Global Environmental Change 79 (2023) 102649

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

The role of adaptive capacity in incremental and transformative adaptation in three large U.S. Urban water systems

Lisa Dilling[a,1,*], Meaghan E. Daly[b,1], William R. Travis[c], Andrea J. Ray[d], Olga V. Wilhelmi[e]

[a] Department of Environmental Studies and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder 80303-0397, United States
[b] Department of Environmental Studies, University of Colorado, Boulder 80303-0397, United States
[c] Department of Geography and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder 80303-0260, United States
[d] National Oceanic and Atmospheric Administration, Physical Sciences Laboratory, Boulder, CO 80305, United States
[e] National Center for Atmospheric Research, Boulder, CO 80301, United States

A R T I C L E I N F O

Keywords:
Climate adaptation
Water governance
Transformation
Resilience
Urban
Adaptive capacity

A B S T R A C T

Urban water systems need to serve increasing numbers of people under a changing climate. Studies of systems facing extreme events, such as drought, can clarify the nature of adaptive capacity and whether this might support incremental (marginal changes) or transformative adaptation (fundamental system shifts) to climate change. We conducted comparative case studies of three major metropolitan water systems in the United States to understand how actions taken in response to drought affected adaptive capacity and whether the adaptive capacity observed in these systems fosters the preconditions needed for transformative adaptation. We find that while there is ample evidence of existing and potential adaptive capacity, this can be either enabled or diminished by the specific actions taken and their cascading effects on other parts of the system. We also find social dimensions, such as public acceptance, learning, trust, and collaboration, to be as critical as physical elements of adaptive capacity in urban water systems. Finally, we suggest that changes in practices initiated during drought, combined with sustained engagement, collaboration, and education, can lead to substantial and long-lasting changes in values around water, a precursor to transformative adaptation.

1. Introduction

Urban water systems worldwide are increasingly under stress as more people live and work in cities and climate change accelerates (Flörke et al., 2018, Nobre et al., 2016, Maxmen, 2018, McDonald et al., 2014, Missimer et al., 2014, Satterthwaite, 2016, Johannessen and Wamsler, 2017, Fleck and Udall, 2021). Adaptation in urban water systems is, thus, an urgent priority to ensure safe and adequate water supplies in the future. Despite the imperative to adapt, questions remain about how to achieve successful adaptation in urban water systems. Empirical evidence to inform how water providers in urban areas of high-income countries can adapt is growing, but still limited (Berrang-Ford et al., 2021).

The climate adaptation literature distinguishes between two main types of adaptation: incremental adaptation – i.e., marginal changes over time within existing system parameters – and transformative adaptation, which fundamentally shifts the function of a system (Pelling et al., 2015). Transformative adaptation is theorized to occur "across technological, economic and social" domains, including fundamental shifts in "paradigms, goals and values" (Visseren-Hamakers et al., 2021). Scholars have pointed out that major transformations may be necessary for water systems to effectively continue to serve human, as well as environmental, needs under global change (Wiek and Larson, 2012). However, there are major gaps in our understanding of how transformative adaptation is initiated and implemented, and whether incremental adaptation can be a pathway toward transformative adaptation (O'Brien, 2012, Kates et al., 2012, Park et al., 2012, Fedele et al., 2019, Pahl-Wostl, 2020).

Adaptation practice in the U.S. has largely focused on maintaining existing systems, with little attention to the enabling conditions needed for transformative change (Shi and Moser, 2021). There is growing consensus that foundational shifts in values, mindsets, power dynamics, and relationships are needed to enable transformative adaptation (Kates et al., 2012, Scoones et al., 2020, Shi and Moser, 2021). Less is known

* Corresponding author.
E-mail address: ldilling@colorado.edu (L. Dilling).
[1] Co-first authors, these two authors contributed equally.

https://doi.org/10.1016/j.gloenvcha.2023.102649
Received 7 December 2021; Received in revised form 17 November 2022; Accepted 4 February 2023
Available online 15 February 2023

about whether and how incremental adaptations to shorter-term extremes like drought may or may not contribute to preconditions for transformative adaptation (Kates et al., 2012). Drought response measures in the U.S. have typically prioritized what Shi and Moser (2021, p. 2) call "surface level" conditions, such as policies, practices, and resource flows – e.g. water conservation during a drought event (Baehler and Biddle, 2018, Dilling et al., 2019) – rather than deeper restructuring of system goals and functions. Recognizing that transformation may be necessary in some systems, questions remain regarding how to advance fundamental shifts in values in urban water systems and how adaptive capacity built during drought may play a role.

Adaptive capacity is composed of the "preconditions necessary to enable adaptation, including social, physical, and economic elements, and the ability to mobilize these elements" for the future (Nelson et al., 2007, pg. 397). Despite the importance of social and economic elements for adaptive water management, research on technical aspects still dominates the literature (Pahl-Wostl, 2020). The adaptive capacity needed to effectively address climate risks is likely to be highly scale- and context-dependent, and more empirical research is needed to understand tradeoffs and interactions (Siders, 2018). It is important to take a systems view of adaptation, looking at connections and the overall effects of actions as they feedback "either positively or negatively into the system as a whole through time" (Nelson et al., 2007, pg. 399). Simply put, "adaptation today must be evaluated on the basis of how it will affect future flexibility" (Ibid.).

Barnes et al. (2020) identified three factors that were particularly important for adaptive capacity across incremental and transformative adaptation: organization, learning, and agency (the power to act). Social learning extends beyond the individual into organizations, communities, networks, and governance institutions and is a key component of adaptive capacity (Bullock et al., 2022). Blackburn and Pelling (2018) highlight changing social contracts, or agreements between publics and authorities on rights and responsibilities, as applied to risk reduction, as possible pathways for transformative adaptation. Flexibility is another key attribute of adaptive capacity for climate change (Engle and Lemos, 2010, Engle, 2011, Kirchhoff and Dilling, 2016, Cinner et al., 2018, Pahl-Wostl, 2020). However, tradeoffs and tensions exist between maintaining flexibility and stability within water systems (Hill & Engle, 2013, Baehler and Biddle, 2018).

Given uncertainty about climate change, much adaptation practice has implemented 'low-regrets' strategies designed to address present-day vulnerabilities (Dilling et al., 2015, Stults and Larsen, 2020). Yet, adaptation actions can produce unintended outcomes for other parts of a system, including reduced adaptive capacity in the future (Cinner et al., 2018, Dilling et al., 2019, Belliveau et al., 2006). Few studies have explicitly examined the dynamic interactions between adaptation strategies for climate variability, such as drought, and long-term adaptive capacity (Jurgilevich et al., 2021, Lemos et al., 2016). Adaptation to climate variability in the water management sector in the past has included enshrinement of historical extremes as planning targets, little use of climate change scenarios, and rigid water allocation rules that can dampen adaptive response to climate change (Hamlet, 2011). Importantly, conflicts can arise between the aims and outcomes of short- and long-term adaptive actions (Adger et al., 2011). Thus, even though it has been theorized that adaptation to existing variability and extreme events – such as drought – will improve adaptive capacity to deal with climate change, additional empirical research is needed to unpack these relationships.

One challenge of empirical studies of adaptive capacity is that it is often latent – that is, not fully observable until a system is stressed during an extreme event (Engle, 2011). Thus, research to characterize adaptive capacity and observe its mobilization has focused on assessing water system dynamics and strategies during extreme events, such as a drought or flooding (Bettini et al., 2015, Engle, 2012, Hill and Engle, 2013). We apply and expand that approach here, using drought-related adaptation actions and their consequences to examine whether incremental adaptation to drought builds adaptive capacity for future climate change, with particular attention to how this may point toward possibilities for transformation.

We focus on two main research questions: 1) How do adaptation actions in response to drought support or detract from building adaptive capacity for the future; and 2) Do adaptive capacities mobilized during drought events indicate the existence of preconditions necessary for transformative change? We conducted comparative case studies across three major metropolitan water systems in the U.S.: Austin Water; Southern Nevada Water Authority; and Tampa Bay Water. These systems are all members of the Water Utility Climate Alliance, an organization dedicated to ensuring "water utilities will be positioned to respond to climate change and protect our water supplies" (WUCA, 2022) and are considered leading water utilities in the climate adaptation space. Thus, while these cases may not be representative of other – especially smaller – water systems, they provide an opportunity to glean key insight at the forefront of adaptation practice in the water management sector.

We focus specifically on the perspectives of professionals working on water supply and quality in these systems—as opposed to other dimensions of water management, such as wastewater, flood risk, or stormwater control. Water managers are key agents in shaping and mobilizing adaptive capacity in water systems. Previously perceived as conservative and "invisible" in their decision-making processes (e.g., Lach et al., 2005, Rayner et al., 2005), water managers in the U.S. have significant capacity to embrace change, drive innovation, and build social capital through collaboration and communication, while simultaneously needing to maintain "no room for error" in reliably delivering sufficient clean water (Baehler and Biddle, 2018, pg. 1).

In the following section, we review methods and present short case backgrounds of the three systems. We then present findings on actions taken to respond to drought, how actions fostered or reduced adaptive capacity, and whether adaptive capacity observed was consistent with preconditions for transformative adaptation. Finally, we discuss the implications of our findings for adaptive capacity in large U.S. urban water systems, the dynamics and feedbacks of adaptive capacity, and prospects for transformative adaptation.

2. Methods

Semi-structured interviews were conducted in case studies of three large metropolitan water systems in the U.S.: Austin Water, serving Austin, Texas; Southern Nevada Water Authority, serving Las Vegas and the surrounding region in Nevada; and Tampa Bay Water, serving the Tampa Bay region in Florida, in 2012 and 2013 (Yin, 2009). Cases were selected to ensure diversity in the types and contexts of water systems across geographic locations, climatic conditions, and water supply. All three systems had recently experienced significant drought eliciting management responses.

