1, 2021).

Dasgupta, A., and Sen, D. S. (2021). Terrestrial water system and hydrological cycle alteration antecedent to adverse climate change in indian sub-continent a literature review. *Asian J. Sci. Technol.* 12, 11939–11945. doi: 10.13140/RG.2.2.29875.35368

Dasgupta, S., Roy, J., Ghosh, M., and Talukdar, J. (2022). Willingness to pay (WTP) for arsenic-safe drinking water: a case study to understand societal embedding of ECAR technology in rural West Bengal, India. *Dev. Eng.*7, 100096. doi: 10.1016/j.deveng.2022.100096

Department of Water Affairs and Forestry (DWAF). (2004). *Water Quality Management Series Sub-Series No. MS 13.3. Operational Policy for the Disposal of Land-Derived Water Containing Waste to the Marine Environment of South Africa – Guidance on Implementation*. Edition 1.DWAF, Pretoria.

Dube, K., Nhamo, G., and Chikodzi, D. (2020). Climate change-induced droughts and tourism: Impacts and responses of Western Cape Province, South Africa. *J. Outdoor Recreat. Tourism*. 39, 100319. doi: 10.1016/j.jort.2020.100319

Dugard, J. (2021). Water rights in a time of fragility: an exploration of contestation and discourse around cape town's "day zero" water crisis. *Water* 13, 3247. doi: 10.3390/w13223247

Egbueri, J. C., and Agbasi, J. C. (2022). Data-driven soft computing modeling of groundwater quality parameters in southeast Nigeria: comparing the performances of different algorithms. *Environ. Sci. Pollut. Res.* 29, 38346–38373. doi: 10.1007/s11356-022-18520-8

Elias, E., Steele, C., Havstad, K., Steenwerth, K., Chambers, J., Deswood, H., et al. (2015). *Southwest Regional Climate Hub and California Subsidiary Hub Assessment of Climate Change Vulnerability and Adaptation and Mitigation Strategies.* Washington, DC: U.S. Department of Agriculture, 76. doi: 10.32747/2015.6879806.ch

Fader, M., Gerten, D., Krause, M., Lucht, W., and Cramer, W. (2013). Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. *Environ. Res. Lett.* 8, 014046. doi: 10.1088/1748-9326/8/1/014046

Finley, R. L. (1974). *An Economic History of the Imperial Valley of California to 1971.* Available online at: https://shareok.org/bitstream/handle/11244/3835/7506513.PDF?sequence=1 (accessed May 20, 2020).

Flanagan, S. V., Johnston, R. B., and Zheng, Y. (2012). Arsenic in tube well water in Bangladesh: health and economic impacts and implications for arsenic mitigation. *Bull. World Health Organ.* 90, 839–846. doi: 10.2471/BLT.11.101253

Greene, C. (2021). "Drought isn't just water, it is living": Narratives of drought vulnerability in California's San Joaquin Valley. *Geoforum* 121: 33–43. doi: 10.1016/j.geoforum.2021.02.007

Grillos, T., Zarychta, A., and Nuñez, J. N. (2021). Water scarcity and procedural justice in Honduras: community-based management meets market-based policy. *World Dev.* 142, 105451. doi: 10.1016/j.worlddev.2021.105451

Hanak, E., Lund, J., Arnold, B., Escriba-Bou, A., Gray, B., Green, S., et al. (2017). *Water Stress and a changing San Joaquin Valley*. Public Policy Institute of California.

Hedden-Nicely, D. R. (2021). Climate change and the future of western US water governance. *Nat Clim Change.* 12, 108–110. doi: 10.1038/s41558-021-01141-3

Hopkins, F. (2018). *Inland Deserts Summary Report.* California's fourth climate change Assessment. Publication number: SUM-CCCA4-2018-008.

