DISSERTATION

FACTORS CONTRIBUTING TO THE ADAPTIVE CAPACITY OF SOUTH PLATTE RIVER BASIN WATER PROVIDERS AND IMPLICATIONS FOR REGIONAL VULNERABILITY

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ABSTRACT

FACTORS CONTRIBUTING TO THE ADAPTIVE CAPACITY OF SOUTH PLATTE RIVER BASIN WATER PROVIDERS AND IMPLICATIONS FOR REGIONAL VULNERABILITY

A 2013 Colorado Water Conservation Board study found that adaptive capacity of water providers increased between drought events in 2002 and 2012, motivating this study to add nuance to those conclusions and investigate what kind of variation of adaptive capacity existed during this period and what factors contributed to the increase. From these findings, strengths and weakness of regional adaptation can be assessed to determine potential vulnerabilities to future drought conditions. To analyze how the capacity of water providers to cope with environmental changes translates to adaptive capacity, this study uses this framework to structure evaluation of how stress affects institutions and water providers, how adaptive capacities were changed, and implications this has for vulnerability to future climate changes. Specifically, it investigates: 1. How adaptive capacity of water providers manifested between two drought periods; 2. What mechanisms caused changes in adaptive capacity; and 3. How stress / exposure may change under future climate scenarios.

Chapter 2 focuses on how water providers' ability to cope with drought changed between the 2002 and 2012 events. While other studies have sought to evaluate these stakeholders' vulnerabilities and adaptive capacities, they have focused on a subset of water providers who are often in large cities and engaged with state agencies, so the scope of differences in providers' abilities to manage severe water shortages and potential vulnerabilities to future changes is still unknown. This study introduces a methodology to assess adaptive strategies used by South Platte

River Basin water providers to increase understanding of their adaptive capacity to cope with shocks and stress. Specifically, it evaluates how water providers altered their drought management strategies during and between two former drought periods and how shifts affected their abilities to cope with extreme events. From this a suite of response options and management patterns that increase adaptive capacity are isolated and potential vulnerabilities to stress are discussed. The research methodology uses an ‘analog approach’ to evaluate how water systems were impacted by two past drought events (in 2002 and again in 2012), alterations made to management strategies after the first drought, and how they performed during the subsequent drought. From this analysis, it was determined that all water providers were less severely impacted by the 2012 drought than they were in 2002. A hierarchical cluster analysis was performed on response strategies to look at groups of water providers to understand what adaptive strategies they adopted and why those decisions were made. This study augments existing knowledge of vulnerability of stakeholders and the region because it provides an understanding of successful adaptive strategies but also sheds light on types of water users and attributes of systems that could create vulnerabilities to worsening drought conditions or water stress.

Qualitative analysis revealed that the impacts of the 2002 drought were varied among providers, ranging from those who completely ran out of water, to others who were minimally affected. The 2012 drought had minimal impacts on all providers, a finding that was confirmed by a quantitative comparison of impacts. Analysis of management ability showed that all providers’ ability to meet their water demand requirements improved from 2002 to 2012, and performance was actually better during the subsequent drought than during the period just before, showing that the adaptive strategies used improved adaptive capacity. Results of specific response strategies, using an Event History Calendar, revealed a shift in the overall number of strategies used and their distributions between the two drought periods. While demand management strategies still made up the majority of management decisions, there was a large shift towards using policy-related strategies and a large decline in emergency-related strategies. To capture common management changes and begin to understand motivations behind adaptive decisions, water providers were divided into groups based on strategies they used to manage the droughts and how they altered their strategies.

Further investigation into specific strategies revealed a shift away from reactive, demand management approaches to forward-looking, policy-centered approaches made up the majority of transitions and served as an underlying reason most providers attributed to their change in attitudes. The qualitative comparative analysis typology revealed that the primary reason water providers adapted can be attributed to their risk perceptions. Determinants of their perceived risk was due to a perception of reliable water supplies, or because they were not heavily impacted by the drought conditions. In a region that is expected to undergo significant demographic, economic, and environmental changes in the coming decades, this has the potential to present novel vulnerabilities if systems degrade or change slowly and are hit by another severe drought. This study augments existing knowledge of vulnerability of stakeholders and the region because it provides an understanding of successful adaptive capacities but also sheds light on types of water users and attributes of systems that could create vulnerabilities to worsening drought conditions or water stress. Findings revealed that most water providers were not heavily impacted by the 2012 drought, largely because the drought ended when it did, but the strategies employed have not completely absolved them from vulnerability to multi-year droughts. It can be expected that those who employed strategies to increase their flexibility and monitoring

would fare better than those who only employed strategies to increase their resources if drought conditions become longer and more severe than in the past. This research indicates that most of the water providers who were adaptive were severely impacted by the 2002 drought, but re-organized their management and, therefore, were less impacted by the subsequent drought, suggesting that some level of stress could actually spur a shift away from unsustainable paths and make water providers more resistant to future stress.

The focus of Chapter 3 is on interactions between institutions and management, specifically institutional processes that arose following the 2002 drought period and how those interactions with those processes facilitated learning by altering water management practices and shaping management alternatives of water providers. Institutions are fundamental to the processes involved in change and there is a need for innovative institutions to effectively guide systems to adapt to change and maintain resiliency. Institutions and management of water systems underwent significant changes in Colorado following a severe drought period in the early 2000s. This study examines the multi-scale learning by water managers and state policy-makers in the SPRB following the 2002 drought. In a region expected to undergo significant changes in the future, assessment of institutions that led to successful management adjustments provides useful lessons for incentivizing more adaptive water management in Colorado in the future and will improve theoretical understandings of institutional arrangements that lead to more robust systems. Additionally, knowledge of drivers and barriers of system change provides a better understanding of levers to pull to enable more robust system transformations in the future. The study combined policy document analysis with key informant interviews to first determine how the 2002 drought changed institutions, then how those changes affected management learning. The most significant institutional processes were identified using process tracing

techniques. Those processes were then used as independent variables with an analysis of water provider learning as a dependent variable and qualitative comparative analysis was performed on the groups of water providers, created in Chapter 2, to evaluate how interactions with these institutional processes affected different types of management changes. Looking at how different types of water providers interacted with institutional processes, and how that affected their management, allowed for a finer analysis of the underlying mechanisms that created adaptive water management.

The research provided empirical evidence supporting the theoretical argument that multi-level learning occurs from stress events. Results showed that the crisis presented in the 2002 drought jumpstarted a system that had become stagnant, leading to the cascade of changes. Because it was not possible to evaluate how all of the institutional changes affected water management, the study determined the most impactful processes and use these for further analysis. Based on interviews with state water policy-makers and expert opinions, three processes were perceived to have high impact on how providers managed water and are discussed below: formal policy processes to increase management options; formal drought impact mitigation processes; and informal networks that were established by water providers. Qualitative comparative analysis was used to elucidate which of these processes water providers who changed their management between the two droughts interacted with, revealing two key pathways: interactions with informal provider networks OR formal policy processes to increase management options AND drought impact mitigation processes. Repeating analysis on specific groups from Chapter 2 (that were split based on types of adjustments made to management strategies following 2002) revealed that the groups interacted differently with the institutional processes. Group 1 (large providers with relatively secure supplies) management change primarily due to cultural changes

and formal arrangements that increase supply security, both stemming from informal provider networks. Group 2 providers interacted more with formal policy processes to increase their management options, a pathway that led to formalization of their conservation and drought planning which helped to shift their culture as well and gave them more strategies to draw from during the subsequent drought. Group 3 interacted with other providers but didn't change their management, showing that the pathway alone is not sufficient.

Key mechanisms that proved effective for improved management were that they caused a shift in culture surrounding water use, they increased access to capital available for water providers, and they formalized drought management. This region is expected to undergo significant changes in the future, so assessment of institutions that led to successful management adjustments provides useful lessons for incentivizing more adaptive water management in Colorado in the future and will improve theoretical understandings of institutional arrangements that lead to more robust systems. Additionally, knowledge of drivers and barriers of system change, provides a better understanding of levers to pull to enable more robust system transformations in the future. Adaptive capacity of water providers increased, at least in part, because of their interactions with institutional processes. While Chapter 2 showed that stress can actually lead to adaptation, this chapter revealed that it also leads to multi-level learning because it spurs adaptation across levels. Interactions between formal and informal policy processes confirmed theoretical findings that a mix of both types is needed to build adaptive capacity. While informal processes affect management the most by allowing for agile institutions, if these processes aren't formalized through policy, they may not be long lasting. Interactions with other providers as well as formalizing drought plans as well as the drought itself shifted the risk perception of water providers (and users), leading to a 'culture of conservation.' However, a culture that promotes conservation can be a double-edged sword, allowing water providers to stretch their supplies further, but attitudes that efficiency is sufficient may prevent them from taking more drastic measures if future droughts and shortages are more severe or present themselves differently than the past. While this really is a case study of things that were done right, there is still a gap where institutional mechanisms don't reach rural, small water providers, who may be particularly vulnerable to future droughts.

Assessments of climate impacts in the United States say that drought may become more frequent and severe in the coming decades. Multiple Colorado-specific studies similarly conclude that Colorado's future droughts will become more frequent and intense by mid-century. While this provides water managers and planners with an understanding that water supplies that are available today may be less reliable in the future, there remains a vague understanding of how drought conditions could change (e.g., will the most severe drought on record occur with more frequency, or will droughts remain the same in severity but last longer?). Limited information remains about the potential frequency or severity of future drought conditions, adding difficulty to planning responses to such events. Chapter 4 is a stand-alone analysis that investigated the characteristics of historical and future droughts (duration, severity, intensity, and frequency) and evaluated how they may change under four scenarios: near future RCP 4.5, near future RCP 8.5, far future RCP 4.5, and far future RCP 8.5. Because drought estimates rely on temperature and precipitation patterns, the study began by evaluating how these climate variables shift under future scenarios helps understand the underlying drivers of changes in drought patterns. It then estimated drought characteristics (duration, severity, and peak) using the theory of runs and Univariate analysis was used to calculate the 20-, 50-, and 100-year return periods for drought characteristics during future and historical climate periods. Because drought

conditions are highly correlated and dependent, Copula functions were then used to calculate the bivariate probability drought characteristics will exceed historically extreme thresholds (specifically, those similar to the 2002 and 2012 droughts). The consequences of this study reveal that reliance on historical drought experiences have limited utility for managing future droughts.

Findings revealed that drought characteristics will likely be similar in the near future scenarios, but could be much more extreme by end of the century. Findings for all scenarios except end of century-RCP 4.5 show that drought severity will increase, while intensity may remain the same or decline, signifying that droughts will likely last longer. The consequences of this finding for the SPRB may be that fewer “flash droughts”, like that experienced in 2012, occur. However, when droughts do occur, they will remain moderately severe for longer. A shorter interarrival time shows a trend towards more frequent droughts as well. Chapters 2 and 3 found that gradual changes and stress allow adaptation to occur and may actually develop climate adaptation. However, if drought conditions lessen towards mid-century then become severe abruptly, there may be inadequate water supply to serve the rapid population growth that is projected to occur during that time period and systems will not have time to adapt. Additionally, Chapter 2 showed that the system is well-prepared to deal with shorter, ‘flash droughts’, but if droughts become longer and more frequent, reservoirs will become severely stressed, leaving providers who do not have additional strategies without reserves.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF DEFINITIONS

Coping capacity: The ability to deal with current variability under stationary conditions (Berman et al. 2012). Coping is strategies and actions undertaken within existing structural conditions and institutions (Birkmann and et al. 2009).

Adaptation: Adjustments to individual or institutional behavior in response to actual or expected environmental or social stimuli (Pielke Jr. 1998, Smit and Wandel 2006). Based on their timing, adaptations can be anticipatory or reactive, and they can be autonomous or planned, depending on their spontaneity. Adaptation typically refers to an action, process, or outcome in a system so it can better manage or adjust to some changing condition (Smit et al. 2000, Smit and Wandel 2006).

Adaptive capacity: The ability of a system to prepare for stresses and changes (e.g., climate change, population growth) in advance or adjust and respond to the effects caused by the stresses (Smit et al. 2001, Engle 2013). It is shaped over long terms (Lemos and Tompkins 2008, Pelling 2011, Berman et al. 2012) through strategic actions that may require institutional changes (Birkmann and et al. 2009). Synonymous with adaptability or adaptiveness.

Adaptive Strategies: Synonymous with adaptation. Measures taken to minimize expected adverse consequences.

CHAPTER 1: INTRODUCTION: A SOCIAL-ECOLOGICAL, DECISION-MAKING FRAMEWORK TO EVALUATE VULNERABILITIES OF WATER PROVIDERS IN THE SOUTH PLATTE RIVER BASIN

The impact of global environmental change on resource-dependent communities raises concerns about their vulnerability and ability to cope with future stress (Karami and Keshavarz 2009, Keshavarz and Karami 2013). Water is a resource that faces unprecedented changes, such as an increase in the frequency and severity of droughts, particularly in arid and semi-arid regions (Arab Water Council 2009, Keshavarz and Karami 2013), altered timing and volume of runoff (Colorado Water Conservation Board 2013, Gordon and Ojima 2014), and altered precipitation and evaporation (Western Water Assessment 2011a).

Environmental stress is often only one of many stressors on water resources and acts as a compounding factor to other, more persistent and growing pressures placed on water systems by population growth and changes to traditional uses. As they experience these changes, water managers face the reality that management strategies that have worked in the past may be insufficient to cope with future conditions. To be prepared to deal with uncertain resource availability, and develop and implement appropriate responses, a better understanding of the processes that affect water availability, the actors that make decisions to manage water, and institutions that shape their decisions is needed (Pahl-Wostl 2002, 2009, Walker et al. 2006, Chapin et al. 2006b, 2009, 2011, Chapin 2009, Huntjens et al. 2012).

Complex water allocation challenges, exacerbated by environmental and social change, are exemplified in the Front Range of Colorado. The South Platte River Basin (SPRB) is the most industrialized region with the highest agricultural production in the state. The Front Range area of the SPRB is also the most densely populated in the state, with an additional two million residents expected to live in the basin by 2030 (Statewide Water Supply Initiative 2010). At the same time, recent studies (Western Water Assessment 2011a, Gordon and Ojima 2014) predict that droughts will become more frequent and severe in the region. In response, water managers are trying to plan for a future where both supply and demand are uncertain. To manage their vulnerability to fluctuations of both, it is critical to understand what contributes to their ability to adapt to environmental and institutional changes.

Water providers are key stakeholders in managing fluctuations of supply and demand due to multiple, interacting stressors. They often act as the link between the environment and end users, and ultimately, the vulnerabilities created by stress in the environmental system are mediated by their actions. Most people in the U.S., particularly in the West, receive their drinking water from these organizations, a percentage that is expected to grow in coming decades (Hutson et al. 2004, Kenny et al. 2009, Engle 2012). Their primary objective, to distribute safe, clean water to customers, is achieved through a variety of strategies (e.g., maintaining large reserves, reservoirs, restrictions, education, pricing, etc.) that are made more difficult when conditions fluctuate far beyond normal. Engle (2012) notes that the increasing dependence of humans and ecosystems on water providers, combined with the potential impacts of climate variability and change, will make the delivery of high-quality water increasingly difficult in the future (Cromwell et al. 2007).

Basin efforts are underway to increase the reliability of supplies by acquiring new water and increasing efficiency of use (Metro Basin Roundtable and South Platte Basin Roundtable 2014, Colorado Water Conservation Board 2015). Meanwhile, Colorado State water planners are looking to water providers to develop and implement “locally-driven solutions” for future water shortages (Colorado Water Conservation Board 2015). In this context, the vulnerabilities created by stress in the environmental system will be mitigated by actions of water providers; however their capacity to adapt to changes is constrained by institutional and organizational factors (laws, regulations, structure, etc.).

A recent study by the Colorado Water Conservation Board (Colorado Water Conservation Board 2013) surveyed water providers to compare the perceived impacts of drought events in 2002 and 2012 Forty-eight percent of SPRB respondents indicated that “they feel they were less susceptible to drought impacts in 2013 than in 2002, although conditions in 2002 and 2013 were similar,” suggesting that actions taken as a result of 2002 increased the adaptive capacity of many water providers. The study acknowledged that there is variance in the ability of providers to cope with water shortages, however the study was conducted by basin, so the differences were not investigated and the actions they took to increase their adaptive capacity were not studied. This conclusion motivates the objective of this study, which is to investigate: <u>What factors contribute to the capacity of water providers to adapt to environmental change and how does this implicate regional vulnerability?</u>

THEORETICAL CONSIDERATIONS FOR EVALUATING ADAPTATION

Reducing vulnerability is the objective of resource managers and policy-makers alike. However figuring out how to do this can be a formidable challenge, requiring an understanding of changes that may occur, resources that are vulnerable to those changes, which resources to consider, how to mitigate the vulnerabilities, who are the right stakeholders to do so, etc. Vulnerability assessments (e.g., Glick et al. 2011, Stein et al. 2014) are often the starting point, and those taking a social-ecological approach, are even better (Gunderson and Holling 2002, Chapin et al. 2006b). However, once existing vulnerabilities are acknowledged, there is still the problem of not knowing exactly what the future will look like or the consequences of decisions-made. Therefore, to reduce vulnerability when conditions are uncertain, it’s important to understand the available strategies that can be used and effects of those strategies, focusing on decision-making. Polasky et al. (2011) state that without certainty about the trajectory of global change or how it is likely to affect individuals, it’s difficult to guide decision-makers on the ‘best’ actions to take today, so it is vital to consider not only the future impacts of current decisions, but also the potential for learning from those choices that can help inform subsequent decision-making.