In each case, we utilized a snowball sampling method to recruit participants for qualitative interviews, starting with focal point(s) for drought response in each water provider organization. We then asked initial and subsequent participants to identify additional interviewees who play an important role in the provider organization's drought response. Based on this sampling method, our interviews included individuals: 1) directly involved in management decisions (e.g., system operations managers, water provider board members), 2) indirectly involved in system management decisions (e.g., city council, citizen advisory groups), or 3) had a stake in system management (e.g., industry and environmental groups). We conducted 52 interviews: 20 for Southern Nevada Water Authority, 17 for Austin Water, and 15 for Tampa Bay Water (Supplementary Materials 1). Interviews were 1 – 1.5 h in length. Interviews were conducted until theoretical saturation was reached (Corbin and Strauss, 2015). In addition to conducting interviews, we reviewed operating plans, websites, and other material obtained from the water providers.

Interview questions focused on experience of drought in the past, actions taken and whether they were seen as successful, perception of readiness for future droughts, and perception of preparedness for climate change (Supplementary Materials 2).

All interviews were audio recorded, with the permission of participants, transcribed verbatim, and coded and analyzed in *N*-Vivo. For each interview, we wrote thematic memos to identify broad, emergent themes to inform subsequent coding (Saldaña, 2016).

Coding was conducted through a combination of inductive and deductive approaches. First, we deductively identified themes and codes from the existing literature on adaptive capacity, such as flexibility, equity, and learning, as well as those related to adaptation and transformation. Second, we inductively developed a set of codes based on the interview data, using thematic memos and by (re-)reading interviews to identify additional and specific elements of adaptive capacity as defined by water managers and stakeholders themselves (Corbin and Strauss, 2015). Following this iterative process to develop a comprehensive coding table, one individual did the final coding after consultation with the lead authors to resolve coding categories and to ensure internal consistency.

3. Case Background

In the following section, we provide a brief description of each of the three water systems, including: physical sources of water supply; primary water governance arrangements; and current trends and expected pressures on water supply. For each case, we include a detailed diagram of key entities mentioned in interviews that are involved in the water system's governance across multiple institutional scales (Figs. 1-3) that also serves to support those findings related to governance explained in greater depth in later sections.

3.1. Austin Water, Texas

Austin Water (AW) served over 850,000 people at the time of our case study in a semi-arid region of Texas. AW draws from the Lower Colorado River via Lake Travis and Lake Austin, three water treatment plants, and two wastewater plants. AW purchases its water from the Lower Colorado River Authority (LCRA), created by the Texas state legislature in 1934 to manage the Lower Colorado River and provide both domestic and agricultural water supplies (Fig. 1). The LCRA is managed by a board appointed by the governor. In Texas, the regulatory frameworks for managing groundwater and surface water are separate, with landowners holding the right to withdraw groundwater under their land, while surface water is owned by the state and withdrawn by permit according to prior appropriation "first in time, first in right" (Texas A&M, 2022). While state level entities (e.g. Texas Water Development Board) support and coordinate drought planning, plans themselves are developed and implemented at the regional level (e.g. Regional Water Planning Group). Austin is one of the fastest growing metropolitan areas in the U.S. and, according to the city demographer, expects to grow by more than 25 % by 2040. Austin, along with much of Texas, has also experienced notable droughts in the past 20 years, including from 2008 to 2016.

3.2. Southern Nevada water Authority (SNWA), Nevada

Located in an arid region, Southern Nevada Water Authority (SNWA) served nearly 2 million residents at the time of our case study. SNWA was formed in 1991 by 7 agencies: Big Bend Water District, Boulder City, Clark County Water Reclamation, Henderson, Las Vegas, Las Vegas Valley Water District, and North Las Vegas (Fig. 2). SNWA is a wholesale water provider "responsible for water treatment and delivery, as well as acquiring and managing long-term water resources for Southern Nevada" (SNWA, 2021). SNWA relies heavily on water from Lake Mead, a reservoir that stores Colorado River water. Boulder City and Henderson, two member utilities, are 100 % reliant on Colorado River water. Water from the Colorado River is governed and apportioned by the 1922 Colorado River Compact – which allocates water among 7 U.S. states and Mexico – as well as other agreements and court decisions. Nevada is a junior rights holder and is apportioned the smallest amount of water annually in the Lower Basin (300,000 acre feet or 370.044 million m^3). The production of hydropower and environmental flows to maintain endangered species are additional considerations, but are not handled directly by SNWA. 10 % of SNWA's water supply comes from local groundwater. In addition, SNWA treats approximately 40 % of its used water and provides "return flows" to Lake Mead for which they receive credit against withdrawals. Since 2000, the Colorado River Basin has experienced "well below normal" snowfall and runoff, and managers speak of a decadal drought marked by especially dry years, such as 2002. They experienced long term droughts in the past (in the 1950 s), but demand at the time was low and storage was sufficient. The Las Vegas

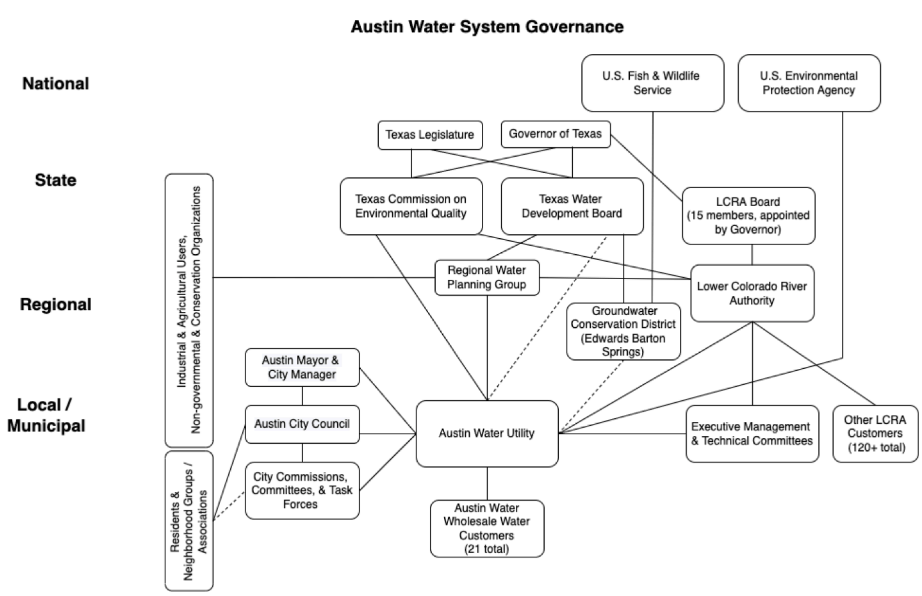

Fig. 1. Governance arrangements in the Austin Water system at different institutional scales. Solid lines between entities represent formal linkages (i.e., legally, legislatively, or contractually), while dashed lines between entities represent informal linkages (i.e., not codified).

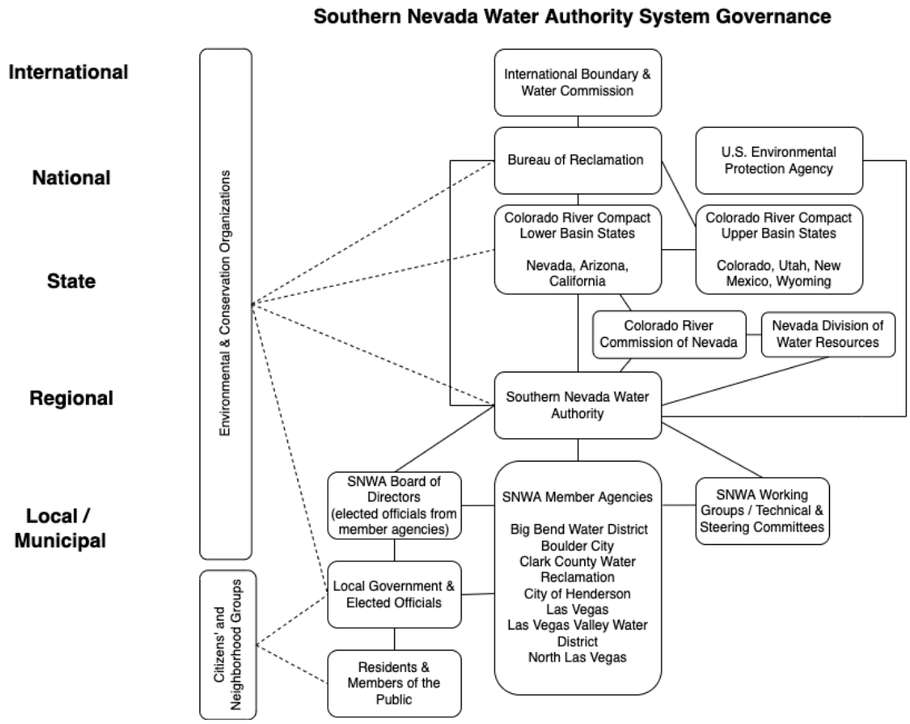

Fig. 2. Governance arrangements in the Southern Nevada Water Authority system at different institutional scales. Solid lines between entities represent formal linkages (i.e., legally, legislatively, or contractually), while dashed lines between entities represent informal linkages (i.e., not codified).