Hossain, M., Bhattacharya, P., Frape, S. K., Jacks, G., Islam, M. M., Rahman, M. M., et al. (2014). Sediment color tool for targeting arsenic-safe aquifers for the installation of shallow drinking water tube wells. *Sci. Tot. Environ.* 493, 615–625. doi: 10.1016/j.scitotenv.2014.05.064

Hossain, M. A., Sengupta, M. K., Ahamed, S., Rahman, M. M., Mondal, D., Lodh, D., et al. (2005). Ineffectiveness and poor reliability of arsenic removal plants in West Bengal, India. *Environ. Sci. Technol.* 39, 4300–4306. doi: 10.1021/es048703u

Hughes, B. (2020). *Turning Off the Tap: Will California Let the Salton Sea Go Down the Drain?* California Western Law Review. Available online at: https://scholarlycommons.law.cwsl.edu/cwlr/vol56/iss1/8 (accessed February 15, 2020).

Islam, A. M. T., Siddiqua, M. T., Zahid, A., Tasnim, S. S., and Rahman, M. M. (2020). Drinking appraisal of coastal groundwater in Bangladesh: an approach of multi -hazards towards water security and health safety. *Chemosphere* 255, 126933. doi: 10.1016/j.chemosphere.2020.126933

Ismail, Z., and Go, Y. I. (2021). Fog-to-water for water scarcity in climate-change hazards hotspots: pilot study in Southeast Asia. *Global Challenges* 5, 2000036. doi: 10.1002/gch2.202000036

Jameel, Y., Mozumder, M. R. H., van Geen, A., and Harvey, C. F. (2021). Well-Switching to Reduce Arsenic Exposure in Bangladesh: Making the Most of Inaccurate Field Kit Measurements. *Geohealth* 5:e2021GH000464. doi: 10.1029/2021GH000464

Jamil, N. B., Feng, H., Ahmed, K. M., Choudhury, I., Barnwal, P., and van Geen, A. (2019). Effectiveness of different approaches to arsenic mitigation over 18 years in Araihazar, Bangladesh: implications for national policy. *Environ. Sci. Technol.* 53, 5596–5604. doi: 10.1021/acs.est.9b01375

Joubert, L., and Ziervogel, G. (2019). *Day Zero One City Response to a Record Breaking Drought. First Edition. Mapula Trust. ISBN 978-0-620-839488.* Available online at: Day-Zero.pdf (dayzero.org.za) (accessed July 22, 2022).

Kelsey, R., Hart, A., Butterfield, H. S., and Vink, D. (2018). Groundwater sustainability in the San Joaquin Valley: Multiple benefits if agricultural lands are retired and restored strategically. *Calif. Agr.* 72, 151–154. doi: 10.3733/ca.2018a0029

Kern County. (2019). *2018 Kern County Agricultural Crop Report*. Bakersfield, CA.

Kern River Groundwater Sustainability Agency (KRGSA). (2020). *Groundwater Sustainability Plan Executive* Summary.

Kinniburgh, D., and Smedley, P. (2001). *Arsenic Contamination of Groundwater in Bangladesh.*

Kisakye, V., and Van der Bruggen, B. (2018). Effects of climate change on water savings and water security from rainwater harvesting systems. *Resour. Conserv. Recycl.* 138, 49–63. doi: 10.1016/j.resconrec.2018.07.009

Konikow, L. F., and Kendy, E. (2005). Groundwater depletion: a global problem. *Hydrogeol. J.* 13: 317–320. doi: 10.1007/s10040-004-0411-8

LaVanchy, G. T., Kerwin, M. W., and Adamson, J. K. (2019). Beyond 'Day Zero': insights and lessons from Cape Town (South Africa). *Hydrogeol. J.* 27, 1537–1540. doi: 10.1007/s10040-019-01979-0

LaVanchy, G. T., Kerwin, M. W., Kerwin, G. J., and McCarroll, M. (2021). The optics of 'Day Zero' and the role of the state in water security for a township in Cape Town (South Africa), *Water Int.* 46:6, 841–860. doi: 10.1080/02508060.2021.1946763

Liu, J., Yang, H., Gosling, S. N., Kummu, M., Fl rke, M., Hanasaki, N., et al. (2017). Water scarcity assessments in the past, present, and future. *Earths Future* 5, 545–559. doi: 10.1002/2016EF000518