Resource managers continually make decisions to minimize their risk or reduce their vulnerability, often with high uncertainty and without the best information. This is often the case in the SPRB where there is high inter-annual weather variability and projected strain on resources is expected to increase greatly. When planning for the future, it’s easy to predict the near future, but when planning further out, it’s more difficult to know the impacts of decisions. Therefore, understanding key decisions that managers make and how and why they make those decisions uncovers decision points that can reduce vulnerability and facilitate the design of policies that are effective, regardless of uncertain future conditions (Moss et al. 2014). Taking this approach, this dissertation uses a social-ecological, decision-making framework to evaluate vulnerabilities in the SPRB.

Vulnerability is often used as a term to describe the estimated net impacts of perturbations or stress to a system (Gallopín 2006, Smit and Wandel 2006). The social-ecological literature conceptualize it as consisting of the degree that a system is susceptible to and is able to cope with adverse effects (Adger 2006). In this regard, vulnerability is most often defined as consisting of components that include exposure to perturbations or external stresses, sensitivity to perturbation, and the capacity to adapt (IPCC 2001, Gallopín 2006). Adaptations are "adjustments in a system's behavior and characteristics to enhance its ability to cope with external stress," (Brooks et al. 2005, Smit and Wandel 2006) or "adjustments in individual, group, and institutional behavior in order to reduce society's vulnerability" (Pielke Jr. 1998, Smit and Wandel 2006). Therefore, to understand a system's true vulnerability, there is a need to understand how society and institutions respond to and their ability to keep up with the rate of change.

When actors in a social-ecological system perceive that a stressor nears a threshold level in the system and poses an obvious risk or vulnerability, an adaptation process is triggered (IPCC 2001, Yohe and Tol 2002, Heikkila et al. 2013). According to Smit and Wandel (2006), adaptation usually refers to a process, action, or outcome in a system to help it better cope with, manage or adjust to some changing condition, stress, hazard, risk or opportunity. Adaptations are not only responses to stressors after the fact, but also involve anticipating and planning for potential changes (McNeeley 2012). This is defined as adaptive capacity, or the potential to respond to or prepare for stress (Turner et al. 2003, Adger et al. 2007, Polsky et al. 2007, McNeeley and Shulski 2011, McNeeley 2014).

Adaptive capacity scholarship is rooted in the study of 'adaptation,' a concept based in the biological sciences that dates as far back as Darwin's seminal work on evolution and natural selection. Darwin defined adaptation as an organism's response to the environment in which it lived (Darwin 1859, Engle 2011). 'Evolutionary adaptation' (or structural adaptation), referenced by Darwin, refers to traits with functional roles that come into existence from natural selection (Williams 1966), differentiated from 'behavioral adaptation', where organisms can adjust their strategies based on changes in their environment and learning (Axelrod 1986, Froncek 2015).

Some species have the ability to adapt through learning and learning processes allow organisms to obtain the knowledge they need modify their behavior to survive in unpredictable environments. Learned adaptive behavior has a psychological as well as a biological component and integration of the two disciplines is needed to understand behavioral adaptation (Tierney 1986, Boyd et al. 2011).

When studying specifically how humans have adapted to their environments, the field of anthropology has paved the way (e.g., Newman 1961). As Engle (2010) succinctly states, 'the primary message from anthropological works that characterize societal or cultural adaptations to climate variability, is that humans are inherently adaptive creatures and when faced with adversity, we will adapt.' However, the combination of psychological, cultural, economic, political, and sociological factors that contribute to whether or not people adapt their behavior through learning or not complicates and muddles this cross-disciplinary study.

The need for people to adapt to the impacts of climate change came into focus in the early 1980s and 1990s, when studies on the potential impacts of climate change led to the realization that reacting to those impacts as they occur is insufficient to prevent harm. Studies showed that surprise events (that fall outside of what has been historically experienced) can severely impact systems reliant on long-lived structures that are slow to adapt, and reactive measures are inadequate; highlighting the need to take anticipatory measures to smooth the path to adaptation early (U.S. Office of Technology Assessment - Volume I 1993).

In the context of climate change, assessment of adaptive capacity is integral to understanding a system, community, or individual's vulnerability (IPCC 2001, Adger 2006). According to Kelly and Adger (2000), vulnerability is contingent on estimates of the potential climate change and adaptive responses. For understanding climate change vulnerability, differentiation between the concepts of adaptation, adaptive capacity, and coping capacity are useful. Berman et al. (2012) defines coping capacity as “the ability of a system or actors to draw on available skills, resources and experiences as an immediate response to manage adverse stress or shocks brought about by climate variability.” It is usually an ad-hoc activity and is the responses that an individual can take to react to a stressor within *existing* structural constraints. Yohe and Tol (2002) define this as a “coping range,” or the extent that a system can deal with change without consequences. Coping ranges fluctuate over time and represent thresholds, beyond which the consequences of experienced conditions become significant. McNeeley (2009) explains that this heuristic provides a conceptualization of how a system is vulnerable to conditions that go beyond the range of expected or “normal” conditions.

The challenge of managing under climate change is that it is not an episodic disturbance, after which conditions will return to a previous state. Milly et al. (2008) argue that “stationarity is dead,” resulting in a combination of directional shifts in baseline conditions (e.g., increasing temperatures) and changes in extreme events (e.g., more frequent and intense droughts and storms) (Fisichelli et al. 2016a). Therefore, conditions may (and likely will) shift beyond coping ranges that have developed under historical conditions, thus requiring adaptive capacity. The ability to expand coping capacity by adopting newer strategies or modifying adaptations is adaptive capacity (Yohe and Tol 2002). It involves transformation of the structure, organization, and functioning of the system in question to prepare in advance for stresses and changes and to adjust, respond, and adapt to the effects caused by stress (Yohe and Tol 2002, Berman et al. 2012). A key difference between adaptive capacity and coping range is that adaptive capacity is the potential to respond to or prepare for stress, in anticipation of future events (McNeeley 2014), whereas coping range is a measure of existing ability to respond. (See Figure 1.1 and

Figure 1.2, below, for the relationship between coping range, vulnerability, adaptations, and adaptive capacity.)

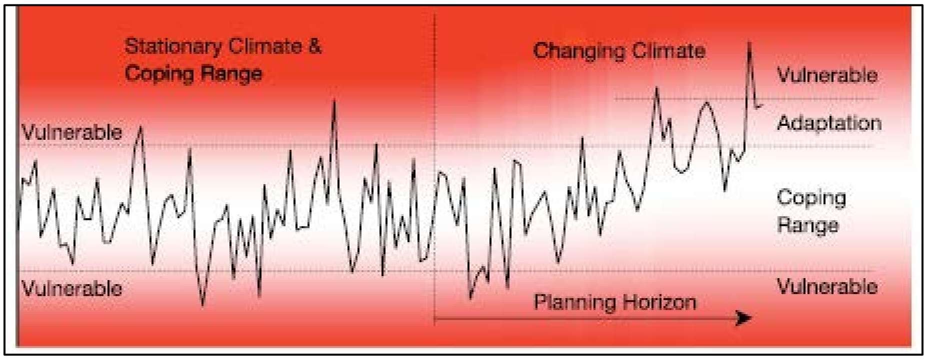

Figure 1.1. Coping range used as a link to understand current adaptation to climate with adaptation needs under future climate change, conceptualized in the IPCC 4th Assessment Report. Conditions extending beyond coping range indicate vulnerability. When new adaptations are implemented, the coping range expands, increasing future adaptive capacity. (Carter et al. 2007)

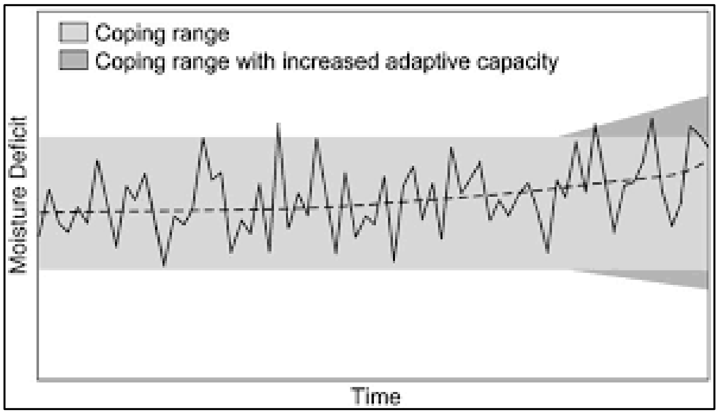

Figure 1.2. Relationship demonstrating how increasing coping range by adopting new adaptations expands future adaptive capacity (Smit and Wandel 2006)

A heuristic presented by Engle (2011) illustrates how adaptive capacity reduces harm caused by exposure, and sensitivity by moderating effects of the properties. As shown in Figure 1.3, vulnerability can be thought of as a window that closes as exposure and sensitivity expand. The narrower the gap between exposure and sensitivity, the more vulnerable a system is to harm. Because exposure and sensitivity are dynamic properties, adaptive capacity is having the ability to adapt by pulling levers to modulate fluctuations of exposure and sensitivity.

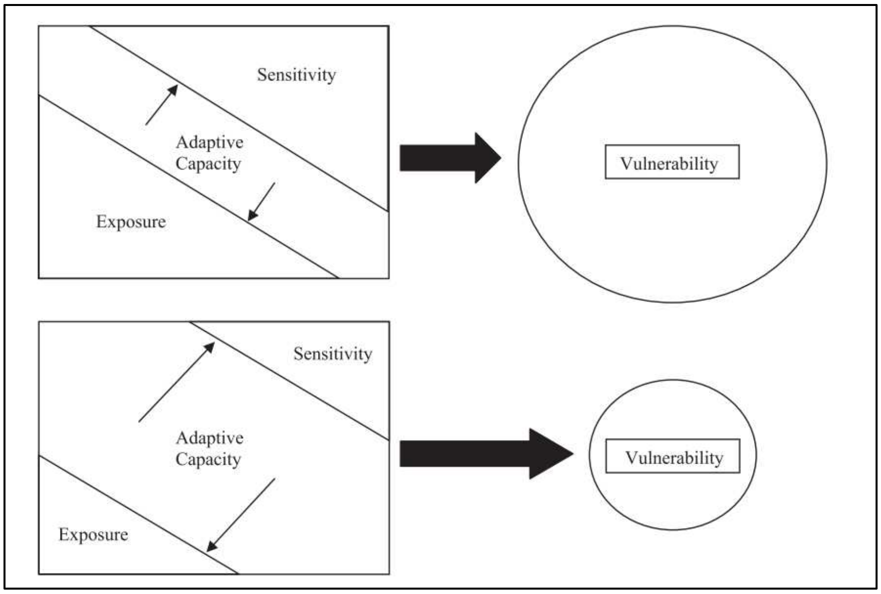

Figure 1.3. Depiction of how adaptive capacity modulates exposure and sensitivity to influence vulnerability. From Engle (2011).

Within this framework, coping capacity is the amount of force needed to be applied to mitigate harm under stationary conditions, an adaptation is an adjustment made to be able to apply more force to keep the 'window' open when exposure or sensitivity fluctuates, and adaptive capacity is having the ability to make those adjustments before it closes. A number of different approaches can be used to mitigate exposure and sensitivity. For example, a water user's exposure to drought will be determined by climatic conditions and their sensitivity will be the extent that they feel those drought conditions. Two users with the same exposure may feel the drought differently if they have different water supply sources or access to storage. They can decrease their sensitivity through actions such as buying more water or storage, so that they may not feel the effects of a drought at all. Adaptive capacity encompasses both the ability to reduce sensitivity, but also learn from past events and add flexibility to respond quickly to signs of increased harm. Adaptations are decisions made to adjust behavior or capital to reduce vulnerability and adaptive capacity is having the flexibility to be able to either react quickly enough to avoid harm or act in anticipation of potential harm.

If resource managers are impacted by a crisis, there is a period afterwards where they learn from and adjust their strategies to better cope in the future. While the impact of the crisis itself affects that adaptation, their interactions with institutional processes also affects their response. These adaptations / policy changes reflect learning that can occur in a variety of ways; with some being new and innovative and others merely incremental refinements to previous policies (Hogwood and Peters 1983, Polsby 1984, Huntjens et al. 2011). Learning is assumed to be an exploratory, stepwise process, where actors experiment with innovation until they meet constraints (Pahl-Wostl 2009). Therefore, policy-refinement and learning may have different levels of intensity and scope (Pahl-Wostl et al. 2007); the different types of which are differentiated by the concept of single-, double- (Argyris and Schön 1974), and triple-loop learning (Hargrove 2002, Pahl-Wostl 2009, Huntjens et al. 2012). It is assumed that higher-learning levels are associated with adaptive management, thus demonstrating a higher adaptive capacity.

Adaptive capacity is not only actions taken to avoid harm, but (in the resilience literature) is also a property that can facilitate transformations to more desirable states (Folke 2006, Engle 2011). In a drought, a system with higher adaptive capacity will be able to manage resources to avoid severe impacts, and will be able to easily return to pre-drought states. But if the drought is severe enough that returning to pre-drought state is impossible, adaptive capacity provides flexibility to transition to a more desirable state.

In recent years, the global change community has experienced a wave of activity in the area of adaptation to climate change studies (Pielke Jr. et al. 2007, Engle 2011) with assessments of adaptive capacity serving as a starting point for planning adaptations or management actions to mitigate climate impacts and achieve desired social-ecological outcomes (Mcclanahan et al. 2008, Marshall et al. 2010, Hill and Engle 2013, Whitney et al. 2017). Numerous methodologies to measure the property exist (and have been covered in other literature reviews and thus won't be reiterated here), but Mortreaux and Barnett (2017) point out that there is still much that is unknown about how people and institutions adapt to climate change and how effective their responses will be. This is in part due to the challenge of researching adaptive capacity because it cannot be directly measured until after it has been realized within a system (Engle 2010, Berman et al. 2012) due to its 'latency'. A commonly used approach to navigate this challenge has been to study actions surrounding past events as a proxy for how systems might mobilize their adaptive capacity to prepare for future stress (or not) (Adger et al. 2007, Engle and Lemos 2010). This methodology reveals structures used to cope with stress in a system and adaptive capacity that was accessible, or referring back to Figure 1.3, it provides a means of assessing the amount of stress that caused the window to close (increasing vulnerability) and adaptive capacity that was drawn upon to hold it open.

However, Engle (2010) points out that future stresses (associated with climate change, population growth, socio-political shifts, etc.) may far exceed what systems have dealt with in the past, rendering learning from historical extreme events incongruous. Similarly, Mortreaux and Barnett (2017) emphasize problems in assessing capacity to adapt by only studying adaptation once it has occurred and equating past adaptation to adaptive capacity. They conclude that theoretical assumption that capacity translates into action does not necessarily play out when tested empirically because adaptation practices arise from nuanced and relational processes. Therefore, <u>the central argument of this study is that evaluating decision points to adopt new</u>

adaptive strategies that increased adaptive capacity will help understand where capacity can be mobilized and expanded to meet future challenges.

While both Figures1.1 and 1.2 show that increasing a coping range by adopting new adaptations increases adaptive capacity, they provide less utility when looking at what leads to the mobilization of adaptive capacity (or not). Humans are inherently adaptive creatures and when faced with adversity, will adapt. Engle (2010) draws a distinction between two types of adaptation: reactive and anticipatory. Reactive (or autonomous) adaptation dominates the climate adaptation discourse and represents a response to stress after it has occurred (Tompkins and Adger 2005). This type of unplanned adaptation can result in maladaptation – actions taken to avoid or reduce vulnerability that impact adversely on, or increases the vulnerability of other systems, sectors or groups (Barnett and O'Neill 2010, Berman et al. 2012) – and coping strategies designed to maintain existing systems may unintentionally undermine their long-term adaptive capacity. For example, if a water user has always relied on purchasing more water as their primary means of preparing for shortages, they may be unprepared to adopt newer strategies to make their existing supplies go further if suddenly there is no more water to purchase or their supplies run out, in addition to the potential harmful effects that stockpiling water may have on other users in the system (Engle 2012).

Alternatively, humans are capable of anticipating future stress and taking proactive measures to mitigate perceived negative impacts, actions referred to as anticipatory adaptation (Engle 2010). These adaptations require an ability to reasonably predict how future stress might manifest but more importantly are influenced by the ability of actors to have learned from past experiences. As Milly et al. (2008) affirm, the past is not necessarily the prologue for what the future will look like, but previous experiences can teach valuable lessons that can be applied when considering proactive adaptations that might increase adaptive capacity (Adger 2001, Haddad 2005, Engle 2010). Anticipatory responses can be driven by stress and a desire to avoid catastrophic risks (e.g., military contingency planning). While there is not an explicit interplay between the two types of adaptive capacity in literature, a hierarchy is implied in that anticipatory adaptive capacity is preferential and stress and institutions can facilitate a shift from reactive actions to anticipatory actions. The distinction between motivations to mobilize adaptation highlights the value of assessing decision-making behind adaptation actions when trying to understand future adaptive capacity and vulnerability.

Grothmann and Patt (2005) argue that designing effective public policy to adapt to climate change necessitates an appreciation of the conditions that lead individuals to make decisions and processes involved. The authors noted[1] few empirics on decision-making sciences into climate adaptation research has led to an assumption that access to resources equates to adaptive capacity (Grothmann and Patt 2005). For example, many studies rely on the rural livelihoods framework, developed by Ellis (2000) as the conceptual underpinnings of a deductive construction of adaptive capacity indices. While the framework is insightful for understanding generalized determinants of adaptive capacity, using it to define pre-determined variables as proxies for adaptive capacity that is measured without context then assumed to result in adaptation action can result in misleading conclusions.