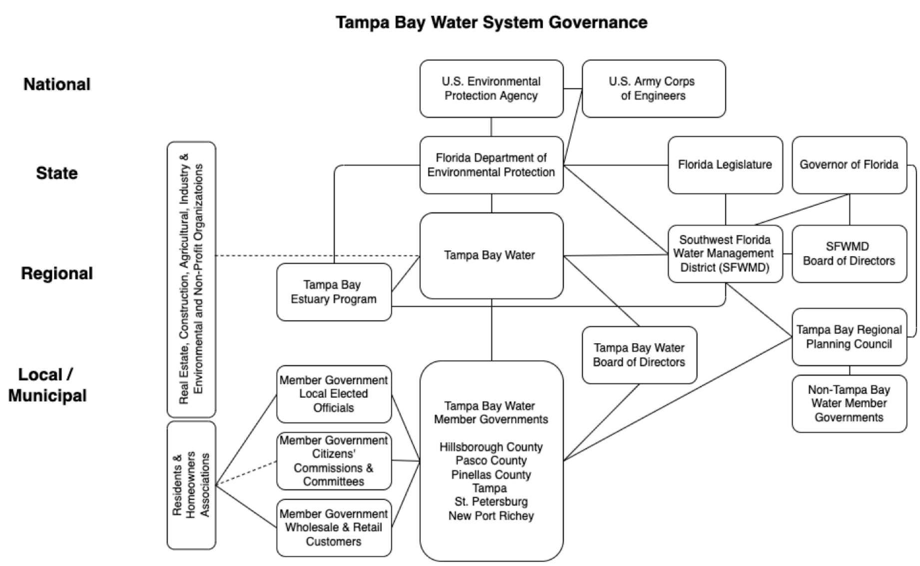

Fig. 3. Governance arrangements in the Tampa Bay Water system at different institutional scales. Solid lines between entities represent formal linkages (i.e., legally, legislatively, or contractually codified), while dashed lines between entities represent informal linkages (i.e., not codified).

area is experiencing high population growth, with annual rates of growth over 3 % since 2000, and growth rates over 6 % since the 1990 s.

3.3. Tampa Bay Water, Florida

Tampa Bay Water (TBW) was formed in 1998, evolving from the West Coast Regional Water Authority, following what is locally known as the “water wars” in which counties and cities were exploiting inexpensive groundwater at unsustainable rates. This led to local environmental degradation, concerns about supply sustainability, and abundant litigation (Dedekorkut-Howes, 2005). Six county and city governments came together across the Tampa Bay region—Hillsborough County, Pasco County, Pinellas County, New Port Richey, St. Petersburg, and Tampa—to form TBW (See Fig. 3). Their key tenets were to supply reliable water for the customers of member governments, to set a single (higher) price for water (thus avoiding the “race to the bottom” to withdraw cheap groundwater), and to build infrastructure to diversify water supplies and take pressure off groundwater. Diversification meant adding surface water reservoirs, pumping stations, other storage facilities, pipe connections, reuse capacity, and desalination plants. Importantly, groundwater supplies formerly under the authority of the individual governments were placed under a Consolidated Permit through the Southwest Florida Water Management District, which controlled groundwater withdrawal according to strict limits, to help meet environmental goals and prevent aquifer depletion. While groundwater was, therefore, limited and subject to a permit, it has been made available in times of need, although over-withdrawal triggers permit violations. Like many areas in Florida, the Tampa Bay region experiences higher population growth relative to the national average and has experienced major multi-year drought episodes.

4. Results

4.1. What adaptation actions did systems take in response to drought?

We observed a wide range of types of actions taken to manage drought, such as infrastructural, collaboration and governance, and incentivizing individual behavior through mandates or communication (Supplementary Materials 3). Below, we present the most common drought response measures cited by interviewees across our cases.

Limiting or Prohibiting Certain Water Uses: All three cases utilized demand-side restrictions to immediately reduce water demand during drought (mentioned in nearly every interview, e.g., AW01-02,04–06; SN 05–09; TBW 02–06). These included restrictions on outdoor residential water use, such as watering lawns or filling pools (either mandatory or voluntary), limitations on commercial fountains or "misters", prohibitions on vehicle washing, and the exercise of interruptible supplies (e.g., in Austin area, where water delivery to agricultural users can be interrupted during severe drought). Some of the restrictions – such as ornamental fountains in small retail parking areas or misters along pedestrian walkways – were implemented not because they yielded large water savings, but rather because there was a perceived benefit of bolstering consistent messages (symbolically or otherwise) regarding limiting non-essential water uses during drought (SN18). Some conservation strategies to reduce customer use of water became permanent across cases and continued to achieve water reductions (AW05-06,11; SN7,12,14,16; TBW12-13).

Public Communication: Communicating with the public was deemed essential to responding to drought. Managers tended to favor voluntary measures and, thus, relied on public acceptance and support. In all cases, interviewees referenced visual cues in the environment (e.g. dropping lake levels or drying wetland areas) as important in affecting the public's awareness of drought conditions (AW01,05–06,12; SN05,18–20, TA03,06), and these were highlighted in communications to galvanize efforts to combat the drought (AW11). As one interviewee put it, "I mean, the drought was just […] on the news pretty frequently, the lake levels how low they were, and I just think the public perception of being in a severe drought was so clear that […] I don't think there was much controversy that I could see over any request to conserve water" (AW11).

Public education also helped over the longer term to shift public attitudes toward a water conservation mindset (SN01). One interviewee said public education was a "huge success in changing the water ethic in our community" (SN19). Public education about the value of water by TBW, including campaigns in schools, helped foster new attitudes toward the value of water and acceptance of drought restrictions (TBW04-05). Unified communications and messaging within and across jurisdictions were considered important to the success of these efforts (TBW13).

Planning, Collaboration, and Governance: Across cases, interviewees mentioned relying on plans, established relationships, collaboration, and trust during times of drought. In some instances, a drought prompted the "dusting off" and implementation of an existing drought plan; other actions included plan revisions, such as adding specific triggers (e.g. lake levels) relevant to current conditions (AW11). Individuals within and external to water provider organizations noted the importance of enhanced collaboration, including strengthened relationships with stakeholders that were key during drought (AW04-05). Regular meetings were held across governance levels to discuss options (AW15), and communication reinforced the sense that "we are all in this together" (TBW08), especially in systems where water is shared across multiple entities and governed collectively. The decision and subsequent strong leadership shown by SNWA and others to set aside litigation in favor of collaboration among the partners of the Colorado River Compact (see Fig. 2) was a key factor that spurred dialogue and creativity (SN02,07,13). Regional cooperation established before a drought crisis, as well as existing plans and agreed-upon triggers, allowed quick action when needed and avoided potential "in the moment" political conflicts (AW07; TBW01,06,13).

New Infrastructure & Supply: Interviewees mentioned accelerating infrastructure that would add flexibility in water supplies. The 2002/3 drought period on the Colorado River galvanized action on building a "snorkel" – or extension – on the upper intake pipe in Lake Mead to access deeper water and spurred discussions of a third intake (completed in 2020 and used in 2022) and pumping station (SN08). The drought also hastened exploration of new groundwater supplies from northern Nevada. In drought emergencies, some TBW member entities ran temporary pipes to physically access water, spurring consideration of a longer-term solution (TBW04-12).

Changing Land Use and Building Codes: Another response galvanized by drought in SNWA was a change in city ordinances to disallow front yard grass turf in new developments (SN01,09). Systems relied on incentives as well that induced permanent water reduction programs such as "Cash for Grass" (SN02,03). In all cases, heightened standards for water-efficient appliances and building codes were implemented to reduce longer-term water consumption.

4.2. How did incremental adaptation actions taken during drought affect future adaptive capacity?

In each of the cases, water providers were effectively able to adapt in response to drought events, although there were also important tensions and tradeoffs that can reduce future adaptive capacity to climate change. All categories of adaptive capacity were important across cases: social, physical, and economic (Nelson et al., 2007). In this section we first trace how incremental adaptation actions taken during drought built adaptive capacity for future climate change, and then we report how some actions actually detracted from adaptive capacity.

4.2.1. Building future adaptive capacity

Maintaining System Goals and Functions: Interviewees from all three systems felt that their systems were able to meet their goals as water providers during drought due to the adaptation actions that were taken. A typical response to questions about fulfilling their mission during drought was: "we were able to provide safe, reliable water and wastewater services to our community in an affordable way" (AW04).

The primary metric cited by interviewees as evidence of meeting the organizational mission was the ability to reduce water use and, thus, maintain reliable delivery even when supply was constrained. For example: "we took our per capita consumption from 320 down to about 222 [gallons per day]" (SN04); "we cut back our use when it was called for" (AW04); and "we were very successful in reaching a very low level […] we're down at around 64 gallons per capita [per day] right now" (TBW04). The ability to reduce per capita consumption when needed is a sign of adaptive capacity and being able to continue to supply water during drought stress can be interpreted as a sign of successful incremental adaptation (helping the existing system adjust to changes).

Enhanced Flexibility: Flexibility emerged as a key element of adaptive capacity that was mobilized during drought or affected through drought adaptation across cases (Table 1). Examples of capacity that were perceived as conferring increased flexibility included: having diverse water supplies and multiple ways to access them; ability to alter demand (short-term and baseline); sufficient revenue and staffing; clear governing agreements; good working relationships with customers and political decision makers; and appropriate governance arrangements. As one interviewee explained: "the general consensus is to advocate

Table 1
Examples of policy levers and specific actions taken to enhance key areas of flexibility across cases. These include examples of new flexibility created directly in response to drought as well as flexibility conferred by pre-existing capacity mobilized during drought. AW = Austin Water; SNWA = Southern Nevada Water Authority; TBW = Tampa Bay Water.