Madonsela, B., Koop, S., van Leeuwen, K., and Carden, K. (2019). Evaluation of water governance processes required to transition towards water sensitive urban design—an indicator assessment approach for the City of Cape Town. *Water* 11, 292. doi: 10.3390/w11020292

Mancosu, N., Snyder, R. L., Kyriakakis, G., and Spano, D. (2015). Water scarcity and future challenges for food production. *Water* 7, 975–992. doi: 10.3390/w7030975

Migdall, S., Dotzler, S., Gleisberg, E., Appel, F., Muerth, M., Bach, H., et al. (2022). Crop water availability mapping in the danube basin based on deep learning, hydrological and crop growth modelling. *Eng. Proc.* 9, 42. doi: 10.3390/engproc2021009042

Mknelly, B. (2021). *The Sustainable Groundwater Management Act (SGMA): Long overdue, but is it living up to its potential?* Scripps Senior Theses, 1697.

Mount, J., and Hanak, E. (2018). "Water use in California," in: Mount, J. eds. *Managing Drought in a Changing Climate: Four Essential Reforms*. Public Policy Institute of California.

Mukherjee, A., and Fryar, A. E. (2008). Deeper groundwater chemistry and geochemical modeling of the arsenic affected western Bengal basin, West Bengal, India. *Appl. Geochemist.* 23, 863–894. doi: 10.1016/j.apgeochem.2007.07.011

Mukherjee, A., Fryar, A. E., and O'Shea, B. M. (2009). *Major occurrences of elevated arsenic in groundwater and other natural waters.* Arsenic: Environmental chemistry, health threats and waste treatment, John Wiley and Sons, 303–350. doi: 10.1002/9780470741122.ch6

Munguia, V. S., and Ganster, P. (2006). *Lining the All-American Canal: Competition or Cooperation for the Water in the U.S.-Mexican Border*? ISBN-10: 0925613495.

Narrandes, N. (2018). Level 6B: Your Guide to 50 Litres a day, *cape town etc*. Available online at: https://www.capetownetc.com/water-crisis/capetown-water-crisis-guide-50-litres/ (accessed October 1, 2022).

Nickson, R. T., McArthur, J. M., Ravenscroft, P., Burgess, W. G., and Ahmed, K. M. (2000). Mechanism of arsenic release to groundwater, Bangladesh and West Bengal. *Appl.Geochemist.* 15, 403–413. doi: 10.1016/S0883-2927(99)00086-4

Nolte, A., Eley, M., Schöniger, M., Gwapedza, D., Tanner, J., Mantel, S. K., et al. (2021). Hydrological modelling for assessing spatio-temporal groundwater recharge variations in the water-stressed Amathole Water Supply System, Eastern Cape, South Africa: spatially distributed groundwater recharge from hydrological model. *Hydrol. Process.* 35, e14264. doi: 10.1002/hyp.14264

Nosetto, M. D., Jobbágy, E. G., Brizuela, A. B., and Jackson, R. B. (2012). The hydrologic consequences of land cover change in central Argentina. *Agric. Ecosyst. Environ.* 154, 2–11. doi: 10.1016/j.agee.2011.01.008

Oki, T., and Quiocho, R. E. (2020). Economically challenged and water scarce: identification of global populations most vulnerable to water crises. *Int. J. Water Resour. Dev.* 36, 416–428. doi: 10.1080/07900627.2019.1698413

Onipe, T., Edokpayi, J. N., and Odiyo, J. O. (2020). A review on the potential sources and health implications of fluoride in groundwater of Sub-Saharan Africa. *J. Environ. Sci. Health Part A,* 55:9. doi: 10.1080/10934529.2020.1770516

Orimoloye, I. R., Belle, J. A., Olusola, A. O., Emmanuel, T., Busayo, E. T., and Ololade, O. O. (2021). Spatial assessment of drought disasters, vulnerability, severity and water shortages: a potential drought disaster mitigation strategy. *Nat. Hazard.* 105, 2735–2754. doi: 10.1007/s11069-020-04421-x