Mortreaux and Barnett (2017) cautions against relying on assessing theoretical factors that *ought* to determine a high adaptive capacity as a proxy for actual adaptation, stating that “the most important limitation...is the theoretical assumption that capacity translates into action.”

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[1] While the Grothmann and Patt (2005) study was over a decade ago, recent studies on the state of adaptation research by Mortreaux and Barnett (2017) and Palutikof and Barnett (2014) similarly conclude that conclusions drawn from adaptation research is based on “too few empirical studies to build robust theories to effectively explain adaptation drivers and constraints.”

Examples exist where adaptation is not occurring in places that theoretically should have high adaptive capacity and vice versa, largely due to a mismatch between institutions and action. This gap between capacity and action demonstrates a need for research focusing on factors that mobilize capacity and result in changes to management strategies (Mortreaux and Barnett 2017) because if there is assumed capacity and no action, vulnerabilities can be missed. Nelson et al. (2007) and Pelling and High (2005) focus on conditions that mobilize adaptive capacity, contending that it must be ‘activated or translated into action through social or biophysical triggers’.

Grothmann and Patt (2005) examined cognitive factors necessary for adaptation, finding that risk perception and perceived adaptive capacity are important preconditions for adaptation to occur. If actors’ risk perception and perceived capacity are high, adaptive responses (those that prevent damages) are taken. High perceptions of risk coupled with low perception of ability to respond often results in avoidant maladaptive responses, whereas low risk perception and high ability results in maladaptation that may unintentionally increase damage to some actors (described above).

SOUTH PLATTE RIVER BASIN RISK

This is a useful framework for evaluating SPRB water providers’ adaptive capacity and vulnerability, where both risks and ability to change systems vary greatly. This dissertation does not focus on socio-cognitive elements of adaptation, but uses past droughts as an analogue for understanding risk attitudes and decision-making that lead to adaptation. From this, vulnerability to different types of risk can be discussed. In this region droughts are frequent although not often severe (see Chapter 4), but they lead to water shortages that are highly variable and unpredictable. Numerous climate vulnerability assessments expect that droughts will become more frequent and severe in the coming decades (Christensen et al. 2007, Morgan et al. 2008, Coles and Scott 2009, Western Water Assessment 2011b, Gordon and Ojima 2014), a stress that will be compounded by other changes expected in the basin.

Past droughts

Jones and Cech (2009) point out that ecological extremes or shifts in ecological characteristics can serve as "flashpoints" that highlight vulnerabilities and provide learning experiences that allow institutions and managers to adjust and restructure. Recent severe droughts in the SPRB have served as examples of such flashpoints where water scarcity was heightened and water managers at all levels recognized that the system status quo was insufficient.

Taking advantage of this, this study used an analogue approach, looking at past drought periods to understand what to expect during future droughts. Conveniently, there were two recent major droughts in the SPRB, in 2002 and 2012-13. The two drought events were quite different; the 2002 drought lasted longer, but the 2012 drought was deeper and more severe (See Figure 1.4). However, studying the impacts of both droughts on water managers and their responses, as well as how they regrouped and altered management between the two droughts provides an opportunity to understand how incremental management and policy adjustments can evolve into long-term capacity to deal with water scarcity.

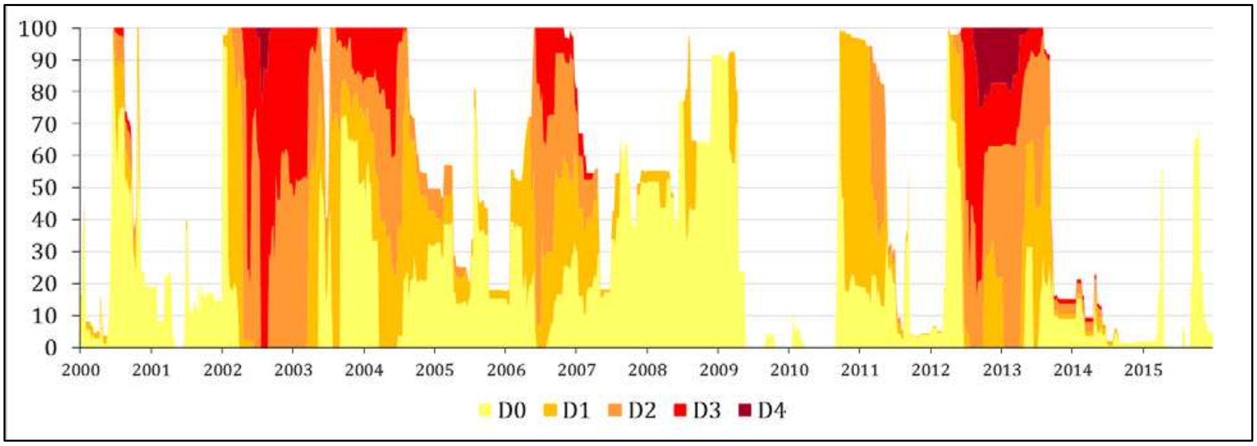

Figure 1.4. Percentage of SPRB classified by Drought Monitor status. Data courtesy of U.S. Drought Monitor[2]

A 2002 drought served as a useful learning experience for Colorado water management. Water managers were forced to come to terms with unsustainability of the trajectory of water use caused by rapidly increasing population growth and potentially decreasing water supply. The realization that status quo water management was insufficient for any future scenarios led to a reevaluation of how water is managed in the state. In 2012, another severe drought occurred, once again stressing water users and providers, with scarcity and historic wildfires.

The 2002 drought was a perfect storm of conditions. The two decades leading up to the drought (1980s and 1990s) were unseasonably wet, causing water users to grow accustomed to greater-than-average water availability (Pielke and Waskom 2003). This allowed the public to become comfortable and water institutions to develop with abundant, above-average water supplies (Doesken and Pielke 2008). In the years preceding 2002, precipitation fell below normal and the winter of 2001-2002 was abnormally dry. Snowfall during this time-period also declined, further hurting the precipitation deficit because the South Platte receives much of its

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[2] U.S. Drought Monitor is a website hosted by the National Drought Mitigation Center that produces a weekly map of drought conditions, based on measurements of climatic, hydrologic, and soil conditions as well as reported observations and impacts from over 350 contributors around the U.S. The map displays the distribution of a drought severity indicator that ranges from no drought through five drought severity levels (D0-D4). (National Drought Mitigation Center (NDMC), the U.S. Department of Agriculture (USDA) and the National Oceanic and Atmospheric Association (NOAA).)

annual flow as a result of spring snowmelt. In 2002, snowpack was only 19% of the average throughout the state (Pielke and Waskom 2003, Kenney et al. 2004, Schuck and Frasier 2004). Above average temperatures during consecutive summers set the stage for the drought by enhancing evaporation, snowmelt, and plant-water uptake, further decreasing the water budget. The combination of below average snow combined with low rainfall led to extremely low surface flow, causing severe water shortages (Davitt 2011).

By as late as March 2002, there were not many hints of the severe drought ahead. Despite the fact that the statewide snow-water equivalent was only 52% of the average, there was little public and government perception of severe drought (Doesken and Pielke 2008). By April, when spring storms that normally dump heavy, widespread precipitation did not arrive, the reality of the drought surfaced. Reservoir storage and river runoff were at a record low level, with flows less than 5% of normal in June 2002 (Schuck and Frasier 2004), when drought was declared, and by late July Colorado was in a serious drought.

Conditions gradually returned to 'normal' and the drought conditions were largely eased after a late-spring blizzard in 2003. However, the 2002 drought served as a learning experience for Colorado water management. Water managers were forced to come to terms with unsustainability of the trajectory of water use caused by rapidly increasing population growth and potentially decreasing water supply.

In 2012, another severe drought occurred, once again stressing water users and providers with scarce supplies and historic wildfires. While the 2002 drought was an example of a "creeping" disaster that was not realized until it had already been going on for some time (Pielke and Waskom 2003, Grigg 2005), the drought in 2012 was a climate surprise with few early warning signs (Hoerling et al. 2014). In some parts of the state it began as early as 2011 and conditions gradually deteriorated statewide as winter snow accumulation in all of the state's mountain regions fell significantly below normal levels. By the end of May 2012, 100% of the state was in classified in drought, including the mountainous areas that supply roughly 80% of the state's water supply (Ryan and Doesken 2012).

Streamflows in the spring of 2011 were comparable to other extreme droughts, including 2002. Record setting temperatures, not seen since the extreme droughts of the 1930s and 1950s, led to extremely low soil moisture, setting the stage for two of Colorado's most destructive wildfires, one of which was in the SPRB. Fortunately, some river basins experience record-setting snowpack in 2011, resulting in more reservoir carryover into 2012 in the SPRB. By the end of the 2012 water year (October 1), reservoir levels had experience the largest decrease in one year in recorded history (Ryan and Doesken 2012), due to evapotranspiration from the extremely high temperatures.

Moving into the beginning of 2013, state and local water managers were preparing for a repeat of the 2002 drought. Drought restrictions were in place and task forces had been activated. However, like in 2003, a late-spring storm changed course in one blizzard and by summer the threat was gone (unpublished interview data).

Intense monitoring proved to be much more effective in identifying drought early enough so that water managers had more information sooner to help support decision making. Response to exceptionally dry conditions in 2011-2012 were much more coordinated than before and during the 2002 drought, which had a false sense of security that conditions would improve when in fact they did not. The 2002 drought was a wake-up call that conditions could deteriorate rapidly and that is exactly what happened in 2012 (Ryan and Doesken 2012).

Population growth

While droughts represent an acute stressor on water supplies, rapid population growth and economic changes associated with that growth are a chronic strain on water systems through increases and shifts in demands. Population forecasts predict that the population of the SPRB will increase from approximately 3.5 million people in 2008 to about 6 million people by the year 2050 (South Platte River Basin Roundtable 2009). This change is expected to significantly alter the landscape, water use, and potentially climatic conditions of the region. Increasing population growth will continue to further stress this system, causing municipal and industrial water providers to seek water from other sources, primarily agriculture. Traditionally, agriculture has been the dominant use of water (see Figure 1.5), but "As municipal water demands increase, economic pressures encourage the retirement of irrigated lands to free up water supplies, because the price for municipal water use is often many orders of magnitude greater than that for agriculture" (Nichols and Kenney 2003). Jones and Cech (2009) assert that these changes will have far-reaching implications, including: decreased economic output from the state's agricultural sector; failure of rural communities who depend upon agriculture; unintended ripple effects into other economic sectors; and social and environmental costs to large-scale cessation of agriculture.

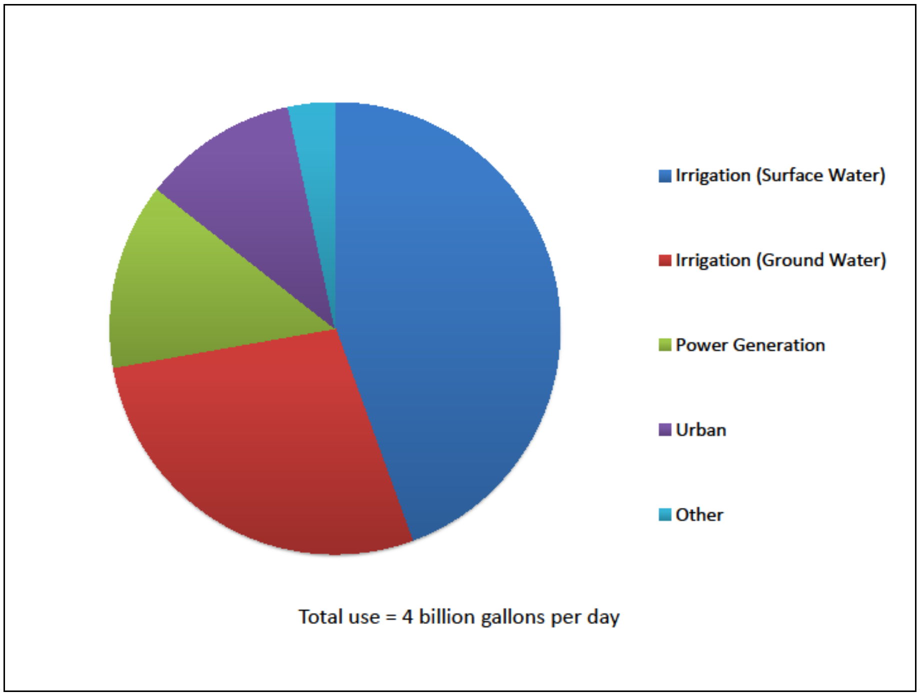

Figure 1.5. Water use in the SPRB adapted from Dennehy et al. (1998)

While a continued high population growth rate is almost certain, the distribution of that population growth rate is less certain and will implicate the rate of adaptation necessary for water providers. Figure 1.6 shows linear growth by county from 1990 until 2040, with rural counties displaying almost no growth and urban counties having the highest rates of population growth.

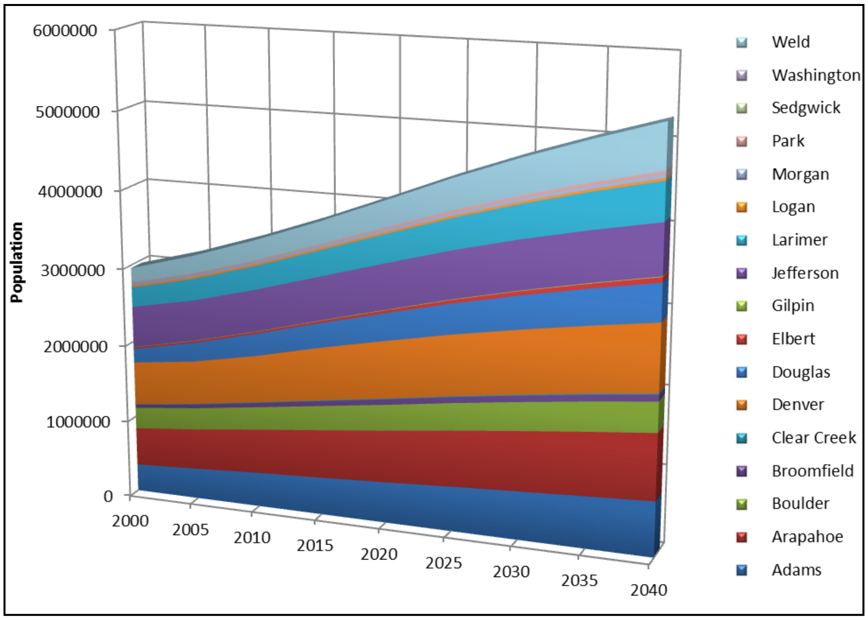

Figure 1.6. SPRB county population projections through 2040 (Statewide Water Supply Initiative 2010)

However, when socio-economic drivers of population growth are considered, population growth (and thus demand) is far more variable throughout the region. For example, Figures Figure 1.7 and Figure 1.8 show projected population distributions just north of the Denver Metro region, where most water providers are small towns or rural districts with relatively junior supplies (meaning the supplies are less secure). The model used to generate the population distributions, the Integrated Climate and Land Use Scenarios (ICLUS) (U.S. Environmental Protection Agency 2016) assumes the same population growth for counties in each scenario, but socio-economic drivers vary. The two figures have divergent global socioeconomic scenario pathways, but use the same climate model (HadGEM2-A0). Both SSPs represent rapid development scenarios (in line with regional expectations), but one represents a “resource exploiting” scenario while the other is a “resource conserving” scenario (U.S. Environmental Protection Agency 2016).

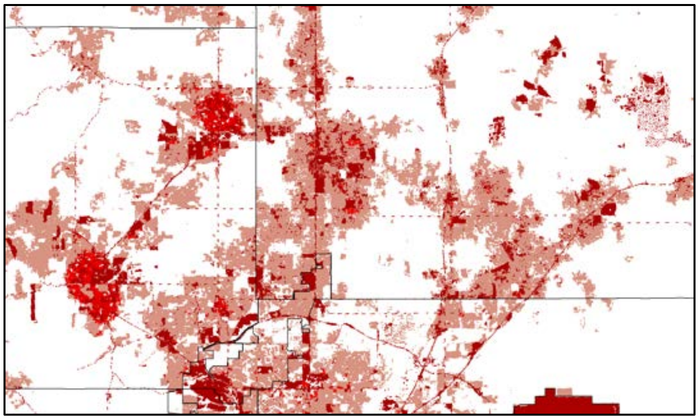

Figure 1.7. North Denver ICLUS population distribution projections in 1950 using SSP1. Pink is low density, red is medium density, and maroon is high density development (data from U.S. Environmental Protection Agency 2016)

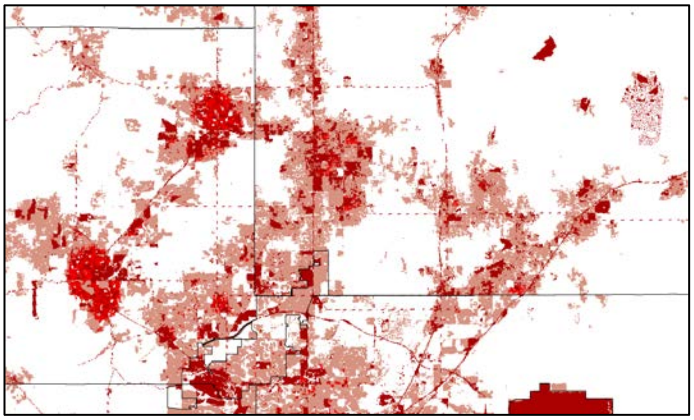

Figure 1.8. North Denver ICLUS population distribution projections in 1950 using SSP5. Pink is low density, red is medium density, and maroon is high density development

ANALYTICAL FRAMEWORK

Past studies aimed at analyzing adaptive capacity have used a number of analytical methods (e.g., analysis of local determinants or having access to assets (i.e., financial, social, institutional, natural, and physical) (Smit and Pilifosova 2001, Yohe and Tol 2002, Eakin and Luers 2006, McNeeley 2014); the ability of actors to engage in social learning (Pahl-Wostl 2009); and the flexibility of institutions to facilitate actors to adjust processes (Smit and Wandel 2006)) that extend from studying the adaptive capacity at national levels, down to analysis of individuals.