Key Areas of Flexibility	Policy Levers That Can Enhance Flexibility	Examples of Actions Taken for Enhanced Flexibility
Water Supply	Diversifying water supplies; developing new ways to access the same water supply; enhancing options to store water when excess is available	*AW*: Initiated planning for new reservoirs to enhance future storage in lower portion of the river basin *SNWA*: Built third intake pipe and new extension to access deeper reservoir water; Aquifer storage and recovery *TBW*: Accessed diversified supply through surface reservoirs, new pipe connections, and desalination
Customer Demand	Limiting non-essential uses; mobilizing ability to curtail non-essential uses; fostering new attitudes on 'appropriate' uses	All Cases: Implemented outdoor watering restrictions *AW*: Interrupted agricultural supplies to ensure supply for essential uses *SNWA:* Decreased outdoor water use by reducing turf grass through programs such as "Cash for Grass" *TBW:* Accessed reclaimed water system to decrease overall demand
Rate Structure and Revenues	Decoupling revenues from volume sold; designing revenues to better support operational fixed costs; building budget to support drought response (e.g., communication, enforcement, planning) into rate structures	*AW:* Instituted across-the-board flat fee to reduce revenue volatility associated with volumetric water rates *SNWA*: Introduced tiered pricing to incentive conservation *TBW:* Relied on uniform water rate for all TBW member entities, pooled financial resources enabled development of new regional infrastructure/supply
Staff and Human Resources	Hiring sufficient staff – both in terms of numbers and specialization; retaining long-term staff beyond drought event; enabling appropriate mechanisms for intra-agency coordination and communication	*AW*: Created inter-departmental 'action teams' to address drought and climate impacts *SNWA*: Hired extra staff during drought to enforce conservation measures – e.g., hotlines, code officers *TBW*: Retained staff before, during, and after drought to facilitate long-term learning, communication, collaboration, and innovation
Governance and Collaboration	Creating institutions, legal frameworks, etc. for drought response; pre-establishing drought triggers and plans; enacting collective agreements to provide political support for responses at the appropriate scale	*Across all cases:* Pre-approved drought triggers allowed quick action when needed, conferred political support *AW*: Instituted routine meetings for drought response supported relationships and collaboration across multiple levels of governance *SNWA*: Strengthened collaboration with other parties to Colorado River Compact during drought prevented litigation and spurred dialogue and creativity *TBW*: Relied on regional governance arrangement for shared water supplies, enhanced financial stability and environmental sustainability
Communication and Public Engagement	Building new awareness of the value and limited nature of water; strengthening trust between customers and water provider	*AW*: Improved communication with customers increased responsiveness to conservation measures *SNWA:* Expanded public education was instrumental to "changing the water ethic in our community" *TBW:* Avoided "back and forth" on watering restrictions shifted public tolerance for conservation

flexibility in water supplies, because invariably things come up that you didn't foresee" (AW12). The role that social factors play in fostering flexibility was also mentioned consistently throughout cases (Table 1).

Proactive Planning: A strong companion theme to flexibility, which also helped to build adaptive capacity, was proactive planning and preparedness. Having a clear drought response plan developed in advance and, therefore, not being caught off guard, was considered a key aspect of building adaptive capacity needed to deal with future climate change. Interviewees highlighted the fact that they have not "had to scramble" (AW03), "we were prepared. We were responsive" (AW15), and that they were "better prepared now" (SN13). Having a response strategy developed ahead of time is highly valued for organizations expected to perform at 100 % reliability, and, again, was indicative of adaptive capacity.

Interviewees in the TBW system further emphasized the value of proactive planning that was spurred by drought as a means of enhancing the adaptive capacity for future climate stress: "we can't just keep going through these situations in […] this solely reactive fashion" (TBW03). TBW began discussion of diversifying water supplies before the drought of 1999/2000 (see Case Background), but "we wouldn't have any of this [planning], probably, if it wasn't for that drought" (TBW12) and the fact that "drought does get people thinking outside of the box" (TBW13). As one interviewee recalled, "that drought was […] very helpful to getting those higher-cost projects initiated because every-one realized that we just couldn't keep pulling more and more water out of the ground, that we needed to have some diversification" (TBW09).

4.2.2. *Detracting from future adaptive capacity*

While adaptations in response to drought enabled these systems to successfully achieve their mission of providing water, interviewees also identified unintended consequences or trade-offs that reduced adaptive capacity in other ways. These tradeoffs were often due to, or else compounded by, existing system attributes.

Reduction in Revenue: All three provider organizations were grappling with revenue reductions caused by conservation measures enacted during drought. Water conservation measures reduced water sales during the drought itself – but these reductions often persisted beyond the duration of the drought event (AW01-03,05–08,10–12,16–17; SN01-02,05,07–09,11,12,14,16–20; TBW01,03–05,09,14). Many utilities have, or have had in the past, a revenue model based mostly on the volume of water sold, so conservation reduces revenues even as operational costs remain the same or even rise. Before conservation became common, utilities were better able to smooth revenues: they typically recovered revenue during dry years, when customers consumed more to irrigate landscapes, to make up for cooler/wetter years when they sold less water. However, as some water conservation measures became more or less permanent in each of these cases, there was little opportunity to make up lost revenue even when the drought abated. In response, AW attempted to implement an across-the-board flat fee as a means of smoothing revenues, but this strategy was highly controversial and raised equity concerns (AW08).

While all systems delivered water during recent drought events, decreased revenues had cascading effects on system maintenance, funding for outreach and enforcement staff, ability to build new infrastructure, and debt servicing (SN01), all of which affect flexibility and long-term adaptive capacity. Staff facilitated learning and innovation; conversely, loss of staff across district committees reduced collaboration and communication (AW02; TBW01). The inflexibility of fixed costs created the need for different rate structures, or even raising rates during drought, which produced conflict with customers. To further complicate the revenue issue, the cost of alternative water supplies (e.g. desalination) for use during drought was a major consideration in all systems (AW12; SN02-03,07,10,12; TBW01-05). While systems were considering, or had even built, alternative supplies to improve reliability, these were substantially more expensive to operate compared to other sources. One interviewee stated that it would be prohibitive to build 100 % reliable capacity into each new supply: “it would cost a lot of money and you would seldom use it” (TBW01).

Compounding drought-induced revenue challenges, SNWA and TBW were still recovering financially from the 2008/09 economic recession at the time of our interviews (SN02,07,13–14; TBW03-04,12). In Las Vegas, revenue was also generated by high hookup fees for new homes, often charged before houses were completed (SN12,16). But, according to one stakeholder external to SNWA, maintaining the revenue stream through large hookup fees and rapid suburban growth was also unsustainable (SN11).

Operational Challenges: The systems all faced operational and engineering challenges during drought because reduced flow through pipes due to conservation measures complicated treatment and delivery. A TBW interviewee explained that lower flow volumes can require additional treatment of water in the pipes due to longer transit times and “water age” problems, such as decay of disinfectant treatments and nitrification (TBW03). In addition, if water restrictions vary by day of the week, fluctuations in demand can lead to water main breaks through rapid changes in pressure and volume and accumulation of solids in pipes (AW06). SNWA observed an increase in total dissolved solids during periods of reduced flows and responded by flushing with additional treated water (SN04). SNWA also added non-reuse treated water to reuse water, because water softeners made the reduced reuse volume too salty for landscaping (SN05,07). Additional steps to meet water quality standards added costs (AW06; SN04). Another unexpected challenge from days-of-the-week watering schedules was larger peaks and valleys of use in different parts of the delivery area, causing challenges with pumping and distribution (AW07). In another example, water conservation measures during drought needed to be set carefully to avoid falling below flow and pressure requirements for firefighting (AW06; SN07).

Some complexities and tradeoffs also emerged as drought responses and outcomes intersected with constraints due to the type of supplies available in each system. TBW’s diversification of sources beyond groundwater (see Case Background) was considered an improvement, but it became more challenging to manage water quality and introduced a new vulnerability to interannual climate variability (e.g. less seasonal rainfall) that did not exist for groundwater supplies (TBW05,09). Even customer preferences for water taste could complicate these strategies (AW06; TBW02,08).

Counterproductive Behavior: In some cases, watering restrictions and rules led to perverse incentives and counterproductive behavior – such as individuals choosing to overwater in home landscaping (AW13) or in agriculture (AW11). For example, some homeowners responded to restricted watering schedules by applying more water on their designated days to “make up” for not being able to water at other times. Another unintended consequence of watering restrictions in AW was that some homeowners who could afford it dug wells to access groundwater (AW01,03,05). While AW restricted use of surface water for outdoor watering, under Texas state law, landowners have a largely unlimited right to draw groundwater from beneath their property—in other words, surface water and groundwater are governed separately under different rules. Thus, although surface water deliveries were reduced by drought measures, because of the drilling of new wells, overall water consumption did not decline in some areas. The impact was to displace some water withdrawal to the aquifer at potentially unsustainable rates, as well as cause resentment among those who could not afford to drill wells (AW01,03,05,11,16).

Perceived Inequity & Erosion of Trust: Public trust in water providers can be threatened if collective agreements are perceived as being broken. For example, in a prolonged drought that coincided with reservoir damage, TBW resorted to withdrawing groundwater, exceeding the environmental permit to maintain water service (TBW01,02). Even though the action was explained and justified in terms of public safety and reliability, TBW experienced intense criticism for exceeding the permit from both the regulator and the public. This boiled down to the perception that the foundational social contract (i.e. the agreement to provide reliable water, albeit at higher cost, to achieve increased environmental protection) of TBW had been violated from a “‘Have you met your promises?’ viewpoint” (TBW10).