Orimoloye, I. R., Ololade, O. O., Mazinyo, S. P., Kalumba, A. M., Ekundayo, O. Y., Busayo, E. T., et al. (2019). Spatial assessment of drought severity in Cape Town area, South Africa. *Heliyon* 5, e02148. doi: 10.1016/j.heliyon.2019.e02148

O'Shea, B., Jankowski, J., and Sammut, J. (2007). The source of naturally occurring arsenic in a coastal sand aquifer of eastern Australia. *Sci. Total Environ.* 379, 151–166. doi: 10.1016/j.scitotenv.2006.07.040

Parrone, D., Ghergo, S., Frollini, E., Rossi, D., and Preziosi, E. (2020). Arsenic-fluoride co-contamination in groundwater: background and anomalies in a volcanic-sedimentary aquifer in central Italy. *J. Geochem. Explor.* 217, 106590. doi: 10.1016/j.gexplo.2020.106590

Pawlak, K., and Kołodziejczak, M. (2020). The role of agriculture in ensuring food security in developing countries: considerations in the context of the problem of sustainable food production. *Sustainability* 12, 5488. doi: 10.3390/su12135488

Pennino, M. J., Leibowitz, S. G., Compton, J. E., Beyene, M. T., and LeDuc, S. D. (2022). Wildfires can increase regulated nitrate, arsenic, and disinfection byproduct violations and concentrations in public drinking water supplies. *Sci. Total Environ.* 804, 149890. doi: 10.1016/j.scitotenv.2021.149890

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., et al. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environ. Sci. Technol.* 56, 1510–1521. doi: 10.1021/acs.est.1c04158

Petruzzello, M. (2021). "*Water scarcity*". *Encyclopedia Britannica.* Available online at: https://www.britannica.com/topic/water-scarcity (accessed March 25, 2022).

Pinter, N., Lund, J., and Moyle. (2019). The California water model: resilience through failure. *Hydrol Process,* 33, 1775–1779. doi: 10.1002/hyp.13447

Pitzer, G. (2019). *As Deadline Looms for California's Badly Overdrafted Groundwater Basins, Kern County Seeks A Balance to Keep Farms Thriving.* Water Education Foundation (accessed March 28, 2019).

Podgorski, J., and Berg, M. (2020). Global threat of arsenic in groundwater. *Science* 368, 845. doi: 10.1126/science.aba1510

Quandt, A. (2022). The role of qualitative social science. discussion of "Guiding principles for hydrologists conducting interdisciplinary research and fieldwork with participants." *Hydrol. Sci. J.* 67, 1141–1144. doi: 10.1080/02626667.2022.2060107

Radloff, K. A., Zheng, Y., Michael, H. A., Stute, M., Bostick, B. C., Mihajlov, I., et al. (2011). Arsenic migration to deep groundwater in Bangladesh influenced by adsorption and water demand. *Nat. Geosci.* 4, 793–798. doi: 10.1038/ngeo1283

Rogerson, J. M., and Visser, G. (2020). "Recent trends in South African tourism geographies," in J. M. Rogerson and G. Visser (Eds.), *New Directions in South African Tourism Geographies*, (Cham, Switzerland, Springer), 1–13. doi: 10.1007/978-3-030-29377-2_1

Rosenberg, D. E. (2021). *Invest in farm water conservation to curtail buy and dry*. Inkstain. Available online at: http://www.inkstain.net/fleck/2021/06/invest-in-farm-water-conservation-to-curtail-buy-and-dry/ (accessed September 1, 2022).

Savenije, H. Z., and Van der Zaag, P. (2002). "Water as an economic good and demand management. paradigms with pitfalls," in *Water International: Volume 27 (International Water Resources Association)*, 98–104.

Schwärzel, K., Zhang, L., Montanarella, L., Wang, Y., and Sun, G. (2020). How afforestation affects the water cycle in drylands: a process-based comparative analysis. *Glob. Chang. Biol.* 26, 944–959. doi: 10.1111/gcb.14875

Simpson, S. (2020). *The City Wants to Build a R1.8billion Desalination Plants.* CapeTown ETC. Available online at: www.theCitywantstobuildaR1.8-billiondesalinationplant (capetownetc.com) (accessed April 27, 2022).