This study is unique in its focus on adaptive capacity of organizations. Berkhout (2012) and Linnenluecke et al. (2012) stress that organizations are the primary actors in societal responses to the impacts of climate variability and change but there is still a lack of how organizations perceive, make sense of and respond to signals about environmental change. Adaptive responses of organizations are due to their social and natural environments and their adaptive capacity rests on the perceptions and capabilities of the organization as well as exogenous structures and processes. Therefore, it is important to understand the role that policy and governance play in enabling and constraining organizational adaptation (Berkhout 2012).

Adaptive capacity literature stresses the importance of understanding institutional and organizational adaptive capacity, often using the two terms interchangeably. In this study, the terminology is distinct and will refer to different elements within the system. Berman et al. (2012) defines institutions as "the formal legal rules and informal social norms that govern the behavior and shape how individuals and organizations interact" (North 1990, Ostrom 1990, Berman et al. 2012). Organizations, defined by Berkhout (2012), are "collectivities of actors whose activities are coordinated within definable social units to achieve certain common goals."

In the Linnenluecke et al. (2012) study of organizational resilience to extreme weather events, they found that anticipatory adaptation is of critical importance when organizations respond to impacts. Linnenluecke et al. (2012) develop a framework illustrating how organizations have some sense of anticipation of extreme events and make adaptations in preparation for those. When they are hit by an event, their response is affected by internal factors (e.g., ideologies, available resources, sensitivities, etc.). Afterwards, they make sense of how their level of functioning was impacted and risks for future events, leading to future (anticipatory) adaptation. Figure 1.9 modifies this framework by illustrating the role that stress and institutions play in organizational response to extreme events and how they affect adaptive capacity.

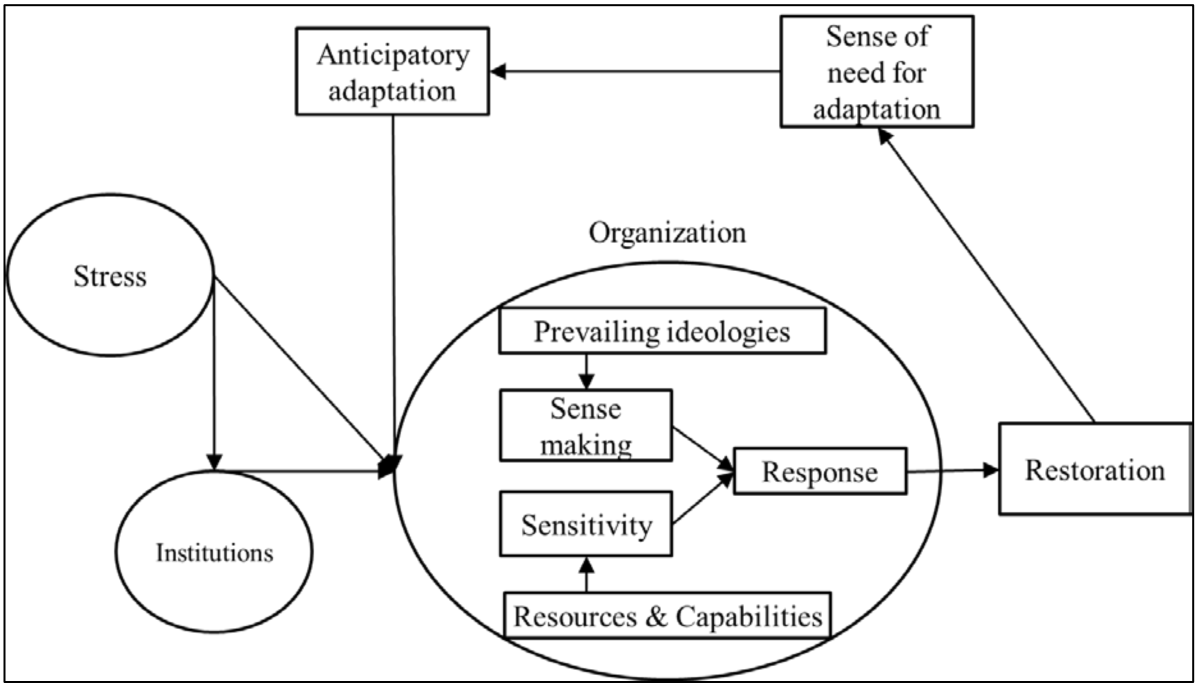

Figure 1.9. Conceptual framework of organizational adaptation and resilience. Modified from Linnenluecke et al. (2012)

The ‘anticipatory adaptation’ described by Linnenluecke et al. (2012) is analogous to adaptive capacity and this framework is useful for analyzing the adaptive capacity of water management organizations. Two modifications were made to their framework to develop Figure 1.9. First, although single, extreme (acute) events affect the coping and adaptive capacities of water providers, it is often longer-term, chronic pressures that more significantly affect the ability of water providers to manage water. When water systems are already strained by chronic stressors, the effects of extreme events are worsened and the ability to respond is compromised. In the case of water management, these long-term pressures would be population growth and climate change; which exacerbate the effects of and reduce management options to deal with droughts. Therefore, the framework used for this analysis is cyclical, to capture compounding effects of chronic and repeated stressors on a system.

Second, because water is a semi-public good with a mix of public-private management, its management is accompanied by a complex institutional setting, with adaptation processes distributed across different actors and organizations (Berkhout 2012). Therefore, the institutional context significantly affects the ability of organizations to adapt and must be included in analysis. Berman et al. (2012) argues that institutions are central to developing adaptive capacity over time. In the SPRB, it may be the case that the adaptive capacity of water providers is heavily augmented by institutional arrangements (e.g., in times of extreme drought, public water use can be prioritized above private or commercial uses), or adaptive capacity could be constrained by institutions (e.g., building additional reservoirs has become almost completely infeasible due to the length of time required and difficulty of passing environmental impact statements, required by the Endangered Species Act). Analysis of institutions helps understand if shifts occur and how those changes either facilitate adaptive capacity or lead to perverse decision-making.

To analyze how the capacity of water providers to cope with environmental changes translates to adaptive capacity, this study uses this framework to structure evaluation of how stress affects institutions and water providers, how adaptive capacities were changed, and implications this has for vulnerability to future climate changes. Specifically, it investigates: 1. How adaptive capacity of water providers manifested between two drought periods; 2. What mechanisms caused changes in adaptive capacity; and 3. How stress / exposure may change under future climate scenarios.

Chapter 2 focuses on how water providers' ability to cope with drought changed between the 2002 and 2012 events. While other studies have sought to evaluate these stakeholders' vulnerabilities and adaptive capacities, they have focused on a subset of water providers who are often in large cities and engaged with state agencies, so the scope of differences in their abilities to manage severe water shortages and potential vulnerabilities to future changes is still unknown. This study introduces a methodology to assess adaptive strategies used by SPRB water providers to increase understanding of their adaptive capacity to cope with shocks and stress. Specifically, it evaluates how water providers altered their drought management strategies during and between two former drought periods and how shifts affected their ability to cope with extreme events. From this a suite of response options and management patterns that increase adaptive capacity are isolated and potential vulnerabilities to stress are discussed. The research methodology uses an 'analog approach' to evaluate how water systems were impacted by two past drought events (in 2002 and again in 2012), alterations made to management strategies after the first drought, and how they performed during the subsequent drought. From this analysis, it was determined that all water providers were less severely impacted by the 2012 drought than they were in 2002. A hierarchical cluster analysis was performed on response strategies look at groups of water providers to understand what adaptive strategies they adopted and why those decisions were made. This study augments existing knowledge of vulnerability of stakeholders and the region because it provides an understanding of successful adaptive strategies but also sheds light on types of water users and attributes of systems that could create vulnerabilities to worsening drought conditions or water stress.

The focus of chapter 3 is on interactions between institutions and management, specifically institutional processes that arose following the 2002 drought period and how those interaction with those processes facilitated learning by altering water management practices and shaping management alternatives of water providers. Institutions are fundamental to the processes involved in change and there is a need for innovative institutions to effectively guide systems to adapt to change and maintain resiliency. Institutions and management of water systems underwent significant changes in Colorado following a severe drought period in the early 2000s. This study examines the multi-scale learning by water managers and state policy-makers in the SPRB following the 2002 drought. In a region expected to undergo significant changes in the future, assessment of institutions that led to successful management adjustments provides useful lessons for incentivizing more adaptive water management in Colorado in the future and will improve theoretical understandings of institutional arrangements that lead to more robust systems. Additionally, knowledge of drivers and barriers of system change, provides a better understanding of levers to pull to enable more robust system transformations in the future. The study combined policy document analysis with key informant interviews to first determine how the 2002 drought changed institutions, then how those changes affected management learning. The most significant institutional processes were identified using process tracing techniques. Those processes were then used as independent variables with an analysis of water provider learning as a dependent variable and qualitative comparative analysis was performed on the groups of water providers, created in Chapter 2, to evaluate how interactions with these institutional processes affected different types of management changes. Looking at how different types of water providers interacted with institutional processes, and how that affected their management allowed for a finer analysis of the underlying mechanisms that created adaptive water management.

Assessments of climate impacts in the United States say that drought may become more frequent and severe in the coming decades (Christensen et al. 2007, Morgan et al. 2008, Coles and Scott 2009, Western Water Assessment 2011a, Gordon and Ojima 2014). Multiple Colorado-specific studies similarly conclude that Colorado's future droughts will become more frequent and intense by mid-century. While this provides water managers and planners with an understanding that water supplies that are available today may be less reliable in the future, there remains a vague understanding of how drought conditions could change (e.g., will the most severe drought on record occur with more frequency, or will droughts remain the same in severity be last longer?). Limited information remains about the potential frequency or severity of future drought conditions, adding difficulty to planning responses to such events. Chapter 4 is a stand-alone analysis that investigated the characteristics of historical and future droughts (duration, severity, intensity, and frequency) and evaluated how they may change under four scenarios: near future RCP 4.5, near future RCP 8.5, far future RCP 4.5, and far future RCP 8.5. Because drought estimates rely on temperature and precipitation patterns, the study began by evaluating how these climate variables shift under future scenarios helps understand the underlying drivers of changes in drought patterns. It then estimated drought characteristics (duration, severity, and peak) using the theory of runs and univariate analysis was used to calculate the 20-, 50-, and 100-year return periods for drought characteristics during future and historical climate periods. Because drought conditions are highly correlated and dependent, Copula functions were then used to calculate the bivariate probability drought characteristics will exceed historically extreme thresholds (specifically, those similar to the 2002 and 2012 droughts). The consequences of this study reveal that reliance on historical drought experiences have limited utility for managing future droughts.

This dissertation concludes with a final chapter that synthesizes findings from the pervious chapters and evaluates the effects of the drought scenarios developed in Chapter 4 on the groups of water providers using different adaptation strategies. From this key insights for vulnerability of water providers and implications for regional vulnerability are discussed and suggestions for institutional adjustments are made.

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CHAPTER 2: ADAPTIVE STRATEGIES USED BY WATER PROVIDERS IN THE SOUTH PLATTE RIVER BASIN TO MANAGE DROUGHT AND IMPLICATIONS FOR ADAPTIVE CAPACITY

INTRODUCTION

Droughts are not uncommon in the western U.S. (Glantz and Katz 1977, Harding et al. 1995, Gray et al. 2011, McNeeley 2014). Water systems were developed to handle these drought conditions and are well adapted to manage the typical shortages they cause. Occasionally, severe droughts test the capability of systems and ability of managers to respond, often leading to "flashpoints" that highlight vulnerabilities and provide learning experiences that allow institutions and managers to adjust and restructure (Jones and Cech 2009). A historic drought in 2002 served as such an event due to widespread environmental, economic, and social impacts it caused (Tronstad and Feuz 2002, Averyt et al. 2009, McNeeley 2014). Water scarcity during this drought was heightened and water managers at all levels recognized that the system status quo was insufficient.

Future projected climate and social changes may worsen the typical strains drought periods places on water systems, requiring innovative and flexible management strategies (Pahl-Wostl et al. 2007, Engle 2013). Complex water allocation challenges, exacerbated by environmental and social change, are exemplified in the Front Range of Colorado. The South Platte River Basin (SPRB) is the most industrialized region with the highest agricultural production in the state. The urban corridor region of the SPRB is also the most densely populated in the state, with an additional two million residents expected to live in the basin by 2030 (Statewide Water Supply Initiative 2010). At the same time, recent studies (Western Water

Assessment 2011a, Gordon and Ojima 2014) predict that droughts will become more frequent and severe in the region, creating uncertainty for water managers' future supply and demand.

To manage managers' vulnerability to fluctuations of both supply and demand and prepare their systems to provide continuous service, it is critical to understand what contributes to their ability to adapt to environmental changes. Building and mobilizing 'adaptive capacity', the ability of a system or its actors to prepare for stresses in advance, or adjust and respond to the effects caused by stresses (Smit et al. 2000) before they become detrimental, can help prevent drought impacts (Engle 2013). McNeeley (2014) points to the utility of analyzing the adaptive capacity of systems and individuals by looking at past events as analogs (Glantz 1988, 1991, Engle 2011). By evaluating the adaptive strategies drawn upon during past events, we are then able to assess how they changed though lessons learned and understand what adaptive capacity may exist to cope with future stresses[3].

Water providers are important stakeholders in managing fluctuations of supply and demand. They often act as the link between the environment and end users, and ultimately, the vulnerabilities created by stress in the environmental system are mediated by their actions. Most people in the U.S., particularly in the West, receive their drinking water from these organizations, and the percentage is expected to grow in coming decades (Hutson et al. 2004, Kenny et al. 2009, Engle 2012). Water providers' primary objective, to distribute safe, clean water to customers, is achieved through a variety of strategies (e.g., maintaining large reserves, reservoirs, restrictions, education, pricing) that are made more difficult when conditions fluctuate far beyond normal. Engle (2012) notes that the increasing dependence of humans and ecosystems on water providers, combined with the potential impacts of climate variability and change, will

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[3] See List of Definitions for precise definitions for adaptation, adaptive capacity, and coping capacity that are used throughout the dissertation.

make the delivery of high-quality water increasingly difficult in the future (Cromwell et al. 2007).

As pressure placed on water systems mounts, water providers who are not able to adapt to a variety of conditions (those rapidly deteriorating or slow-onset stress), may face the potential of either not being able to service their demand, or adopting mal-adaptive strategies to cope with stress in the short-run, impacting others in the region. Therefore, there is a need to understand the adaptive capacity of water providers. However the types of water providers, their systems, and strategies they use to manage water are as diverse as the region itself, making it difficult to fully understand the adaptions they draw upon to manage stress, and implications on their adaptive capacity. Therefore, the central objective of this study is to evaluate adaptive strategies used by SPRB water providers to manage drought to increase understanding of their adaptive capacity to cope with shocks and stresses.

Context: The South Platte River Basin

The geography and land use of the basin varies from prairies to the east to high alpine systems that stretch to the Continental Divide in the west. The SPRB is located in the northeast corner of Colorado and is, at the same time, the most densely population region of the state and the greatest agricultural producer of the state. It is categorized as a semi-arid prairie, according to EPA level II eco-regions (U.S. Environmental Protection Agency 2013) and receives relatively low precipitation, which can be highly variable from year to year and throughout the region. Droughts or dry periods occur frequently, but typically don’t last very long. As Chapter 4 details, drought conditions below -1 Standardized Precipitation-Evapotranspiration Index (a reference level signifying drier than average conditions), have historically occurred in the SPRB about every 16 months but they typically are not very severe or last very long (see Chapter 4 for more details).

Colorado is a “snow-melt” system, so most water supplies do not come from rainfall, but are acquired from snow-melt that is captured as surface water as it runs off down rivers. To manage the ephemerality caused by natural sources, a network of reservoirs and diversion canals have been created to store water during high flows for use during low flow or drought periods. These surface water systems are essential throughout Colorado (Hobbs 2004). However, the SPRB actually has the most groundwater in the state as well, with a higher percentages of water coming from below ground, increasing towards the east, according to Topper et al. (2003). There are two primary types of groundwater that are regulated separately by state agencies: South Platte alluvial groundwater that is managed conjunctively with surface water and Denver Basin Aquifer groundwater that is not connected to alluvial aquifers and is therefore not managed within Colorado’s Prior Appropriation system.

Agriculture dominates the economy of the lower SPRB, with about forty percent of the state receipts from agriculture coming from the SPRB alone (Waskom 2013). Although irrigation makes up a large percentage of water use in the SPRB, there are other competing demands for the scarce resource. According to Dennehy et al. (1998), irrigation makes up about 75% of water use in the SPRB (surface water about 45% and groundwater about 30%). Power generation and municipal usage makes up about 12% each of the remaining water usage.

Numerous studies and reports suggest that droughts are likely to become more common and intense as regional and seasonal patterns change (Statewide Water Supply Initiative 2010, Western Water Assessment 2011a, Ojima et al. 2012, Colorado Water Conservation Board 2013, Gordon and Ojima 2014). Shifts in timing and intensity of stream flows and runoff, reductions in summer flows, decreases in runoff, declines in snowpack, and hotter temperatures will inevitably further stress the water system. These projected changes reveal that water managers must be able to adapt to changes and alter their management strategies to ones appropriate to deal with future conditions.