There was also a strong sense among interviewees that every-one needed to do their ‘fair share’ of bearing the burden for changing behavior and restricting water uses. When the regional water authority for AW, the Lower Colorado River Authority (see Fig. 1), sought additional water use reductions from municipalities, AW pushed to obtain credit for the conservation measures already implemented. Managers argued it was more difficult to conserve further if ‘low hanging fruit’ conservation had already been enacted, and it was important for municipalities that had not yet implemented measures to ‘do their part’ (AW06-07,12). One AW stakeholder summed this up: “There’s this real mixed message that people get when you have one entity doing aggressive drought response and another entity just basically up the street that’s not doing any. People are like ‘this doesn’t seem fair.’ It’s very confusing for people” (AW16).

Furthermore, when members of the public successfully reduced their water use, they were resistant to the idea that their cost of water might still go up. As TBW and SNWA tried to restructure water rates away from volume pricing, they experienced intense public opposition to higher rates (SN01,18; TBW04,09,14). As one interviewee paraphrased: “now you zap me with a higher water bill per unit […] my reward for conserving is you make my rates higher” (TBW02). Public outcry can be especially intense if users have been told conserving water saves money. And, ultimately, this comes back to affecting trust in water providers. As one interviewee in SNWA put it:

> *“And that can almost turn deadly for the organization sometimes, because I feel like our single greatest asset is our credibility. […] I mean, you make water come out of the tap every single day and it’s clean and I’m not going to die from drinking it. I mean, everything about us is reliable, credible, believable, loyal. That’s the water industry. When you run into a situation where you raise people’s rates because you need conservation and then people conserve beyond your expectations and then you come up short on revenue and so you change the rates […] And the thing that’s most harmed is your credibility. And in many cases, you may have built that with the community over decades. It can be quickly lost. When you lose your credibility, it makes it much harder to implement any other strategies that you may want.”* (SN18)

Increased Strain on Governance: While the coalition approach of TBW held together successfully at the time of our case study, it was still subject to ongoing tension and (re-negotiation) around what is fair and how to weigh individual member government interests. Drought responses can put further strain on existing governance systems and collaborative arrangements. Rate changes were also controversial within the consortium of member agencies in TBW (see Fig. 3), as one TBW interviewee stated, "our member governments are watching us. They're always watching us to see whether or not we're going to raise the rates" (TBW01). Moreover, some TBW members that had already implemented strong conservation questioned what their responsibility was to other governments: "…we are indirectly subsidizing the development of well water sources for developing member governments […] we don't need more water, they do" (TBW15). While members of TBW "went in with good intentions of sharing the responsibilities and understanding […] we were all in this together and needed to be realistic about the region and its growth and how we're all going to get water" (TBW08), at the time of our interviews, economic recession and the higher cost of TBW water resulted in some municipalities threatening to defect from TBW and go back to withdrawing groundwater (TBW04,08).

4.3. Does adaptive capacity mobilized during drought indicate preconditions for transformative adaptation?

In addition to examining how incremental adaptation to drought events shapes future adaptive capacity, this research also investigated whether such adaptive capacity fosters the preconditions required for transformative change. In this section, we present findings to show how the mobilization of adaptive capacity during drought indicates the existence of such preconditions, including: social learning, renegotiating social contracts, and changing values.

Social Learning: Some interviewees mentioned that building public support produced learning and new attitudes: "So I don't want to say it's universal, but there's a lot of shift in the way people have been thinking, but that kind of transformation was very difficult" (SN12). Several interviewees mentioned that the learning process takes time, e.g., "you don't turn a community around on a dime; it's a journey, it's not an event" (SN14). For example, the change in policies for watering landscaping meant that, while there was "a lot of grumbling" about limits, over the years people learned "that's the way of life" (TBW02). AW also iterated their watering rules with "a pretty extensive public process" that ultimately resulted in a more flexible and effective set of rules (AW07).

Policies enacted during drought can become unexpected flashpoints for larger social conversations around the use and value of water. Nearly every interviewee in our SNWA case mentioned that restrictions on using water for small ornamental fountains (e.g., in outdoor malls, commercial landscaping) were extremely contentious—it turned out "people love fountains" (SN09). Some municipalities rescinded those restrictions under public pressure (SN01,19), but others stayed the course by removing fountains (SN15,18) or else compromised by allowing the choice of removing additional turf grass in lieu of turning off fountains (SN14). Some felt that turning off small ornamental fountains "got their [the public's] attention" (SN03) and helped to create a conservation mindset more generally – one interviewee speculated that outlawing small fountains "maybe wouldn't be as contentious nowadays" (SN14).

In TBW, a combination of factors, including drought, increasing concern for environmental impacts, and direct experience of the impacts of over withdrawal, resulted in organizational learning that fundamentally "changed the way [they] did business" (TBW02). Similarly, prolonged drought fundamentally shifted how SNWA thought about their response approach – as one interviewee said, "I don't think culturally or organizationally we think in terms of drought response anymore. I think where we've come from the year 2000 to the year 2013 is we think in terms of adaptation, not temporally finite measures" (SN19).

Re-negotiating Social Contracts: All cases demonstrated examples of water systems asking their publics for new behavior and/or acceptance of higher prices for water in recognition of scarcity generally or drought needs specifically. Citizen support and avoiding mandatory requirements whenever possible was mentioned throughout the interviews (e.g., AW07,11; TBW03,05,09; SN05,07) alongside bringing stakeholders together and anticipating and avoiding opposition to emergency orders. As one interviewee stated: "nobody wants to regulate. Nobody wants to tell people what to do. I can tell you people are like, 'We can't do that. We can't write that. You mean we have to fine them? No.'" (AW13). One interviewee recounted stories of judicial enforcement of fines and watering offenses, noting that: "the public did not willingly accept that violating watering days at your home was a criminal action" (TBW06). Water managers are therefore very aware that their power to enact system-wide adaptation strategies ultimately rests with the public, elected officials, and applicable administrative law.

Changing Values Beyond Water: There were signs that drought adaptation actions spurred shifts in community values, not only around water, but around working together. As one interviewee put it: "We saw a lot of things happen. I had somebody that lived here her whole life. So, she's lived here for over 50 years. And she said, 'This is the first time that I actually felt like people in this city were working together to accomplish something.' And I thought that was probably the highest compliment, the most important thing I'd ever heard anybody say while we were working on this" (SN18). This is echoed by another SNWA interviewee on the process of working with other Colorado River Compact states: "To me, it seems like working together and working with the other interests is going to be critical going forward. That doesn't mean there won't be conflict, but it's a matter of how you resolve and address it" (SN13). Similarly, a TBW interviewee mentioned a benefit that "I think it does instill much more [of a] sense of community that this is a region, that we need to behave like a region – and let's have a plan that we can all manage, live together harmoniously with each other and with our environment, because that's as big a part of it is trying to figure out how to live here with the lakes and wetlands and not destroy them" (TBW03).

5. Discussion

The overarching goal of our research is to understand how incremental adaptation to drought events affects adaptive capacity for future climate change, and whether those actions may foster the preconditions needed to facilitate transformative adaptation. We find that drought responses can help to build adaptive capacity, but whether this in fact happens depends on their interaction with a connected, complex socio-technical system, and unintended consequences and tradeoffs can in some cases reduce adaptive capacity. Secondly, we find that incremental adaptation and the adaptive capacities observed during drought in these case studies suggest the existence of necessary prerequisites for the emergence of transformative adaptation, but such transformation is not guaranteed. These capacities can be fragile and the preconditions for transformation must be nurtured through trust-building and communication to be robust over time. Using Shi and Moser's (2021) six "conditions of systems change" as a lens (listed in the shapes inside the triangle in Fig. 4), we argue that the drought responses reported both perpetuate and challenge existing systems and functions. We find evidence of all of Shi and Moser's conditions in our cases and add to their conceptual diagram to suggest that the relationship across domains is multidirectional and interactive (Fig. 4). Given the dynamic nature of adaptive capacities and adaptation outcomes, it is important to note that our findings reflect research participants' perceptions of the interaction between drought response and adaptive capacity at the time these case studies were conducted (in the 2010s). Following Engle (2011), this study provides a baseline or 'snapshot' that is grounded in a specific place and time to illustrate how latent adaptive capacity can be mobilized during an extreme event – in this case drought. However, Fawcett et al. (2017) have argued that longitudinal approaches may be needed to help to uncover the dynamism of adaptation processes. While beyond

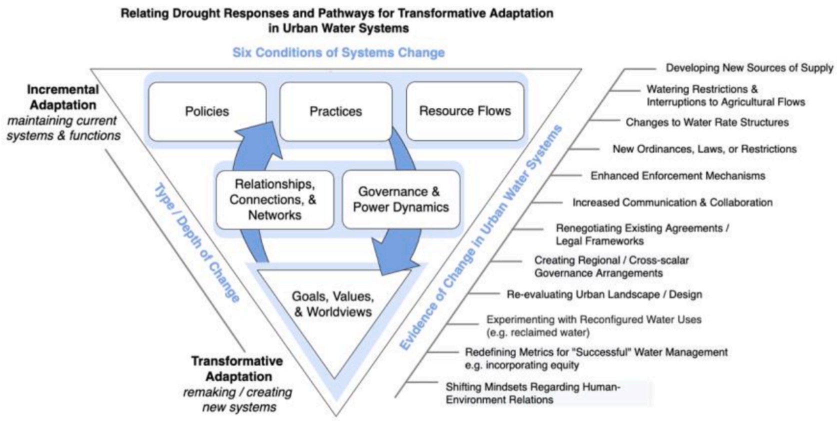

Fig. 4. Drought response and transformative adaptation. Drought responses can facilitate adaptation along a spectrum between incremental and transformative adaptation. Drought response actions reported (see also Supplementary Material 3) addressed all six conditions of change identified by Shi & Moser (2021) and enabled adaptation all along the incremental/transformative spectrum. The relationship between drought actions that support incremental adaptation and those that foster transformative adaptation is dynamic, with the potential for multi-directional interactions and feedback between these domains, as represented by the large blue arrows. (Adapted from Shi & Moser 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the scope of this study, our findings indicate that it will be important to conduct additional follow up studies to determine whether the indication of preconditions for transformative adaptation does *in fact* translate to more transformative change over time.