Smith, A. H., Lingas, E. O., and Rahman, M. (2000). Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. *Bull. World Health Organ.* 78, 1093–1103.

State of California. (2019). *Household Water Supply Shortage Reporting System*. Available online at: https://~mydrywatersupply.water.ca.gov/report/publicpage (accessed September 1, 2022).

Stringer, L. C., Mirzabaev, A., Benjaminsen, T. A., Harris, R. M., Jafari, M., Lissner, T. K., et al. (2021). Climate change impacts on water security in global drylands. One *Earth* 4, 851–864. doi: 10.1016/j.oneear.2021.05.010

Tindula, G. N., Morteza, N. O., and Snyder, R. L. (2013). Survey of irrigation methods in California in 2010. *J. Irrig. Drain. Eng.* 139, 233–238. doi: 10.1061/(ASCE)IR.1943-4774.0000538

Tyson, P. D., and Preston-Whyte, R. A. (2000). The Weather and Climate of Southern Africa. *Cape Town: Oxford University Press*. p. 396.

United Nations Food and Agricultural Organization (FAO). (2018). *The United Nations World Water Development Report* 2018. *Technology of Water Treatment*, 4, 34.

United States Department of Agriculture (USDA). (2017). *(United States Department of Agriculture)*. Census of Agriculture Imperial County Profile. USDA National Agricultural Statistics Service.

Van Geen, A., Ahsan, H., Horneman, A. H., Dhar, R. K., Zheng, Y., Hussain, I., et al. (2002). Promotion of well-switching to mitigate the current arsenic crisis in Bangladesh. *Bull. World Health Organ.* 80, 732–737.

van Vliet, M. T., Jones, E. R., Flörke, M., Franssen, W. H., Hanasaki, N., Wada, Y., et al. (2021). Global water scarcity including surface water quality and expansions of clean water technologies. *Environ. Res. Lett.* 16, 024020. doi: 10.1088/1748-9326/abbfc3

Visser, W. P. (2018). A perfect storm: the ramifications of Cape Town's drought crisis. *J. Transdiscip. Res. South Africa*. 14, a567. doi: 10.4102/td.v14i1.567

Visser-Quinn, A., Beevers, L., Lau, T., and Gosling, R. (2021). Mapping future water scarcity in a water abundant nation: near-term projections for Scotland. *Climate Risk Manage.* 32, 100302. doi: 10.1016/j.crm.2021.100302

Wartenberg, A. C., Moanga, D., Potts, M. D., and Butsic, V. (2021). Limited economic-ecological trade-offs in a shifting agricultural landscape: A case study from Kern County, California. *Front. Sustain. Food Syst.* 5.

WWAP (United Nations World Water Assessment Programme). (2017). *The United Nations World Water Development Report 2017*: *Wastewater, The Untapped Resource.* Paris, UNESCO.

Young, S. L., Frongillo, E. A., Jamaluddine, Z., Melgar-Quiñonez, H., Pérez-Escamilla, R., Ringler, C., et al. (2021). Perspective: the importance of water security for ensuring food security, good nutrition, and well-being. *Adv. Nutr.* 12, 1058–1073. doi: 10.1093/advances/nmab003

Zhang, D., Sial, M. S., Ahmad, N., Filipe, A. J., Thu, P. A., Zia-Ud-Din, M., et al. (2020). Water scarcity and sustainability in an emerging economy: a management perspective for future. *Sustainability* 13, 144. doi: 10.3390/su13010144

Ziervogel, G. (2019). *Unpacking the Cape Town Drought: Lesson Learned. Report for City Support Program Undertaking by African Centre for Cities.* Available online at: Ziervogel-2019-Lessons-from-Cape-Town-Drought_A.pdf (africancentreforcities.net) (accessed July 20, 2022).

Zisopoulou, K., and Panagoulia, D. (2021). An in-depth analysis of physical blue and green water scarcity in agriculture in terms of causes and events and perceived amenability to economic interpretation. *Water* 13, 1693. doi: 10.3390/w13121693