Context: Recent SPRB droughts

This study used an analogue approach, looking at past drought periods to understand what can be expected during future droughts (if future conditions behave similarly to the past). Conveniently, there were two recent major droughts in the SPRB, in 2000-2002 and 2012-13. The two drought events were quite different; the 2002 drought lasted longer, but the 2012 drought was deeper and more severe (See Figure 2.1). However, studying the impacts of both droughts on water managers and their responses, as well as how they regrouped and altered management between the two droughts provides an opportunity to understand how incremental management and policy adjustments can evolve into long-term capacity to deal with water scarcity.

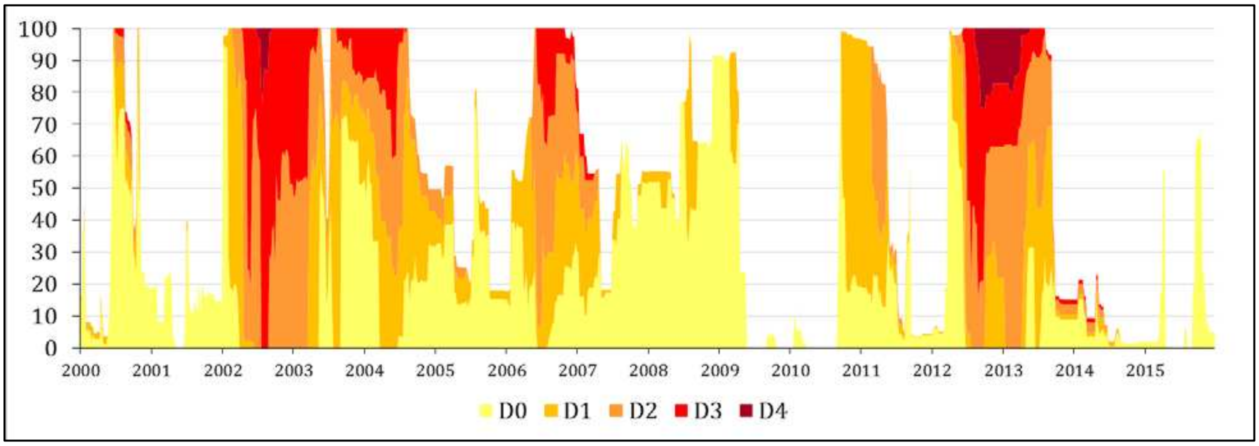

Figure 2.10. Percentage of SPRB classified by Drought Monitor Status. Data courtesy of U.S. Drought Monitor[4]

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[4] U.S. Drought Monitor is a website hosted by the National Drought Mitigation Center that produces a weekly map of drought conditions, based on measurements of climatic, hydrologic, and soil conditions as well as reported observations and impacts from over 350 contributors around the U.S. The map displays the distribution of a drought

The 2002 drought served as a useful learning experience for Colorado water management. Water managers were forced to come to terms with unsustainability of the trajectory of water use caused by rapidly increasing population growth and potentially decreasing water supply. The realization that status quo water management was insufficient for any future scenarios led to a reevaluation of how water is managed in the state. In 2012, another severe drought occurred, once again stressing water users and providers, with scarcity and historic wildfires.

ANALYTICAL FRAMEWORK

The objective of this study is to evaluate how adjustments providers made to drought response options evolved into adaptive capacity. Therefore, this study takes a unique approach of looking at how both their management and their ability to handle stress changed between two drought periods. A number of other studies have evaluated characteristics and indicators of adaptive management at organizational- and regional-scales (e.g., Huntjens et al. 2011, Wilby and Vaughan 2011), but this approach differs by using past events (droughts, floods, etc.) as a focal point to investigate processes that linked the availability of adaptive choices to actual adaptive responses. Results are used to learn lessons from decision-making patterns that increased adaptive capacity in the past, so that it may be expanded to meet future challenges. Using mixed methods, this study evaluates how water providers altered their drought management strategies during and between two former drought periods and how these adjustments affected their ability to cope with the extreme events. From this, a suite of response options and management actions that increase adaptive capacity are isolated and potential vulnerabilities to stresses are discussed.

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severity indicator that ranges from no drought through five drought severity levels (D0-D4). (National Drought Mitigation Center (NDMC), the U.S. Department of Agriculture (USDA) and the National Oceanic and Atmospheric Association (NOAA).)

Adaptiveness is embedded in providers' ability to fundamentally change strategies they use in anticipation of future changes (Smithers and Smit 1997), which is different than just altering strategies to get by for the time being. Adaptations are behavioral adjustments in response to stressors both after the fact as well as in anticipation of and planning for potential changes (McNeeley 2012). The term is synonymous with 'adaptive strategies', measures taken to minimize expected adverse consequences. Having the ability to adapt is defined as adaptive capacity, or the potential to respond to or prepare for climate stress (Turner et al. 2003, Adger et al. 2007, Polsky et al. 2007, McNeeley and Shulski 2011, McNeeley 2014). Put differently by Smit and Wandel (2006), "adaptations combined with expected changes in natural and social systems lead to anticipated[5] adaptive capacity." Therefore, 'adaptive strategies' are not just any strategy that has always been used to manage stress (i.e., drought), but they are new measures taken in response to or anticipation of stress.

A mixed methods approach, used here, combines the rich data analysis that comes from bottom-up studies (Smit and Wandel 2006, McNeeley 2014) with an ability to extrapolate to larger groups that a top-down, quantified analysis provides. McNeeley (2014) successfully uses this methodology to evaluate drought risk and responses in the Yampa White River Basin of Colorado, stating that "combining top-down, data-driven assessments with participatory 'on-the-ground' methods that include both data and experience is important for understanding the full picture of climate and drought risk and vulnerability (Kenney et al. 2010)." The use of quantitative and qualitative methods to empirically assess the influences of drought management strategies on adaptive capacity across spatial and temporal scales provides a major contribution to a field that, as Engle (2011) points out, is lacking empirical studies on adaptive capacity.

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[5] Note the definition used here and by Smit and Wandel (2006) is analogous to 'anticipatory adaptation' referenced by Engle (2010) and discussed in Chapter 1.

Additionally, complimenting data-driven assessments with insights from local water managers provides an invaluable understanding of how drought risk manifests locally and informs decision-making for climate adaptation (McNeeley 2014).

A unique tool, the event history calendar (EHC) was used to collect qualitative and quantitative data from water provider managers in the SPRB. Engle (2013) proposed using the EHC to gather temporal data on CWS management. It is similar to and adapted from the 'life history calendar', a tool more commonly used in anthropology and sociology to collect temporal data on individuals (Freedman et al. 1988, Axinn et al. 1999, Engle 2012). The EHC (and life history calendar) uses a matrix of visual cues and an interactive interview process to make memory recall easier for participants. While a life history calendar focuses on personal information about an individual's history, aided by recalling external events, the EHC was designed to collect time-series data of water providers' management strategies and functioning through time. Interviews are also aided by recalling personal histories of the participants. A benefit of using this tool is that this allows for simultaneous collection of qualitative and quantitative data (Engle 2013) (Example in Appendix 2.1).

The EHC collected two primary pieces of information from water providers over a time period (2000-2015): 1. Strategies they used and how they varied; and 2. Their relative ability to meet water delivery requirements (referred to simply as management ability). The strategies asked in the EHC were modeled similarly to those used by Engle (2013), however, their study used theoretically-based strategies as indicators for adaptive and integrated water management. This study objective was to compare strategies actually used (rather than those theoretically-derived), based on region-specific strategies. To determine Colorado-relevant strategies used by water providers, this study surveyed recent literature and documents relating to SPRB water management strategies. Primary sources for this information included review of: a 2013 survey the Colorado Water Conservation Board sent to water providers as part of the state Drought Mitigation and Response Plan (Colorado Water Conservation Board 2013); a journal article reviewing strategies used by a small group of water providers during the 2002 drought (Kenney et al. 2004); and data from expert interviews in response to inquiries about strategies that are used and which are considered to be adaptive (unpublished data, see Chapter 3). A complete list of strategies analyzed in the EHC can be viewed in Table 2.1. If providers used different strategies than those in the EHC, they were marked and used for qualitative analysis, but were not considered, as they could not be compared to others.

Table 2.1. Drought management strategies evaluated in the EHC. Letters prior to the code refer to the type of strategy. P – Policy, C – Communication, R – Emergency Response, S – Supply, D – Demand, A – Management Ability.

Code		**Management Strategy**
Policy	P1	Drought Plan
	P2	Conservation Plan
	P3	Develop triggers for drought-related actions
	P4	Coordination between water and land-use planning efforts
Comms	C1	Communicate – State
	C2	Communicate – Local
	C3	Formal education and public communication
Emergency	R1	Declare a drought emergency
	R2	Establish water hauling programs
	R3	Restrict / prohibit new taps
Supply Management	S1	Rehabilitate reservoirs to operate at design capacity
	S2	Develop new storage facilities
	S3	Use mechanism for storing conserved water
	S4	Use of reservoir distribution techniques
	S5	Review water rights for modifications / flexibility during drought
	S6	Dry year leasing of water rights from agriculture

	S7	Water banks established for the sale, transfer, and exchange of water
	S8	Interruptible water supply agreements
	S9	Reuse
	S10	Wet year leasing water rights to agriculture
Demand Management	D1	Voluntary outdoor watering restrictions
	D2	Mandatory outdoor watering restrictions
	D3	Enforcement of watering restrictions
	D4	Implement, upgrade water metering and water loss control systems
	D5	Water-efficient fixtures and appliances
	D6	Low water use landscapes and efficient irrigation
	D7	Rate structures to influence water use
	A1	Water Management Ability

To measure their system's water management ability through time, participants were asked to rank from 0 to 3 their ability to meet their water delivery requirements: where 3 = no impairment, full ability; 2 = moderately impaired but still able to meet all commitments; 1 = seriously impaired with questionable ability to meet commitments, and 0 = unable to meet commitments. While a self-scored measurement is subjective it allows for the ascertainment of relative rankings, and the degree to which it increased or decreased. A change in this management ability score between the two drought events, resulting from strategies adopted, is an indication that adaptation occurred and resulted in an increased of adaptive capacity.

Adaptation literature differentiates between changes to "coping capacity" in the short term, as a response to external stressors or strategies taken to mitigate them, versus the ability to draw upon those strategies and reduce exposure or sensitivity to the stressor in the first place (respectively known as coping capacity and adaptive capacity). Coping is considered to be the effects of immediate disaster impacts, and adaptive capacity is something that is shaped over longer term (Lemos and Tompkins 2008, Pelling 2011, Berman et al. 2012). Coping refers to strategies and actions that are undertaken within existing conditions and adaptive capacity is associated with longer-term strategic actions that may require institutional changes (Birkmann et al. 2009). Some studies equate the measure of ability to cope with stress at a given time with adaptive capacity, but data collected in the EHC, allows this study to analyze both. Their coping capacity was a measure at a given time (a snapshot of their management ability), but changes to their adaptive capacity could be determined by assessing if there was a shift in their management ability and the types of strategies used from one severe drought to the next. ‘Adaptive strategies’ are adjustments or changes to coping strategies (known as adaptation).

Data Collection

Senior-level water managers for each provider filled out the EHC, guided by the interviewer in a semi-structured interview. Senior-level managers were chosen as the participants because they are the most likely to have worked at the organization over a long period of time and would have the institutional memory to fill in the EHC, going back to 2000. A document review of all management documents and web content was also conducted and was used as a source of triangulation (Yin 1994, Imperial 2005) or to fill in gaps where managers were unsure of strategies used or exact timing. Particularly useful documents were conservation plans that are required for providers that sell more than 2,000 AF (e.g., enough to provide to about 4000 households) water per year under the 2004 Colorado Water Conservation Act (see Chapter 3 for more detail about this requirement).

Although previous studies have provided some insight to how water providers manage drought, they have been limited in scope, analyzing a small subset of providers who were often the largest and most engaged providers in the basin. Engle 2013 shows a clear positive relationship between the size of water providers and their use of adaptive and integrated water management techniques. Since this study sought to measure how different factors affected adaptation of providers, it was necessary to have a sample from a broad range of provider types to fill in gaps from previous studies.

To achieve a broad sample, I used stratified purposeful sampling (cluster sampling) (Harsh 2011, Creswell 2012) based on characteristics from all 257 providers in the basin: type of provider (municipal, special district), primary source of water (surface, groundwater, purchased surface water), population served, and their sub-region. The target population of 257 water providers was divided into five strata using cluster analysis. From each of these strata, I randomized the organizations and selected the top five to contact. I continued to contact water providers until I had interviewed five providers from each strata. Of the 257 water providers in the SPRB, I reached out to a total of 78 providers before achieving 25 interviews, equating to a response rate of 33%. Many of those I reached out to simply did not respond, but the other primary reason some declined to be interviewed was because no one at the organization had worked there through both droughts. See Figure 2.2 for a map of the areas providers supply with water, for those I interviewed.

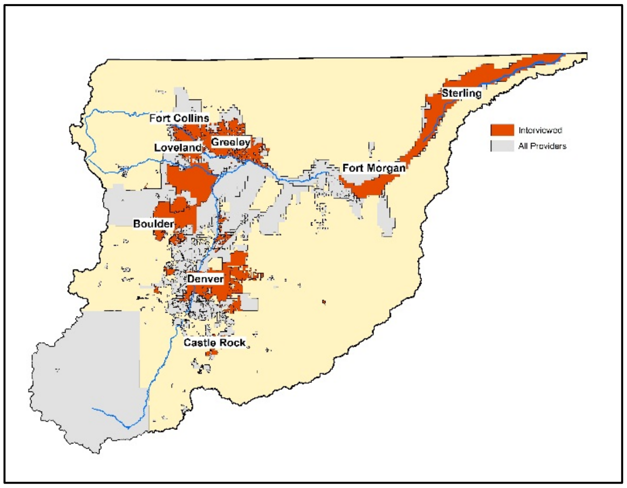

Figure 2.11. Map of SPRB water providers interviewed (orange) and those not interviewed (grey).

The interviews were interactive and typically conducted sitting next to the water manager(s). The EHC itself was a large document, printed as 36” by 24” posters (see Appendix 2.1 for example), to provide plenty of room to take notes in the margins. The management strategies of interest (see Table 2.1) were portrayed in the rows, and the primary periods were depicted as columns. Each of the fifteen years covered in the study were divided into two six-month periods: one beginning with the start of the water year (October – March), and the other beginning with the start of the irrigation season (April - September). Since water management decisions are commonly remembered along seasonal terms (Engle 2010), these time periods were designed to reflect periods when distinct water management decisions would be made and given seasonal names, winter and summer. This division also provided more data points to quantify the timing of management changes. For additional reference, a graph of the U.S. Drought Monitor status for the HUC-8 where the water provider was located was displayed along the bottom.

To begin the interview, the interviewer[6] explained the study objectives and had the participant sign a consent form. The interviews followed a semi-structured pattern (typically lasting 1.5 hours), where the interviewer explained the nature of the EHC, walked the participant through significant state and national events, to reorient them around significant periods during the time period (See Appendix 2.2 for sample interview schedule). Similarly to the methodology developed by Engle (2010), the interviewer and manager then identified (in the white space) any other important local (e.g., local elections, flood events), or life events (e.g., age milestones, career advancements, significant events related to children) that occurred during the period to serve as important memory anchors and further facilitate memory recall and reorient the participant to the time period. The remainder of the interview was spent walking through each row (management strategy) and assigning values during each of the time periods indicating whether the strategy was used (1) or not (0). The participants were encouraged to focus intently on when numbers changed and discuss why changes were made. For each of the questions, the interviewer was recording notes in the white space (as well as audio recording), as the respondents described when, why, and how the approaches were implemented or not. During the final part of the interview, the water provider was asked to rate the ability of their system to meet its water delivery requirements (from 0=completely unable, 1=low ability, 2=medium ability, 3=high ability) since 2000. They were asked to pay particular attention to when they felt the status had changed and explain why those changes occurred. This score was translated into their *management ability* score, which was used to compare how water providers were impacted by the two droughts and their recovery. The interviewer asked participants to explain why those scores changed, focusing on the impacts of water shortages versus their ability to respond, given the tools at their disposal. They were also asked to signify when their system was the most and

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[6] I conducted all interviews for this research project.

least prepared to face a significant drought during this period, and factors that contributed to that assessment. The qualitative data from this portion of the interview served to provide context about how their management ability was reflective of a capacity to adapt.

One of the many benefits of using the EHC was that it allowed for simultaneous collection of qualitative and quantitative data, which can be used for statistical or content analysis (Engle 2013). This resulted in an abundance of data used to analyze how providers managed their water systems over the course of 15 years, the functioning of their system over that time, characteristics of their system, and motivations for changes. However, here only evaluation of impacts and adaptive strategies of water providers as well as motivations for changes in strategies are presented.

RESULTS

To evaluate the evolution of drought management, between the two drought periods, this study began by evaluating providers' responses when asked about the impacts of each. Analysis of changes in self-scoring of their ability to meet water commitments (management ability) was then quantified to assess relative impacts between the two droughts. The drought response strategies water providers used to manage the shortages were reviewed and shifts in (adaptive) strategies were evaluated to determine processes that led to emergent strategies. Finally, the study characterizes those strategies associated with changes in management ability to provide insights about theoretical implications for adaptive capacity and vulnerabilities to future stress.