5.1. Mobilizing and building adaptive capacity

We find that adaptation to drought across these three systems relies on mobilizing existing capacity and also builds new adaptive capacity to maintain existing systems and functions. Many of the responses could be considered incremental, as defined by Barnes et al. (2020), as in "changes to existing practices or behaviors that allow existing social-ecological system structures to absorb, accommodate, or embrace change" (pg. 824). Moreover, our results show that incremental adaptation actions can employ social or technical approaches to building adaptive capacity – and in some cases a combination of both. For example, measures designed to reduce water use on a temporary basis, such as watering restrictions, were fundamentally social, since they required behavioral change (Fig. 4, near top; see also Dilling et al., 2019). And while the outcomes of mobilizing adaptive capacity were often expressed technically in terms of gallons of water saved, achieving these goals required both technical and social forms of adaptive capacity. Nonetheless, technical adaptation actions – such as the construction and improvement of water infrastructure – have elsewhere been shown to be a key source of adaptive capacity (Hall et al., 2014), and this was also true in our cases. For example, during the time of our interviews, SNWA was constructing (and has subsequently finished) a deep, third intake into Lake Mead to ensure ongoing access to its main water supply during drought.

Nonetheless, infrastructure does not always keep pace with environmental changes. Indeed, "highly optimized" social-ecological systems (Janssen et al., 2007), or those with "high adaptedness" (Nelson et al., 2007) achieved through highly-engineered water infrastructure, may in fact be more "brittle" and vulnerable to changes in variability or new types of disturbances than less optimized systems (Janssen et al., 2007). Thus, it will be important for future research to examine how water infrastructure built in response to drought may either improve long-term adaptive capacity or, conversely, contribute to future lock-ins that may constrain adaptation options and outcomes over time.

In our cases, social forms of adaptive capacity – such as effective communication, trust in leadership, collaborative relationships, governance, and financial and human resources – were all important in addition to the technical adaptive capacity conferred by physical infrastructure. As Cinner et al. (2018) discuss, adaptive capacity is not just about having resources, but having "the willingness and capability to convert resources into effective action" (pg. 117).

5.2. Trade-offs and growing pains

Furthermore, we find that adaptive capacity in urban water systems is dynamic, with mobilization of some types of adaptive capacity affecting capacity or flexibility in other parts of the system, such as damaging the financial health of the system or creating public backlash to current or future system changes (e.g. Cinner et al., 2018, Dilling et al., 2019). For this reason, adaptation actions must be assessed holistically: accounting for water provision, social and political impacts, and future flexibility (Nelson et al., 2007). Flexibility may also come at a price, such as making water more expensive overall, which disproportionately affects vulnerable lower-income households. Understanding trade-offs in adaptive capacity and how to avoid undesirable unintended consequences is a critical area for future adaptation policy research (Cinner et al., 2018).

Our cases demonstrate that water providers are learning during droughts how different forms of adaptive capacity interact with each other and making adjustments to financial structures, governance, and staffing. Baehler and Biddle (2018) identify the tension experienced by water managers between avoiding risks, maintaining system reliability, and promoting organizational learning and experimentation. Analyses of tradeoffs, forms of water pricing, and conservation impacts can help enlarge options for water providers and consumers going forward (Zeff et al., 2020, Kenney, 2014, Luby et al., 2018, Teodoro et al., 2020, Pérez-Urdiales and Baerenklau, 2019, Neale et al., 2020).

5.3. Pathways to transformative adaptation

While many drought responses maintained existing system functions and were, therefore, incremental, our data suggest that these have the potential to lead to transformative adaptation – or more "fundamental changes that can alter dominant social-ecological relationships" and can be mutually reinforcing (Barnes et al., 2020). This suggests that incremental and transformative adaptation – which are often treated as distinct – may overlap more than previously theorized. These results also identify a pathway for transformative adaptation to emerge over time, not only as a crisis response, but as an outcome of sustained actions taken in response to ongoing environmental pressures (Kates et al., 2012).

Incremental actions such as pricing, land use changes, and water use reductions that disrupt the *status quo* can have elements of transformative change (Fig. 4; Shi and Moser, 2021). All suggest changing values – often with attendant changes in mindsets regarding human-environment relations – and new objectives that may signal capacities for transformative change. For example, in the SNWA case, the controversy over small ornamental fountains or the relatively easy shift to change building codes to deemphasize turf, which might have been unthinkable decades ago (see Robbins, 2012), indicate pursuit of and capacity for transformative adaptation – i.e., via the potential for changes in policies and practices to facilitate fundamental shifts in systems and values over time.

Shi and Moser (2021) argue that public mindsets, values, and beliefs are the foundation of transformative change—leading to changes in relationships, power dynamics, and then policies, practices, and flows. The emergence of new discourses, behaviors, and agreements around resource use can also indicate a changing social contract around water, which is also an element of transformation (Pelling et al., 2015, Blackburn and Pelling, 2018). In our cases, managers actively sought to avoid coercive or unpopular techniques to achieve adaptation actions, and yet they needed to produce changes in behavior and values around using water. This required dedicated, ongoing efforts at communication and awareness-raising to translate otherwise fleeting, crisis-related attention (Wilhite, 2011) into a lasting source of adaptive capacity, enabling further innovation by the water provider.

Further advancing Shi and Moser's theorization, we also suggest that these processes may be more interactive and multidirectional in the messy, ongoing real-world effort to mobilize adaptive capacity and "muddle through" toward transformation (sensu Lindblom, 1959). By enacting incremental, 'surface level' changes, water providers have the potential to influence 'deeper' conditions, including relationships and, ultimately, values in collaboration with their publics. No matter how they are initiated, transformative change requires difficult conversations that challenge dominant systems and paradigms – such as questions of what is fair and what uses are most valued (Shi and Moser, 2021) – and care must be taken to ensure that transformation does not exacerbate existing inequality (Blythe et al., 2018). Yet, these changes are by no means automatic or guaranteed – entrenched mindsets, preferences, and assumptions about how to construct and manage water systems may limit the ability to transform (Pincetl et al., 2019). Furthermore, smaller systems or systems in other parts of the country may not see the same outcomes from organizational learning; indeed, in some circumstances experimentation can lead to a rejection of new forms of adaptive capacity and ways of managing water (Page and Dilling, 2020).

The consistent need to build and maintain public support across our cases – raising awareness, seeking engagement and communication with stakeholders, and maintaining collaborative governance – points to the overarching importance of building trust in institutions. Trust is foundational to mobilizing adaptive capacity, whether for incremental adaptation, such as watering restrictions, or more transformative adaptation, such as moving away from unsustainable water sources or experimenting with new water technologies (Cinner et al., 2018, Barnes et al., 2020, Pelling et al., 2015, Ormerod and Scott, 2013). Indeed, the ability to experiment is a key part of adaptive capacity and learning (Armitage, 2005, Farrelly and Brown, 2011). Trust allows managers to be more flexible and adjust plans in some cases, but it can also be an essential component for enacting previously negotiated plans and agreements, thereby enabling them to be prepared and "not have to scramble." Thus, in contrast to prevalent approaches to water management that focus largely on ensuring physical supply and managing demand, these findings indicate that adaptation efforts should focus more explicitly on interventions that can increase trust and collaboration among actors.

Finally, perhaps the most important element of maintaining trust is ensuring that enacted policies appear fair and just (Adger, 2013), efficacious, and commensurate with the problem at hand. In our cases, trust suffered when policies appeared to apply unequally, did not acknowledge prior 'good' behavior, were mismatched to the scale of the problem, or were perceived as capricious or overly burdensome. Public trust was also jeopardized when goals of policies were obviously ignored.

6. Conclusion

Our cases reveal significant adaptive capacity for drought and climate change in large urban water systems, marked by awareness of the changing nature of the resource, a priority on building trust through public involvement and interorganizational collaboration, diversified supplies and/or infrastructure, and a nascent willingness to embrace different values around water. This adaptive capacity may be somewhat fragile and can be eroded by difficult economic conditions, perceptions of 'unfair' decision making, and unsustainable economic models of water provider operation. Furthermore, adaptations themselves can create new sources of vulnerability, emphasizing the need for integrated and iterative planning that stresses a dynamic approach, more complete understanding of connections within the integrated system, and attention to potential consequences – intended or otherwise – of adaptation.

Furthermore, our cases suggest that the adaptive capacity that is mobilized or built in response to drought can lay the groundwork for transformative adaptation, to the extent that it fosters changing values around water availability, pricing, and the provision of water as a basic service, and emphasizes communication, collaboration, and engagement with publics and decision makers as key elements of building adaptive capacity for the future. It remains to be seen whether these systems will ultimately follow a pathway of transformative adaptation. As adaptation champions, water managers are no longer "invisible," passive executors of long-term, rigid plans, but have the potential to mobilize the adaptive capacity that emerges from drought to support transformative change in water management that can meet the challenges of climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

The authors acknowledge funding from the National Oceanic and Atmospheric Administration's Societal Applications Research Program under grant # NA10OAR4310172, and the NOAA Physical Sciences Laboratory. Additional support was provided by the Western Water Assessment (a NOAA-funded Regional Integrated Sciences and Assessment (RISA) Grant Number NA15OAR4310144). The National Center for Atmospheric Research is sponsored by the National Science Foundation. We also thank Roberta Klein, Kathy Miller and Doug Kenney who collaborated in conceptualizing and designing this research, and Luke Nordgren for assistance with coding interviews. We deeply appreciate the cooperation of the water providers involved and thank all the interview participants. We also thank the members of our IDCA Advisory Working Group of practicing water managers who participated in framing the project and provided invaluable guidance. We thank the three anonymous reviewers who provided comments and helped us strengthen this paper. All responsibility for content rests with the authors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2023.102649.