2002 Drought Impacts

The 2002 drought caught almost everyone off guard. Pielke and Waskom (2003) observed that drought conditions had been going on for some time before its extent was fully realized. By as late as March 2002, there were not many hints of the severe drought ahead.

Despite the fact that the statewide snow-water equivalent was only 52% of the average, neither the public nor government perceived that a severe drought was occurring (Doesken and Pielke 2008). By April, when spring storms that usually dump heavy, widespread precipitation did not arrive, the reality of the dire conditions surfaced. Reservoir storage and river runoff were at a record low level, with flows less than 5% of normal in June 2002 (Schuck and Frasier 2004), when drought was declared, and by late July Colorado was in a serious drought.

The impacts were widespread but not uniform among water providers, due to the diversity of their systems and users. On one end of the spectrum, multiple small, mountain water districts reported coming within weeks of, or completely, running out of water supplies. They stretched their supplies by imposing complete outdoor watering bans, dramatic rate hikes and hauling water in from neighboring cities. A manager from one of these districts reported,

> *"In 2002 we were flat out of water and were at the mercy of upstream towns to flush their toilets…so there was water running in the stream between the hours of 9am and 1pm (but no other time)…It was extremely serious for about 18 days."*

On the other end of the spectrum were water providers who were minimally impacted by the drought because their supplies are primarily non-conjunctive groundwater (see footnote 11). These users reported minimal effects. As a water manager from Castle Rock said, *"Our water supply system is primarily groundwater based – which is different than many other Front Range water users that rely on surface water sources…it is less subject to the impacts of drought."*

Somewhere between these two extremes exists most providers' experience of the 2002 drought, each as unique as their water systems. Those serving large, urban areas (e.g., Denver Water, Fort Collins, Boulder) have senior water rights and a diverse portfolio from multiple basins ensuring a secure supply through the very worst of drought conditions. Because no one knew how long the drought would continue or how bad it would get, they enacted outdoor water restrictions to stretch supplies if needed, but otherwise their systems were not heavily impacted.

Other cities like Aurora or Lafayette met their shortage issues with severe water restrictions for fear that their supplies would not last through the drought. An Aurora water manager described,

> *"2002-2003 was somewhat of a tragedy. By 2003, we were actually down to less than one year's supply of water, with 26% in our reservoirs (sic). Had something else happened, had another year equaled '02-'03, we would have been without water completely."*

Water providers with more diverse supplies, particularly those with Colorado-Big Thompson[7] (C-BT) shares fared better than those with single-source, surface-water supplies. Many of the water districts in the northern part of the region, that primarily source their water from C-BT, reported few impacts from the drought conditions, but even among this smaller group experiences varied. One water district had no reserves in 2002 because they had no storage, so they prohibited any outdoor use of water entirely. On the other hand, another water district with a similar portfolio, 20 miles up the road, said they were not heavily impacted because their C-BT quota was still relatively high but conditions in 2003 were actually worse for them.

2012 Drought Impacts

After a warm, dry winter and spring in 2012, water managers were anticipating severe drought conditions by the time summer began. Without much compromise to their supplies, nor activation of the Municipal Drought Impact Task Force[8], most water providers declared outdoor water restrictions early in the summer, in case drought conditions worsened. Because the 2002

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[7] The Colorado-Big Thompson (C-BT) Project captures water on Colorado's West Slope (from the Colorado River basin) and delivers it through a tunnel to the Front Range. Because this water is not native to the SPRB, usual consumptive use and return flow requirements under Colorado Water Law do not apply, making it more valuable. Additionally, because it is transferred from another region, at times when there are drought conditions in the SPRB, there will still be an abundance of C-BT water. For these reasons, C-BT water is highly valuable and becoming increasingly difficult and prohibitively expensive to purchase additional shares.

[8] See Chapter 3 for discussion of the Drought Task Force and Impact Task Forces. The Drought Task Force recommended activation of the Agricultural Impact Task Force for Southeastern Colorado in May 2011, and in the North-Central Mountains in June 2012. In August 2012, the Drought Mitigation Response Plan was activated at level 3 for agriculture only. Stating dry conditions, below-average reservoir storage, and continued water restrictions by municipal water providers, the Governor officially activated the Municipal Impact Task Force on May 10, 2013, and deactivated it on April 2014 (source: Water Availability Task Force Monthly Governor's Report).

drought was still fresh in managers' memories and drought monitoring by State agencies indicated conditions could quickly worsen, they declared a drought and enacted conservation measures quickly. Because of the quick response by water managers and users alike, most reported no impacts on their system but some provided a caveat that they would have been in real danger again had the drought lasted through another summer. Fort Collins was the most affected by the drought conditions, but because a large forest fire in the watershed where their primary source was located created water quality concerns, rather than simply due to supply shortages.

Evaluation of changes in drought impacts between the two periods

The *management ability* scores (a self-evaluated, semi-annual rank from 0-3 of each provider's ability to meet their water demand obligations[9]) collected in the EHCs provide a useful metric to compare how water providers were impacted by the two droughts. Discussion during the interviews provides context for the reasons that scores changed, creating a good indicator of whether changes to their drought response options were responsible for any improvements. In this study, 'improvement' is evaluated as an improvement in their ability to deal with two somewhat similar droughts (2002 and 2012). Figure 2.3 illustrates how this management ability varied over the period investigated by this study. Of importance to note is that most providers' scores dropped during the 2002 drought. Some rebounded immediately after, others took several years, but most did not decrease during the 2012-2013 drought.

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[9] While their score could have also been affected by other conditions, when asked about the reasons they attribute changes, environmental conditions were overwhelmingly the main factor affecting a change in score. Drought conditions was the reason given for stress to systems water management ability for all providers at all times, except two water systems were also adversely impacted by a major flood event that occurred in September 2013. One water provider lost significant portions of its water treatment plant and the community it served was forced to evacuate for multiple months, the other also lost use of its water treatment plant due to sedimentation for a short time.

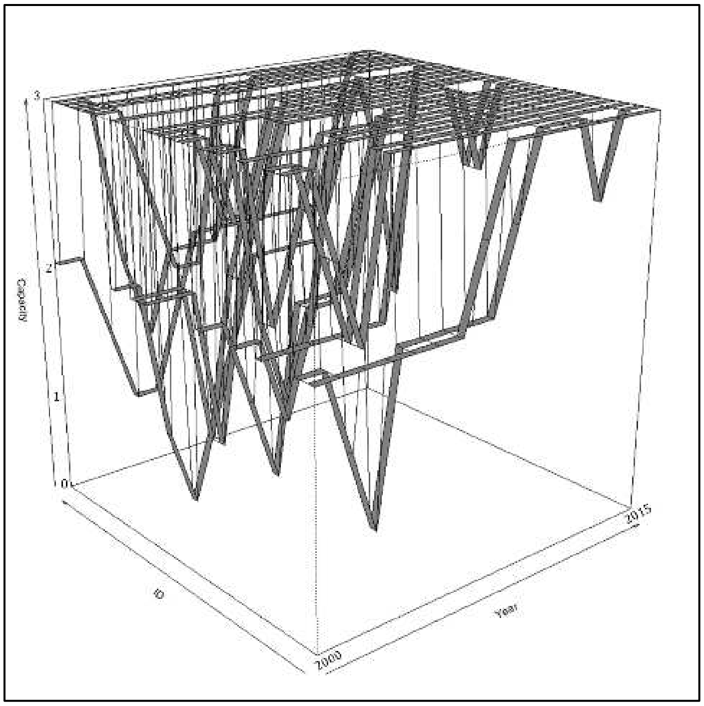

Figure 2.12. Management Ability of water providers surveyed to meet their demand commitments over time

To quantify the changes between these periods, I split the data into groups based on the time periods. The drought periods were assigned as times of prolonged drought, when greater than 20% of the SPRB experienced Level 3 U.S. Drought Monitor status for 6 months or longer or any part of the basin experienced a Level 4 status for 6 months or longer (See Figure 1). These periods were summer 2002 through summer 2003 (assigned as D1), and summer 2012 through summer 2013 (assigned as D2). Periods when the basin was not in drought were also split into before and after the 2002 drought, because of an expectation that business-as-usual (non-drought) management ability would also increase due to changes made to improve overall management following the 2002 drought. These periods are assigned as Normal Before and Normal After. The average scores providers gave for their management ability in the EHC during these periods are shown in Figure 2.4.

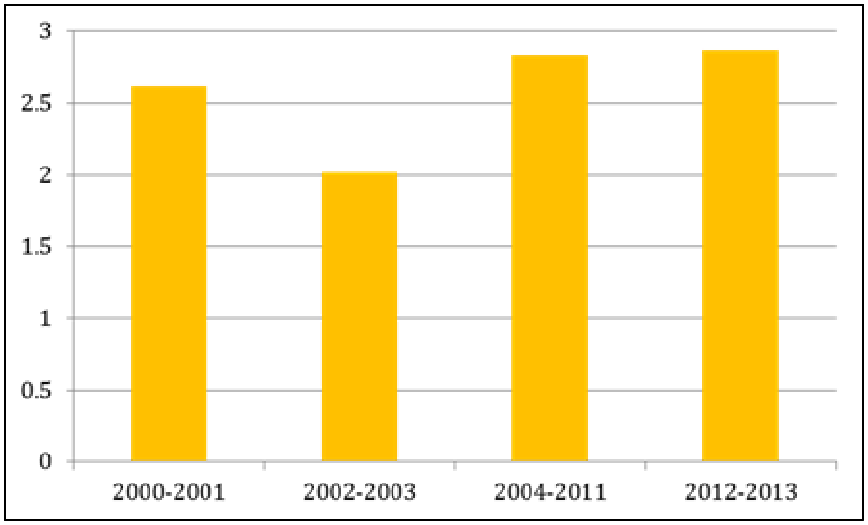

Figure 2.13. Average management ability scores for all water providers surveyed during the four periods compared, before a significant drought, during the drought, after the drought, and during a second, significant drought.

Results from a Wilcoxon Signed Rank Test ($p < 0.01$) comparing differences in mean management ability scores between periods revealed that capacity was reduced from normal levels during the 2002 drought but not in 2012. In fact, during the 2012 drought management ability was higher than in non-drought periods, indicating an increase in overall adaptive capacity.

Determining which providers improved in D2 versus D1 involved a simple comparison of each water provider between the time periods. The difference between the time was used to identify which providers improved from drought 1 to drought 2 (n=18), those that performed the same during the two drought periods (n=6), or performed worse in the second drought (n=0). Figure 2.5 and Figure 2.6 illustrate the number of providers who showed improvement, but also the variance of management ability scores during the time periods tested. Interestingly, the variance was highest during the first drought but continued to decrease through time, so that during the second drought period, the variance was quite low, demonstrating that overall management ability was relative high in 2012.

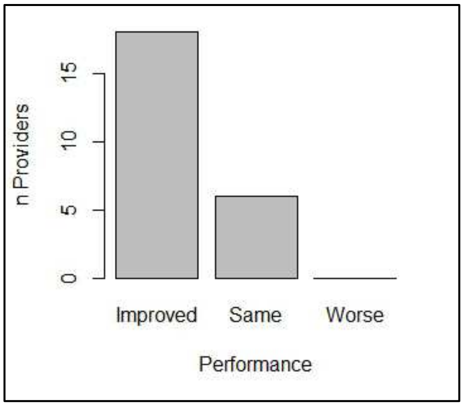

Figure 2.14. Number of providers surveyed who improved in their ability to meet water delivery requirements, remained the same, or worsened in their ability.

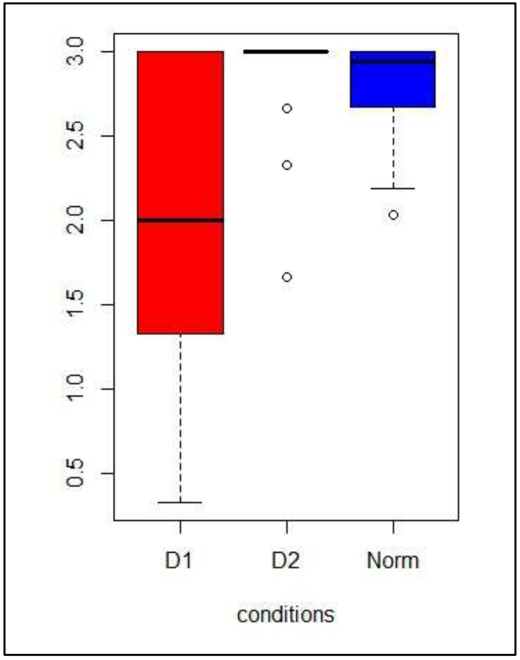

Figure 2.15. Boxplot illustrating variance in management ability scores during the 2002 drought (D1), the 2012 drought (D2) and other times of normal conditions (Norm).

It should be noted that providers whose management ability scores remained the same between the droughts did not necessarily fare poorly during both, most of those providers were not impacted during either drought event. This is discussed more below, but these were generally two types of water providers, those who primarily relied on groundwater supplies that were not affected by drought and those who leased water from other providers, providing both groups with relatively secure supplies that were minimally impacted during both periods.

Changes in drought response strategies between the two events

While there was no correlation between specific strategies used by water providers and changes in to their management ability scores, exploring the adaptive strategies used by water providers reveals how lessons they learned from the drought were used to build adaptive capacity. Many water providers altered the number and types of strategies they used during the 2002 and 2012 droughts. The strategies evaluated in the EHC fell into five management categories: policy / planning, communication, emergency, supply-management, and demand-management. Figure 2.8 shows that in 2002, policy, communication, emergency, and supply management strategies were all used relatively equally, but demand management totaled about 40 percent of the strategy choices. However, 2012 brought a shift both in the overall number of strategies used and their distributions. Demand management strategies still made up the majority of management decisions, but there was a large shift towards using policy-related strategies and a large decline in emergency-related strategies.

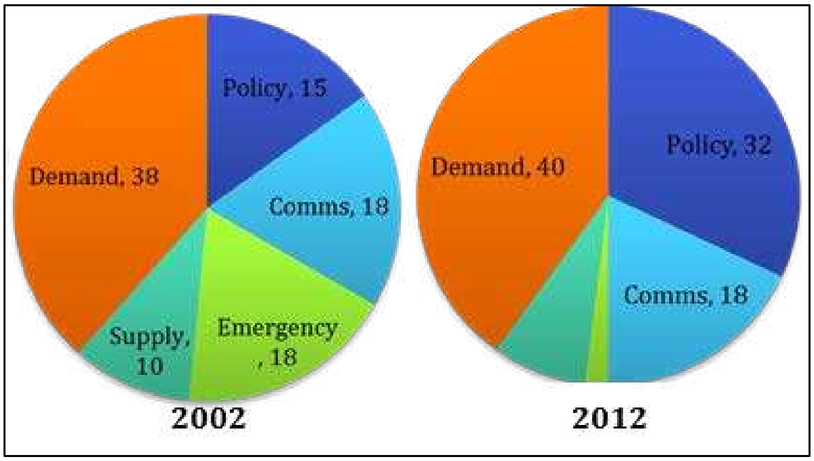

Figure 2.16. Types of strategies used to manage the 2002 and 2012 droughts. Number of uses next to groups

By the time the 2012 drought occurred, the increase in strategies providers used gave them a larger quiver of strategies to draw from and a shift in the types of strategies used that included more planning and communication, both factors water providers attributed to their improvement during the subsequent shortage (See Appendix 2.2 for table of specific strategies used during both droughts). A quote from one water provider sums up the experience many expressed, that they were caught off guard in 2002, but were able to learn from their experiences and build more robust systems that were better prepared for the 2012 drought. *"There was a lot of learning during the 2002 drought. In the 2012 drought, we had all the tools in place to be able to deal with it and talk to customers, so it seemed a little smoother."*

Although types of strategies used by water providers to manage droughts were as diverse as the water systems themselves, evaluating how management differed between periods provides insights about how adaptive strategies to manage risk evolved among the different types of water providers, which can be extrapolated to others in the basin who were not studied. Because of the diversity of adaptive strategies, it is not very useful to evaluate aggregated management changes, but at the same time, it is difficult to draw conclusions from individuals. To capture common management changes and begin to understand why different types of providers made these decisions, water providers were divided into groups, based on strategies they used to manage the droughts and how they altered their strategies, using cluster analysis .

The EHC serves as a useful tool for evaluating changes to response strategies drawn upon over time. However analyzing every combination of strategies throughout the whole time period is not possible due to a lack of statistical power. Clustering allows for analysis of distinct subgroups within a sample, so using this to analyze changes to drought management strategies helps to group together types of adaptive strategies drawn upon. The subgroups were further analyzed qualitatively, to evaluate *what* changes were made to their drought response strategies and *why* those decisions were made. Eight indicators of management strategies were evaluated in the cluster analysis (see Table 2.2), designed to capture common changes in management strategies, most specifically shifts the types of strategies, resource- or planning-related responses, and changes in their management flexibility.

Table 2.2. Internal factors assessed

Variable	Description
Percent_P	Percent change in planning responses between the period prior to 2004 and after
Percent_C	Percent change in communication responses between the period prior to 2004 and after
Percent_S	Percent change in supply responses between the period prior to 2004 and after
Percent_D	Percent change in demand responses between the period prior to 2004 and after
Resource	Percent of total responses that were aimed at increasing resources
Planning	Percent of total responses that were planning focused
RP_ratio	Ratio of planning : resource increasing responses, normalized by the average number of planning and resource responses among all providers
Flexibility	The change in number of strategies used by water providers per year is used as an indicator for their management flexibility

While a number of approaches can be used to cluster data, Gower distance, used here, is optimal for mixed data types (e.g., continuous, ordinal, nominal) (Gower 1971, Özlem and Güzin 2017). The "partitioning around medoids" algorithm was chosen for clustering, which is similar to k-means clustering, except that instead of cell centers defined by Euclidian distance, cluster centers are restricted to be the observations themselves, to reduce noise and outliers that could be problematic from the original dataset. Silhouette width (Kodinariya and Makwana 2013) was used to determine that four clusters were the optimal number to be extracted for the analysis[10].