References

Adger, W.N., 2013. Emerging dimensions of fair process for adaptation decision-making. In: Palutikof, J., Boulter, S.L., Ash, A.J., Smith, M.S., Parry, M., Waschka, M., Guitart, D. (Eds.), Climate Adaptation Futures, First Edition. John Wiley & Sons Ltd, pp. 69–74.

Adger, W.N., Brown, K., Nelson, D.R., Berkes, F., Eakin, H., Folke, C., Galvin, K., Gunderson, L., Goulden, M., O'Brien, K., Ruitenbeek, J., Tompkins, E.L., 2011. Resilience implications of policy responses to climate change. Wiley Interdiscip. Rev. Clim. Chang. 2, 757–766. https://doi.org/10.1002/wcc.133.

Armitage, D., 2005. Adaptive Capacity and Community-Based Natural Resource Management. Environ. Manag. 35, 703–715. https://doi.org/10.1007/s00267-004-0076-z.

Baehler, K.J., Biddle, J.C., 2018. Governance for adaptive capacity and resilience in the U.S. water sector. Ecol. Soc. 23, art24. https://doi.org/10.5751/ES-10537-230424.

Barnes, M.L., Wang, P., Cinner, J.E., Graham, N.A.J., Guerrero, A.M., Jasny, L., Lau, J., Sutcliffe, S.R., Zamborain-Mason, J., 2020. Social determinants of adaptive and transformative responses to climate change. Nat. Clim. Chang. 10, 823–828. https://doi.org/10.1038/s41558-020-0871-4.

Belliveau, S., Smit, B., Bradshaw, B., 2006. Multiple exposures and dynamic vulnerability: Evidence from the grape industry in the Okanagan Valley, Canada 16, 364–378. doi:10.1016/j.gloenvcha.2006.03.003.

Berrang-Ford, L., Siders, A.R., Lesnikowski, A., Fischer, A.P., Callaghan, M.W., Haddaway, N.R., Mach, K.J., Araos, M., Shah, M.A.R., Wannewitz, M., Doshi, D., Leiter, T., Matavel, C., Musah-Surugu, J.I., Wong-Parodi, G., Antwi-Agyei, P., Ajibade, I., Chauhan, N., Kakenmaster, W., Grady, C., Chalastani, V.I., Jagannathan, K., Galappaththi, E.K., Sitati, A., Scarpa, G., Totin, E., Davis, K., Hamilton, N.C., Kirchhoff, C.J., Kumar, P., Pentz, B., Simpson, N.P., Theokritoff, E., Deryng, D., Reckien, D., Zavaleta-Cortijo, C., Ulibarri, N., Segnon, A.C., Khavhagali, V., Shang, Y., Zvobgo, L., Zommers, Z., Xu, J., Williams, P.A., Canosa, I. V., van Maanen, N., van Bavel, B., van Aalst, M., Turek-Hankins, L.L., Trivedi, H., Trisos, C.H., Thomas, A., Thakur, S., Templeman, S., Stringer, L.C., Sotnik, G., Sjostrom, K.D., Singh, C., Siña, M.Z., Shukla, R., Sardans, J., Salubi, E.A., Safaee Chalkasra, L.S., Ruiz-Díaz, R., Richards, C., Pokharel, P., Petzold, J., Penuelas, J., Pelaez Avila, J., Murillo, J.B.P., Ouni, S., Niemann, J., Nielsen, M., New, M., Nayna Schwerdtle, P., Nagle Alverio, G., Mullin, C.A., Mullenite, J., Mosurska, A., Morecroft, M.D., Minx, J.C., Maskell, G., Nunbogu, A.M., Magnan, A.K., Lwasa, S., Lukas-Sithole, M., Lissner, T., Lilford, O., Koller, S.F., Jurjonas, M., Joe, E.T., Huynh, L.T.M., Hill, A., Hernandez, R.R., Hegde, G., Hawxwell, T., Harper, S., Harden, A., Haasnoot, M., Gilmore, E.A., Gichuki, L., Gatt, A., Garschagen, M., Ford, J.D., Forbes, A., Farrell, A.D., Enquist, C.A.F., Elliott, S., Duncan, E., Coughlan de Perez, E., Coggins, S., Chen, T., Campbell, D., Browne, K.E., Bowen, K.J., Biesbroek, R., Bhatt, I.D., Bezner Kerr, R., Barr, S.L., Baker, E., Austin, S.E., Arotoma-Rojas, I., Anderson, C., Ajaz, W., Agrawal, T., Abu, T.Z., 2021. A systematic global stocktake of evidence on human adaptation to climate change. Nat. Clim. Chang. 11 (11), 989–1000.

Bettini, Y., Brown, R.R., de Haan, F.J., 2015. Exploring institutional adaptive capacity in practice: examining water governance adaptation in Australia. Ecol. Soc. 20, art47. https://doi.org/10.5751/ES-07291-200147.

Blackburn, S., Pelling, M., 2018. The political impacts of adaptation actions: Social contracts, a research agenda. Wiley Interdiscip. Rev. Clim. Chang. 9 (6) https://doi.org/10.1002/wcc.549.

Blythe, J., Silver, J., Evans, L., Armitage, D., Bennett, N.J., Moore, M.-L., Morrison, T.H., Brown, K., 2018. The dark side of transformation: latent risks in contemporary sustainability discourse. Antipode 50 (5), 1206–1223.

Bullock, R.C.L., Diduck, A., Luedee, J., Zurba, M., 2022. Integrating Social Learning. Environ. Manag. 69 (6), 1217–1230. https://doi.org/10.1007/s00267-022-01630-x.

Cinner, J.E., Adger, W.N., Allison, E.H., Barnes, M.L., Brown, K., Cohen, P.J., Gelcich, S., Hicks, C.C., Hughes, T.P., Lau, J., Marshall, N.A., Morrison, T.H., 2018. Building adaptive capacity to climate change in tropical coastal communities. NatureClim Change 8, 117–123. https://doi.org/10.1038/s41558-017-0065-x.

Corbin, J., Strauss, A., 2015. Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory, Fourth edition. Sage, Thousand Oaks, Ca.

Dedekorkut-Howes, A., 2005. Chapter 4: Tampa Bay Water Wars: From Conflict to Collaboration?, in: Scholtz, John, S., Bruce (Ed.), Adaptive Governance and Water Conflict: New Institutions for Collaborative Planning. Resources for the Future.

Dilling, L., Daly, M.E., Travis, W.R., Wilhelmi, O.V., Klein, R.A., 2015. The dynamics of vulnerability: why adapting to climate variability will not always prepare us for climate change. Wiley Interdiscip. Rev. Clim. Chang. 6, 413–425. https://doi.org/10.1002/wcc.341.

Dilling, L., Daly, M.E., Kenney, D.A., Klein, R., Miller, K., Ray, A.J., Travis, W.R., Wilhelmi, O., 2019. Drought in urban water systems: Learning lessons for climate adaptive capacity. Clim. Risk Manag. 23, 32–42. https://doi.org/10.1016/j.crm.2018.11.001.

Engle, N.L., 2011. Adaptive capacity and its assessment. Glob. Environ. Chang. 21, 647–656. https://doi.org/10.1016/j.gloenvcha.2011.01.019.

Engle, N.L., Lemos, M.C., 2010. Unpacking governance: Building adaptive capacity to climate change of river basins in Brazil. Glob. Environ. Chang. 20, 4–13. https://doi.org/10.1016/j.gloenvcha.2009.07.001.

Engle, N.L 2012. Adaptation Bridges and Barriers in Water Planning and Management: Insight from Recent Extreme Droughts in Arizona and Georgia. JAWRA Journal of the American Water Resources Association 1–12.doi: 10.1111 ⁄j.1752-1688.2012.00676.x.

Farrelly, M., Brown, R., 2011. Rethinking urban water management: Experimentation as a way forward? Glob. Environ. Chang. 21, 721–732. https://doi.org/10.1016/j.gloenvcha.2011.01.007.

Fawcett, D., Pearce, T., Ford, J.D., Archer, L., 2017. Operationalizing longitudinal approaches to climate change vulnerability assessment. Glob. Environ. Chang. 45, 79–88.

Fedele, G., Donatti, C.I., Harvey, C.A., Hannah, L., Hole, D.G., 2019. Transformative adaptation to climate change for sustainable social-ecological systems. Environ. Sci. Policy 101, 116–125. https://doi.org/10.1016/j.envsci.2019.07.001.

Fleck, J., Udall, B., 2021. Managing Colorado River risk. Science 372, 885. https://doi.org/10.1126/science.abj5498.

Flörke, M., Schneider, C., McDonald, R.I., 2018. Water competition between cities and agriculture driven by climate change and urban growth. Nat. Sustainability 1 (1), 51–58.

Hall, J.W., Henriques, J.J., Hickford, A.J., Nicholls, R.J., Baruah, P., Birkin, M., Chaudry, M., Curtis, T.P., Eyre, N., Jones, C., Kilsby, C.G., Leathard, A., Lorenz, A., Malleson, N., McLeod, F., Powrie, W., Preston, J., Rai, N., Street, R., Stringfellow, A., Thoung, C., Tyler, P., Velykiene, R., Watson, G., Watson, J.W., 2014. Assessing the Long-Term Performance of Cross-Sectoral Strategies for National Infrastructure. J. Infrastruct. Syst. 20, 04014014. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000196.

Hamlet, A.F., 2011. Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America. Hydrol. Earth Syst. Sci. 15, 1427–1443. https://doi.org/10.5194/hess-15-1427-2011.

Hill, M., Engle, N.L., 2013. Adaptive Capacity: Tensions across Scales: Water Governance and Adaptive Capacity. Env. Pol. Gov. 23, 177–192. https://doi.org/10.1002/eet.1610.

Janssen, M.A., Anderies, J.M., Ostrom, E., 2007. Robustness of Social-Ecological Systems to Spatial and Temporal Variability. Soc. Nat. Resour. 20, 307–322. https://doi.org/10.1080/08941920601161320.

Johannessen, Å., Wamsler, C., 2017. What does resilience mean for urban water services? Ecol. Soc. 22 https://doi.org/10.5751/ES-08870-220101 art1.

Jurgilevich, A., Räsänen, A., Juhola, S., 2021. Assessing the dynamics of urban vulnerability to climate change: Case of Helsinki, Finland. Environ. Sci. Policy 125, 32–43. https://doi.org/10.1016/j.envsci.2021.08.002.

Kates, R.W., Travis, W.R., Wilbanks, T.J., 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. PNAS 109, 7156–7161. https://doi.org/10.1073/pnas.1115521109.

Kenney, D.S., 2014. Understanding utility disincentives to water conservation as a means of adapting to climate change pressures. J. Am. Water Works Assn. 106, 36–46. https://doi.org/10.5942/jawwa.2014.106.0008.

Kirchhoff, C.J., Dilling, L., 2016. The role of U.S. states in facilitating effective water governance under stress and change. Water Resour. Res. 52, 2951–2964. https://doi.org/10.1002/2015wr018431.

Lach, D., Ingram, H., Rayner, S., 2005. Maintaining the Status Quo: How Institutional Norms and Practices. Texas Law Rev. 83, 2027–2053.

Lemos, M.C., Lo, Y.-J., Nelson, D.R., Eakin, H., Bedran-Martins, A.M., 2016. Linking development to climate adaptation: Leveraging generic and specific capacities to reduce vulnerability to drought in NE Brazil. Glob. Environ. Chang. 39, 170–179. https://doi.org/10.1016/j.gloenvcha.2016.05.001.

Lindblom, C.E., 1959. The science of" muddling through". Public Adm. Rev. 19 (2), 79–88.

Luby, I.H., Polasky, S., Swackhamer, D.L., 2018. U.S. Urban Water Prices: Cheaper When Drier. Water Resour. Res. 54, 6126–6132. https://doi.org/10.1029/2018WR023258.

Maxmen, A., 2018. As Cape Town water crisis deepens, scientists prepare for 'Day Zero'. Nature 554 (7690), 13–15.

McDonald, R.I., Weber, K., Padowski, J., Flörke, M., Schneider, C., Green, P.A., Gleeson, T., Eckman, S., Lehner, B., Balk, D., Boucher, T., Grill, G., Montgomery, M., 2014. Water on an urban planet: Urbanization and the reach of urban water infrastructure. Glob. Environ. Chang. 27, 96–105. https://doi.org/10.1016/j.gloenvcha.2014.04.022.

Missimer, T.M., Danser, P.A., Amy, G., Pankratz, T., 2014. Water crisis: The metropolitan Atlanta, Georgia, regional water supply conflict. Water Policy 16 (4), 669–689.

Neale, M.R., Sharvelle, S., Arabi, M., Dozier, A., Goemans, C., 2020. Assessing tradeoffs of strategies for urban water conservation and fit for purpose water. J. Hydrol. X 8, 100059. https://doi.org/10.1016/j.hydroa.2020.100059.

Nelson, D.R., Adger, W.N., Brown, K., 2007. Adaptation to Environmental Change: Contributions of a Resilience Framework. Annu. Rev. Env. Resour. 32, 395–419. https://doi.org/10.1146/annurev.energy.32.051807.090348.

Nobre, C.A., Marengo, J.A., Seluchi, M.E., Cuartas, L.A., Alves, L.M., 2016. Some characteristics and impacts of the drought and water crisis in Southeastern Brazil during 2014 and 2015. J. Water Resour. Prot. 8 (2), 252–262.

O'Brien, K., 2012. Global environmental change II: From adaptation to deliberate transformation. Prog. Hum. Geogr. 36, 667–676. https://doi.org/10.1177/0309132511425767.

Ormerod, K.J., Scott, C.A., 2013. Drinking Wastewater: Public Trust in Potable Reuse. Sci. Technol. Hum. Values 38, 351–373. https://doi.org/10.1177/0162243912444736.

Page, R., Dilling, L., 2020. How experiences of climate extremes motivate adaptation among water managers. Clim. Change 161 (3), 499–516. https://doi.org/10.1007/s10584-020-02712-7.

Pahl-Wostl, C., 2020. Adaptive and sustainable water management: from improved conceptual foundations to transformative change. Int. J. Water Resour. Dev. 36, 397–415. https://doi.org/10.1080/07900627.2020.1721268.

Park, S.E., Marshall, N.A., Jakku, E., Dowd, A.M., Howden, S.M., Mendham, E., Fleming, A., 2012. Informing adaptation responses to climate change through theories of transformation. Glob. Environ. Chang. 22, 115–126. https://doi.org/10.1016/j.gloenvcha.2011.10.003.

Pelling, M., O'Brien, K., Matyas, D., 2015. Adaptation and transformation. Clim. Change 133, 113–127. https://doi.org/10.1007/s10584-014-1303-0.

Pérez-Urdiales, M., Baerenklau, K.A., 2019. Learning to live within your (water) budget: Evidence from allocation-based rates. Resour. Energy Econ. 57, 205–221. https://doi.org/10.1016/j.reseneeco.2019.06.002.

Pincetl, S., Porse, E., Mika, K.B., Litvak, E., Manago, K.F., Hogue, T.S., Gillespie, T., Pataki, D.E., Gold, M., 2019. Adapting Urban Water Systems to Manage Scarcity in the 21st Century: The Case of Los Angeles. Environ. Manag. 63, 293–308. https://doi.org/10.1007/s00267-018-1118-2.

Rayner, S., Lach, D., Ingram, H., 2005. Weather Forecasts are for Wimps: Why Water Resource Managers Do Not Use Climate Forecasts. Clim. Change 69, 197–227. https://doi.org/10.1007/s10584-005-3148-z.

Robbins, P., 2012. Lawn people: How grasses, weeds, and chemicals make us who we are. Temple University Press.

Saldaña, J., 2016. The coding manual for qualitative researchers, 3rd ed. Sage, Thousand Oaks, CA.

Satterthwaite, D., 2016. Missing the Millennium Development Goal Targets for Water and Sanitation in Urban Areas. Environ. Urban. 28 (1), 99–118. https://doi.org/10.1177/0956247816628435.

Scoones, I., Stirling, A., Abrol, D., Atela, J., Charli-Joseph, L., Eakin, H., Ely, A., Olsson, P., Pereira, L., Priya, R., van Zwanenberg, P., Yang, L., 2020. Transformations to sustainability: combining structural, systemic and enabling approaches. Curr. Opin. Environ. Sustain. 42, 65–75. https://doi.org/10.1016/j.cosust.2019.12.004.

Shi, L., Moser, S., 2021. Transformative climate adaptation in the United States: Trends and prospects. Science 372. https://doi.org/10.1126/science.abc8054.

Siders, A.R., 2018. Social justice implications of US managed retreat buyout programs. Clim. Change 152, 239–257. https://doi.org/10.1007/s10584-018-2272-5.

SNWA. 2021. Agency Website. Available at: https://www.snwa.com/about/mission/index.html (last accessed November 23, 2021).

Stults, M., Larsen, L., 2020. Tackling Uncertainty in US Local Climate Adaptation Planning. J. Plan. Educ. Res. 40, 416–431. https://doi.org/10.1177/0739456X18769134.

Teodoro, M.P., Zhang, Y., Switzer, D., 2020. Political Decoupling: Private Implementation of Public Policy. Policy Stud. J. 48, 401–424. https://doi.org/10.1111/psj.12287.

Texas A&M AgriLife Extension 2022 Website: https://agrilifeextension.tamu.edu/library/agricultural-law/basics-of-texas-water-law. Last Accessed March 21, 2022.

Visseren-Hamakers, I.J., Razzaque, J., McElwee, P., Turnhout, E., Kelemen, E., Rusch, G. M., Fernández-Llamazares, Á., Chan, I., Lim, M., Islar, M., Gautam, A.P., Williams, M., Mungatana, E., Karim, M.S., Muradian, R., Gerber, L.R., Lui, G., Liu, J., Spangenberg, J.H., Zaleski, D., 2021. Transformative governance of biodiversity: insights for sustainable development. Curr. Opin. Environ. Sustain. 53, 20–28. https://doi.org/10.1016/j.cosust.2021.06.002.

Wiek, A., Larson, K., 2012. Water, people and sustainability– A systems Framework for Analyzing and Assessing Water Governance Regimes. Water Resour. Manag. 26, 3153–3171. https://doi.org/10.1007/s11269-012-0065-6.

Wilhite, D., 2011. Breaking the Hydro-Illogical Cycle: Progress or Status Quo for Drought Management in the United States. European Water 34.

WUCA, 2022. Water Utility Climate Alliance Homepage. https://www.wucaonline.org/ Last accessed March 21, 2022.

Yin, R.K., 2009. Case study research: Design and methods. Sage.

Zeff, H., Characklis, G.W., Thurman, W., 2020. How Do Price Surcharges Impact Water Utility Financial Incentives to Pursue Alternative Supplies during Drought? J. Water Resour. Plan. Manag. 146, 04020042. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001228.