Factor analysis (using principal component analysis) was run on variables included in the cluster analysis to determine which variables were most similar (and thus excluded or combined) and which were the most significant determinants of clusters. Figure 2.8 illustrates the four clusters, plotted against the variables RP_ratio and flexibility, determined by ANOVA to be the most significant determinants of unique clusters.

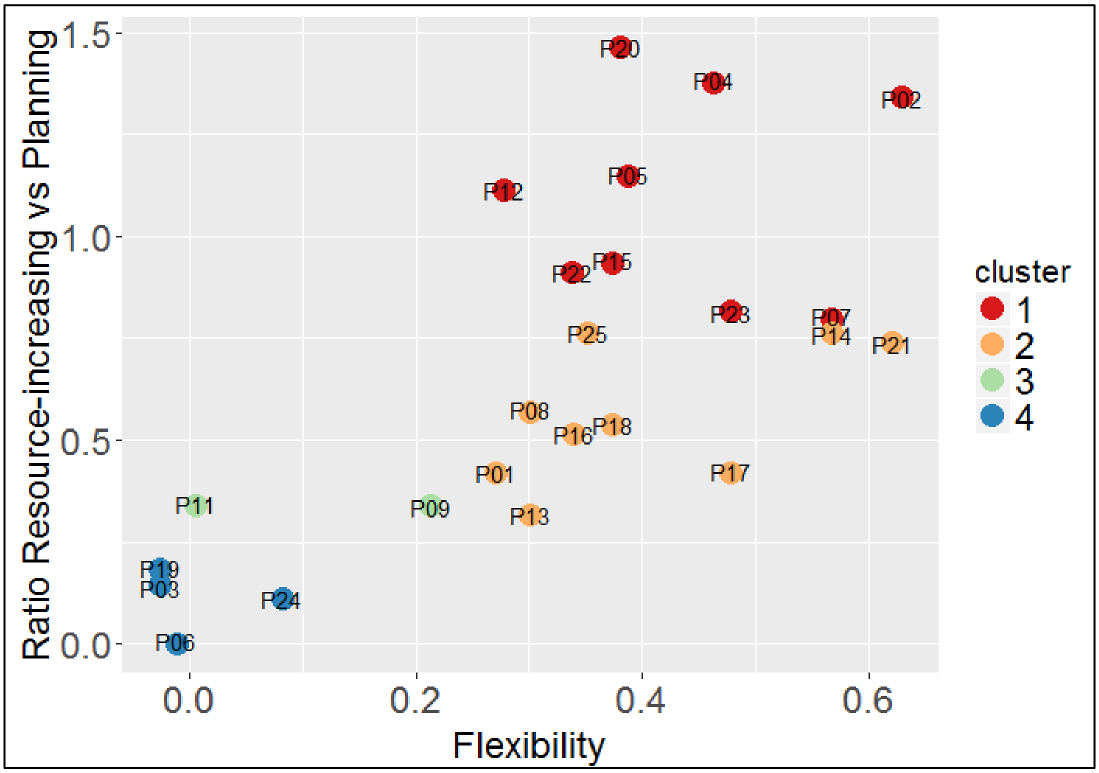

Figure 2.17. Water provider groups by strategy type. Labels are providers interviewed, by ID number

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[10] Silhouette values measure (from -1 to + 1) how similar an object is to its own cluster compared to other clusters. High values indicate that the object is well matched to its own cluster and poorly matched to neighboring clusters. Four clusters had a silhouette width = 0.27.

Evaluating the motivations behind adaptive responses helps to better understand features that were central to the groups' decision making. This analysis also supports the characterization of barriers that may exist to adaptation (discussed further in Chapter 3), by helping to identify types of providers not included in the study who may be vulnerable to future extremes, and understand the magnitude of vulnerability and allow policy-makers to know where and how to target interventions. Vincent (2007) states that whether adaptive strategies are utilized or not depends on a number of factors. Previous studies have determined that two large classes of variables determine adaptive capacity: internal characteristics (e.g., their assets and resources) and institutions (which govern their access to assets and resources) (Pahl-Wostl 2009, Engle and Lemos 2010). Chapter 3 analyzes how institutions affected management decisions, but here the internal characteristics that determine providers' adaptive strategies are evaluated by looking at those who utilized similar response strategies (clusters).

Large- and medium-sized urban providers make up cluster 1 (e.g., Denver Water, Fort Collins, Castle Rock). These providers typically (although not exclusively) have secure supply sources, senior surface-water supplies or non-conjunctive (Denver Basin[11]) groundwater as well as a diversified portfolio of water supplies, often from multiple sources (e.g., surface-water and groundwater) and basins (e.g., native, SPRB surface-water as well as trans-mountain diversions, such as C-BT water). While this source of secure water supplies doesn't completely reduce drought risk, it does provide a secure source from all but the most extreme droughts. While these water providers were impacted by the 2002 drought, the impacts were less severe than

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[11] In the SPRB there are two types of groundwater, classified under Colorado water law. Tributary (conjunctive) groundwater is hydrologically connected to a stream system that influences the rate and/or direction of flow on that stream. Only one provider in this analysis primarily used tributary groundwater and they were classified as being adaptive. The other type of groundwater is Non-tributary groundwater, which occupies Denver Basin aquifer water. Non-tributary groundwater, pursuant to section 37-90-103(10.5), C.R.S., is groundwater that, "the withdrawal of which will not, within 100 years, deplete the flow of a natural stream, …at a rate greater than one tenth of a percent of the annual rate of withdrawal." These waters do not fall within usual Prior Appropriation, because they are not hydrologically connected to the rest of the system, their supplies are little affected by drought.

others reported in the basin. High mean management ability scores in Table 2.3 and low differences in management ability shows that these providers were not heavily impacted and, therefore, didn’t need to make many adjustments following the 2002 drought. Efforts to acquire or construct additional resources were undertaken to meet growing demand, but this was not their primary response following the 2002 drought. They were quick to respond to the shortages in the 2002 drought by implementing demand-reduction efforts, despite indication that few had formal response drought plans in place. Following the drought, Group 1 water providers primarily focused on augmenting planning-related efforts, particularly drought-management, public education, and creation of drought response plans with fixed indicators, all of which added flexibility to respond quickly in the subsequent drought. Table 2.3 outlines the principal drought response options each group reported creating, following the 2002 drought. These water providers reported few impacts in the 2012 drought, indicating that they were able to test the new systems they had just put in place and the quick response due to those systems prevented impacts of the shortages.

Table 2.3. New management strategies that emerged between the 2002 and 2012 drought, mean management ability scores, and mean difference in management ability scores between the two drought periods for each cluster

Group	Novel management strategies	A0 mean* A0 delta**
1	Reuse systems, active demand management, integrated plans, adjusting rate structures, pipelines for exchanges, Drought plans, Conservation plans, aquifer storage and recovery (for those with non-conjunctive GW), expand reservoirs, more communication with customers, ET-based watering, monitoring systems	2.77
		0.89
2	Gravel pit construction, purchase C-BT water, purchase more water, Conservation plan, active demand management, Drought plan, more education of customers, tap categories, reuse irrigation water	2.72
		0.74
3	Reservoir construction, monitoring systems	2.56
		1.83
4	None	2.72
		0.58

*A0 mean is the mean management ability score for the cluster

**A0 delta is the mean difference in management ability scores from the 2002 to 2012 droughts for each cluster

Water providers in medium-sized suburban areas or rural, but rapidly developing water districts represent Group 2 (e.g., Brighton, Little Thompson Water District). They tended to have junior surface- or groundwater rights that were less reliable during the 2002 drought due to a lack of storage. In three cases, ditches that distribute water from reservoirs to their systems dried up, so they were unable to physically get their water. The lack of reliable supplies caused many of these providers to be severely impacted during the 2002 drought and led them to seek out physical, ‘hard’ adaptation strategies of acquiring more capital to reduce their sensitivity to droughts as their primary strategies, through acquisition of more water supplies or increasing their storage capacity. These providers also switched to more active demand management strategies through creation of conservation plans and engagement with customers to increase their efficiency. The combination of more secure supplies, reduced per capita demand, and the ability to respond more quickly to drought signals were indicated as reasons these water providers fared better in 2012. As one stated:

> *It used to be where our max day demand exceeded our supply for some time…but we added additional deep wells and increased our supplies…I would say 2012 was just kind of a reminder, but there were no significant impacts.*

Group 3 only contains two providers, both serving small, mountain communities. They were likely clustered into their own group because they had similar strategies that were distinct from others. Both water providers were severely impacted by the 2002 drought, within days of completely running out of water. Their supply source was surface-water, with very little storage. During the drought, they enacted drastic use restrictions, banning outdoor use and strictly monitoring and limiting household use. The water manager for one district described their policy, “*If I caught one house that violated the standard, the first week I would warn them, the second week I simply turned them off…Nobody ever violated twice on me.*” Once drought conditions subsided, both water providers built reservoirs with storage capacity enabling them to withstand drought conditions far worse than 2002, such that, “*2012 wasn’t even a bump for us.*” Aside from demand-management measures when conditions are abnormally dry, neither water provider altered their water management otherwise. P09 created a drought response plan but did not enact it during 2012.

The final group is made up of rural water providers who made very few changes to their drought response. They were minimally impacted by the 2002 drought because they either lease from other providers or have groundwater supplies that are not affected by drought. While they indicated normal maintenance (e.g., restoring storage tanks), their management tended to be reactionary. To be fair, these water providers were also not affected during the 2012 drought, potentially indicating systems that are fairly drought-resistant.

The adaptive strategies implemented following the 2002 drought successfully reduced vulnerability to the 2012 drought for all water providers, as indicated by lower impact scores for most water providers and learning by all. The adaptations fell into two categories: they added resources to reduce sensitivity to droughts (e.g., acquisition of water, construction of reservoirs, creation of water reuse systems, etc.); and they created mechanisms to respond to water shortages more quickly, through more effective monitoring, demand management, and creation of clear drought indicators.

DISCUSSION

From the strategies water providers used to make their systems more robust to droughts, we can begin to understand their adaptive capacity to deal with future stress events brought on by climate change and population growth. By evaluating the strategies drawn upon during past events, we are then able to assess how they changed though lessons learned and understand what adaptive capacity may exist to cope with future stresses. Looking at how water providers adapted their management responses, provides insights about how their incremental adjustments can evolve into longer-term ‘adaptive capacity’ (the ability of a system to prepare for stresses and changes in advance, or adjust and response to the effects caused by stresses (Smit et al. 2000)). This is important because learning lessons about how water providers can build and mobilize their ‘adaptive capacity’ can help them prevent, respond to, and adapt to drought impacts in advance (Engle 2013).

According to Jones et al. (2010), understanding processes that support adaptive capacity requires shifting from simply looking at what a system *has* that enables it to adapt, to recognizing what a system *does* to enable it to adapt. A key component is ensuring that actors actively engage in processes of change, particularly relating to changes in behavior, not just resources and technologies (Pettengell 2010). However, because direct assessments of adaptive capacity are not feasible (Engle and Lemos 2010), it is necessary to identify characteristics and features that influence it. Adaptation and vulnerability literature describe multiple pathways through which adaptive capacity can be built over time. The Overseas Development Institute created a framework aiming to capture the interrelated dimensions of adaptive capacity, finding that asset-based frameworks (e.g., the Sustainable Livelihoods Framework (Ellis 2000)) are often used, but fail to capture the dynamic, intangible processes that often influence adaptive capacity, such as flexible management and institutions (Jones et al. 2010). Their Local Adaptive Capacity Framework suggests five interrelated characteristics encourage adaptive capacity at the local level: asset base, institutions, information, innovation, and flexible forward-looking decision-making. This framework provides a means to start assessing how actions taken by water providers following the 2002 drought helped to increase their flexibility to respond to future crises and reduce their exposure to future stress.

While the adaptive capacity of water providers largely depends on their assets (reliability of supplies and access to storage), the strategies they used to manage droughts and willingness to alter their management strategies ultimately depended upon attitudes of the managers themselves. The quantitative data the EHC provided was unable to capture this nuance, but qualitative analysis from interview transcripts revealed that attitudes toward risk and uncertainty was a key differentiation between water providers who took steps to shift toward more flexible management styles, than those who only sought to increase their resources or did nothing.

Water providers who perceived that their systems were at risk of being impacted as severely or worse to the 2002 drought in the future, took actions to prepare and altered their water management strategies. Although this was true for all water providers who were heavily impacted by the 2002 drought, it was not limited to them. Some water providers with supplies that were not even impacted by droughts, but who perceived threat to future supplies due to other factors (population growth or changes to demand types, overall supply shortages due to climate changes) proactively adapted their management to prepare for the future.

As long as there is a perceived risk, water providers adjust management to prepare for the risk. Grothmann and Patt (2005) describe this process as ‘risk appraisal’, where a person assesses a threat’s probability and damage potential if there is no change to their behavior. If no action presents a risk, the person responds to the threat in the form of either adaptation or maladaptation.

> *Adaptive responses are those that prevent damage, and are taken if the risk perception of the perceived adaptive capacity are high. Maladaptive responses include avoidant reactions and wrong adaptations that actually increase damage.* (Burton 1996, Grothmann and Patt 2005)

This explains why mountain and rural providers who built reservoirs right after the drought didn’t alter their management after (cluster 3). Without high population growth rates expected, and supplies secure enough to withstand drought far more severe than 2002 following storage construction, there was no need to alter management further. Others with moderate risk continually adjusted their water management throughout the decade to add additional drought response and water efficiency mechanisms.

This relationship between risk and adaptation action provides insights to vulnerability. Where there is a perceived low risk currently, a potential vulnerability exists due to maladaptation. For example, non-conjunctive groundwater supplies are dwindling, in a region that is experiencing rapid population growth. However, without perceived risk caused by drought stress, water managers may underestimate their risk and will face more difficulty motivating users to conserve supplies. Depending on the type, groundwater supplies are either completely unaffected by drought (Denver Basin, non-conjunctive groundwater), or have a muted and delayed response to drought (conjunctive groundwater), smoothing out supply and drought vulnerability for providers who have access to the source. The effects of this is that groundwater-reliant systems have not had to be adaptive in the past and thus may not be well adapted to manage future challenges the region faces, although buffered to a degree from those challenges. This same conclusion applies to all water providers who have traditionally had 'safe' C-BT water supplies. C-BT is known to be among the most reliable, drought resistant surface water source in the basin. However, as water scarcity issues in the southwest deteriorate, an inevitable "call[12]" on the Colorado River would impact the amount of water a share yields.

Similarly, adaptive strategies that have been available to water providers in the past, particularly acquiring additional water and storage may not be viable options in the future. Through the 1980s and 1990s, when rapid population growth brought the need for additional supplies, water providers either purchased water from agricultural users or bought additional C-BT shares. However, purchasing water out of agriculture has been viewed as a socially undesirable option recently and water near areas where it is needed may be not be available for purchase. Similarly, due to the reliability of return, the value of C-BT shares has increased

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[12] A "call" begins when a senior water user requests to restrict the use of water among junior water users, when there is not enough water in the system to allow all water diversions. Starting with the most junior user, water diversions are shut off until the more senior rights are satisfied.

dramatically, limiting availability of shares to purchase. One water provider described, "*In 2002 C-BT was probably $5,000 for an acre-foot, now it's $26,000. That change has caused people to look at their portfolio and ask if they're requiring too much water dedication*."

CONCLUSION

The 2002 drought served as a learning experience for Colorado water managers, particularly water providers. Its severe impacts made them realized the unsustainability of their trajectory and that the status quo water management would be insufficient for any future scenarios of population growth and decreased supply. As a result, most water providers re-evaluated their management paradigms and adapted the strategies they used to balance supply and demand. Therefore, the objective of this paper was to assess how they adapted, how those adaptations improved / altered their drought management, and implications for their adaptive capacity.

Most studies seeking to evaluate determinants of adaptation or vulnerability focus on evaluating characteristics relating to strategies used or groups of entities with a particular outcome to hazards (e.g., Brooks et al. 2005, Sarker et al. 2013). However, this study took a combined approach to reverse engineer an understanding of potential regional vulnerabilities by assessing how stakeholders were affected by drought in the past, adaptations they made to their systems following the drought, and characteristics of those who took different strategy pathways that would make them more or less adaptable to future stressors. From this, potential areas for maladaptation and vulnerability were derived from an understanding of the underlying decision-making process.

While the EHC and quantitative analysis presented above provided a mechanism to draw comparisons between the providers, the context from interviews and document reviews augment the analysis to understand the nuance behind the results. The EHC was a useful tool to study a broad group of water managers and provided a significant methodological improvement over previous studies. However, future studies using the same tools could be improved upon. The strategies inquired about were limited and did not capture all of those used by water providers or capture variation with strategies (e.g., low water use landscaping and irrigation efficiency is achieved through a variety of different strategies such as irrigation audits, rebates for xeriscaping, or demonstration gardens.). Similarly, it would have been helpful to have used a broader range of categorical variables to assess strategy use, rather than the binary assessment conducted in this study. This would have helped provide a better understanding of the intensity of strategy use and their ramping-up and down. However, collection and analysis of qualitative data helped provide nuance to these methodological shortcomings and differentiate between the subjectivity of the survey due to differences in interpretation of study participants.

A benefit of this analysis is that identifying characteristics of providers and strategies that they use will help provide direction for policy makers. As they design policy to strengthen future adaptive capacity, state- and local-level decision-makers should target improving the significant determinants outlined above to boost water providers' adaptation and therefore reduce their vulnerability to future droughts. Accordingly, efforts to reduce future vulnerability should focus on increasing involvement of these communities in regional efforts and particularly reaching out to rural and mountain communities.

Additionally, this research indicates that most of the water providers who were adaptive were severely impacted by the 2002 drought, but re-organized their management and, therefore, were less impacted by the subsequent drought. This suggests that some level of stress could actually spur a shift away from unsustainable paths and make water providers more resistant to future stress. Additional research on other basins in Colorado or other regions would help determine if these findings are specific to this region or generalizable.

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CHAPTER 3: ANALYSIS OF RELATIONSHIPS BETWEEN FORMAL AND INFORMAL POLICY PROCESSES IN THE TRANSFORMATION OF SOUTH PLATTE RIVER BASIN WATER MANAGEMENT

INTRODUCTION

In recent years considerable attention has been given to the need to adapt to changing environmental conditions and to take advantages of opportunities that are presented. As resource managers and policy-makers prepare to address unprecedented changes, they will be required to proactively manage change to foster both resistance to stress (by sustaining attributes that are important in the face of change) and adaptation (developing new social-ecological arrangements that function effectively under changed conditions) (Chapin et al. 2006a). According to Walker and Salt (2006), increasing resilience (resistance) necessitates understanding how and why the system as a whole is changing, so policy-makers and managers are better placed to build capacity and work with change, rather than being a victim to it.

Institutions play a significant role in this challenge (Agrawal 2010), but many of today's institutions were established under different conditions and for different purposes, and are thus inadequate to manage new conditions and challenges (Huntjens et al. 2012). Various scholars have broadly recognized that institutions are fundamental to the processes involved in change and that there is a need for adaptive institutions to effectively guide systems along the most appropriate trajectory (Ostrom 1990, Pahl-Wostl 2009, Berman et al. 2012, McLennan et al. 2014). Blomquist et al. (2004) highlights the importance of institutions because they affect management at every step and can either magnify existing stress and present substantial barriers to adaptation or can alleviate pressure and lead to opportunities for growth. McNeeley (2014) echoes this concern, stating that “capacity to action is not possible where barriers exist” (Burch 2010). Institutions can play a prominent role both in contributions to environmental problems and in devising responses that have a reasonable chance of succeeding (Young 2003). However, a significant challenge for future institutional research is to go beyond observation of the importance of institutions and look inside the ‘black box’ of institutional processes and effects to explain how institutions matter – specifically, how they induce or hinder changes to management practices, how they shape management alternatives, and how they affect resulting outcomes (Blomquist et al. 2004).

Institutions and management of water systems underwent a significant change in Colorado following a severe drought period in the early 2000s. The 2002 drought caught water users off guard, leading water managers and policy-makers to re-examine their policies and strategies after the drought ended. A decade later another severe drought was addressed with revised policies and management, and resulted in less severe impacts (see Chapter 2). Therefore, evaluation of how managers responded to each drought and institutional and management adjustments made as a result of the impacts serves as a good case study to understand how system responses to periods of crisis can make it more (or less) resistant to future stress.

This study examines the multi-scale learning and changes to institutions that are made by water managers and state policy-makers in the South Platte River Basin (SPRB) following the 2002 drought. Particular emphasis is placed on institutional processes that enabled water providers to respond differently to the 2012 drought than they did in 2002, specifically how these processes facilitated learning by altering management practices and shaping management alternatives. This region is expected to undergo significant changes in the future (see Chapter 4 for details), so assessment of institutional processes that led to successful management adjustments will provide useful lessons for incentivizing more adaptive water management in Colorado in the future and will improve theoretical understandings of institutional arrangements that lead to more robust systems. Additionally, knowledge of drivers and barriers of system change will provide a better understanding of levers to pull to enable more robust system transformations in the future.

THEORETICAL FRAMEWORKS FOR UNDERSTANDING DROUGHT EFFECTS ON INSTITUTIONS AND MANAGEMENT

The key objective of this research is to evaluate which institutional processes that were developed in response to the 2002 drought altered drought management during subsequent droughts. Theory on institutional and management responses to crises is well developed both in the climate adaptation and disaster risk-reduction fields (Engle 2011, Berman et al. 2012). Because institutions can be the source of or solution to the problem, it is important to understand their interactions with stressors. Ecological extremes or shifts in ecological characteristics can serve as "flashpoints" that highlight vulnerabilities and provide learning experiences that allow institutions to adjust and restructure (Jones and Cech 2009). Institutions are responsive to changes to both ecological components and social status of a system; making them an intermediary between crises and management and therefore a good indicator for system transformations (Berman et al. 2012).

A number of theoretical frameworks depict how institutions interact across scales, responding to and fostering change. Drawing elements from these frameworks aids with this analysis of how institutions facilitated a transformation that increased resilience in the SPRB following a severe drought period. The seminal work of Ostrom (1990, 1999) provides a framework for understanding how institutions, situated in an ecological context, affect human incentives, actions, and outcomes (Ostrom 2005, Ostrom and Cox 2010).This Institutional Analysis and Design Framework (IAD) emphasizes the importance of institutional arrangements in shaping solutions to collective action problems (such as water management) (Ostrom 1999, Heikkila 2004) and identifies relationships among institutional, situational, and environmental variables in explaining decision-making (Crawford and Ostrom 1995, Ostrom 1999).

The IAD emphasizes the role of formal, rule-based institutions and their effects on outcomes among actors in public organizations (Heikkila 2004). It is often used to empirically evaluate how institutions shape policy and management situations, making it ideal for structuring this study. The IAD is particularly useful for analyzing this case study for three additional reasons. First, analyzing water management in Colorado can be particularly challenging because jurisdictions often overlap, there are many competing interests, and there are many loosely applied guidelines for water management with few hard-and-fast rules, leaving much of water governance and management to 'local control.' The use of a multi-tier conceptual map, a core component of the IAD framework allows researchers to distinguish between nested levels of institutional activity (Bettini and Brown 2011), linking institutions, decisions, and outcomes across levels[13] (Ostrom 2011). This organization aids analysis of this case study, where local, state, and national institutions affect a resource that is primarily managed locally. Second, the framework was initially designed to identify design principles for 'robust' common-pool resource institutions and contextualize how interactions among local actors and institutions shape

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[13] The IAD framework defines nested tiers of decision-making and the relationships among them: constitutional, collective-choice, and operational decisions. Decisions are determined by rules, which are a shared understanding among those involved about which actions are required, prohibited, or permitted (Ostrom 2005). McGinnis (2011) defines the rules as:

- Constitutional choice rules determine the processes through which collective choice procedures are defined;
- Collective choice rules are the processes through which institutions are constructed and policy decisions are made by actors authorized to participate in the collective decisions as a consequence of the constitutional choice process; and
- Operational choice rules are the implementation of practical decisions by individuals who have been allowed to act as a consequence of collective choice processes.

individual and collective action (Kiser and Ostrom 1982, Ostrom et al. 1994), therefore it is optimally used for analysis at the local, community level (Kadirbeyoglu and Özertan 2015), the primary level that water management occurs in Colorado and the focus of this study. Lastly, the IAD provides a framework for capturing how the institutional setting operates in reality, which may not match how it operates in formal documentation (Bettini and Brown 2011), thus allowing analysis of the functioning of formal rules in addition to informal situations affecting water management.

While the framework provides a thorough evaluation of the context surrounding institutions and management, one shortfall of the IAD is that it is a static diagnostic tool, providing a snapshot in time but lacking the ability to evaluate a dynamic system and its processes. It can be used as a comparative tool between periods of time or contexts, but to perform empirical analysis on the dynamics of a complex system (like this study where I am evaluating continuous change in a system over a decade), it helps to look to literature on system dynamics. The "adaptive cycle" is a heuristic that focuses attention on system processes of growth, conservation, destruction, and reorganization (Gunderson and Holling 2002), and aids in analysis of periods of change within systems, particularly leading up to and following events that strain the system to a point of release.

Chaffin and Gunderson (2016) explain that the processes during and following periods of crisis allow governmental experimentation to emerge, and it becomes possible to create institutions that that are more adaptive to change. If flexible institutions are not in place, the phase shift from conservation to release is initiated by a catastrophic event, leading to a system collapse. However, the presence of agile institutional structures allows for system adaptation and readjustment without a collapse. Chaffin and Gunderson (2016) discuss situations when grievous events lead to institutional adjustments that served as mechanisms that prevented collapse during subsequent catastrophic events.

Institutions and their processes are most open to dramatic transformations during and immediately after crises (Walker and Salt 2006). Significant release periods (following extreme stress) catalyze previously inert institutions that had grown stable and rigid (and less resilient to disturbances) to change by the disruption (Chaffin et al. 2014). Once the system readjusts, institutions and structures are formalized and legitimacy of the new institutions is gained through policy changes and shifting social norms (Olsson et al. 2004b, 2006, Chaffin and Gunderson 2016). Periods of crisis followed by development, allows institutional settings formalize and adaptive capacity to increase (Folke et al. 2005). With this framework in mind, the first part of this study examines how the crisis of the 2002 drought altered existing institutions.

Berman et al. (2012) review the role institutions play in navigating the transition from coping with crisis during and immediately after to increasing long-term adaptive capacity. They conclude that, while the importance of institutions is commonly recognized, an understanding of *how* institutional processes affect management strategies has yet to be sufficiently researched. Informal social and cultural norms, and formal policies affect how individuals, communities, and organizations are able to respond in the short term to stressors (Young 2002) and these institutions serve as a form of social memory following crises (Adger and Vincent 2005, Berkes 2007). In addition to enabling existing capacities to cope with the present, institutions enable capacities that support longer-term adaptive changes in preparation for future events.

McNeeley (2014) states that ‘adaptive capacity can be either enhanced or constrained by institutional and regulatory settings for water management,’ but by building on present strategies to enable enduring sustainability, institutions increase adaptive capacity. To learn transferrable policy lessons, it is important to understand how different types of institutions at multiple levels influence the ability of a community to respond through short term coping, as well as to adapt over the longer term (Agrawal et al. 2009).

Heikkila and Isett (2004) present a model illustrating that institutions play a significant role affecting elements of operational level (management) decision-making processes by determining both the set of decisions that an actor has to choose from and the cognitive elements affecting their ultimate choice. Pahl-Wostl et al. (2010) addresses how two types of institutional processes – formal policy processes and informal learning processes – interact to affect management and learning at an operational level. If resource managers are impacted by a crisis, there is a period afterwards where they learn from and readjust their strategies to better cope in the future. While the impact of the crisis itself affects that adaptation, their interactions with institutional processes also affects their response. These adaptations / policy changes reflect learning that can occur in a variety of ways; with some being new and innovative and others merely incremental refinements to previous policies (Hogwood and Peters 1983, Polsby 1984, Huntjens et al. 2011). Learning is assumed to be an exploratory, stepwise process, where actors experiment with innovation until they meet constraints (Pahl-Wostl 2009). Therefore, policy-refinement and learning may have different levels of intensity and scope (Pahl-Wostl et al. 2007); the different types of which are differentiated by the concept of single-, double- (Argyris and Schön 1974), and triple-loop learning (Hargrove 2002) (Pahl-Wostl 2009, Huntjens et al. 2012). It is assumed that higher-learning levels are associated with adaptive management, thus demonstrating a higher adaptive capacity. Pahl-Wostl et al. (2010) suggests that the informality of learning processes is assumed to support higher levels of learning, but without connections to formal policy and management processes, those informal learning processes will be short-lived.

With this in mind, the latter part of study evaluates the management adjustments made by water providers and how they interacted with formal and informal learning processes following the 2002 drought to better understand institutional mechanisms that affected water provider management and facilitated learning.

METHODS

A case study approach was used to evaluate this multi-part study. The SPRB was chosen as the site for this case study analysis because it is a region facing extreme water pressures that was hard-hit by a drought in the early 2000s, resulting in a large number of policy and management changes. According to Yin (2003), a case study design should be considered when: the focus of the study is to answer “how” and “why” questions; you cannot manipulate the behavior of those involved in the study; you want to cover contextual conditions because you believe they are relevant to the phenomenon under study; or the boundaries are not clear between the phenomenon and context (Baxter and Jack 2008). This research presents a single case study of water providers’ management in SPRB in early 2000s. It is designed with embedded units-of-analysis, water providers, and evaluates if institutional processes contributed to their shifts towards more adaptive management.

Data Collection

This study used a mixed methods approach combining policy document analysis with key informant interviews, conducted in the spring of 2016 and water manager interviews, conducted in the summer and fall of 2016. The policy documents disclosed the objectives and history of each of the institutional processes and disclose the formal basis by which water providers adopted different management strategies. Interviews gave a ‘behind the scenes’ look at how policy makers and managers designed and implemented policies, revealing the rationale guiding decision-making. This illuminated how managers actually interacted with those formal processes in practice and revealed informal institutional processes. Research was conducted iteratively, with data collection interspersed with periods of analysis to enhance the validity of analysis by exploiting the complementarities and potential for source triangulation.

Policy documents were collected by performing systematic searches in the Colorado Water Conservation Board archives database[14], using keywords "Drought" OR "Task Force" between January 1, 2000 and December 31, 2014. This was then narrowed down to documents pertaining to drought, water providers, or water management. All legislative records and Supreme Court decisions pertaining to water were also queried in reference to water issues, with the greatest attention given to time-periods post-2002 and specifically dealing with drought. All state and local planning documents and meeting minutes from drought task forces were also reviewed for the time period of the study. The aforementioned search criteria were not applied to local policy documents, but for each water provider in the basin any water master plans, conservation plans, drought plans, or other water policy document was evaluated.[15]

The sample frame for interviews targeted informants from academia, non-profits, and state agencies who have been working on water and drought responses through the period of study who could provide insights about how drought events over the past decade affected institutional changes and how those changes affected water management strategies of providers. Three water management experts provided contextual information, while six state employees (three from the Division of Natural Resources and three from the state legislature) provided specifics on decision-making rationale and how the state interacted with water providers.

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[14] http://cwcbweblink.state.co.us/weblink/search.aspx?dbid=0

[15] Ultimately this study reviewed 887 documents from the Colorado Water Conservation Board search criteria and 95 local management plans.

Additionally, key personnel from 25 water providers were interviewed, using stratified purposive sampling techniques to ensure a broad sample of providers were evaluated (See Chapter 2 sampling technique). Interviews were semi-structured and interactive, discussing if a range of management decisions were made, why they were made, interactions with the state or other local providers, and how they were impacted by drought. The interview protocol (See Chapter 2 for interview protocol) comprised specific questions about whether strategies were used or not, coupled with open-ended questions inspired by theoretical concerns about adaptive capacity and institutional change as well as exploratory questions to elicit information about actors' particular views on how their water system have changed, whether performance had improved over time, and their general perceptions of water management. Interviews were recorded and transcribed for analysis.

Data Analysis

The study ultimately involved determining *how* the 2002 drought changed institutions, and *how* those changes affected their water management. Therefore, the analysis was conducted in two steps, each connected to one of the research objectives. The first step was to determine the most significant formal and informal institutional processes (that affected water providers) made in response to the drought using deductive process tracing methods. The second step was to test if those processes were responsible for changes in adaptive strategies using qualitative comparative analysis followed by qualitative analysis to elicit mechanisms that resulted in management influence.

Process tracing, a tool often used for within-case analysis, is a systematic examination of evidence to draw causal inferences about events (Collier 2011). The tool gives close attention to sequences of independent, dependent, and intervening variables to draw descriptive and causal inferences. The focus on causal mechanisms distinguishes process tracing from historical mechanisms, where merely describing a chronology of events without detailing necessary explanatory mechanisms is not sufficient (Blatter and Blume 2008, Biesbroek et al. 2014). According to Biesbroek et al. (2014), the inferential challenge is to abstract the important from the less important processes and provide a convincing causal account of which identified mechanisms are responsible for explaining the outcome. The methodology does not aim to map out all possible mechanisms that were present preceding the outcome, but instead abstracts the important from the less important processes by rendering alternative explanations less plausible (Biesbroek et al. 2014).

Process tracing can be used build theory, starting with empirical material and using a structured analysis to detect plausible causable mechanisms where X is linked with Y, as well as test theory, where assessment of whether the existence of theorized causal mechanisms are present in a particular case (Beach and Pedersen 2012). The two-step process of this study began with constructing a chain of events of institutional processes that occurred following the 2002 drought and their impacts on water management to develop a theoretical hypothesis of key formal policy and informal learning processes that affected management. Cross-case research methods were then used to test if these causal mechanisms were responsible for changes towards more adaptive management.

The first part of data analysis consisted of iterative coding with an initial set of deductively derived analytical codes that was expanded with codes derived inductively through initial readings of interview transcripts and policy documents. This list of codes was then applied systematically to the dataset using the qualitative data analytical software NVivo. Each document and interview were reviewed specifically to note actions taken or changes to status quo policies / management made, reasons for those changes, and outcomes (if described). A category was given to the reasons, whether they were organizational, institutional, or environmental. If a particular process or institution was noted to be significant, it was marked as such. Based on a methodology used by Bisaro et al. (2010) to analyze multi-level water governance and evaluate adaptive management, a causal map (see Appendix 3.2) was then created for state level institutional processes and each water providers management actions. From this, key institutional processes were selected for further review. Pahl-Wostl et al. (2010) describes that this methodology for creating causal maps is good for analyzing the flow of influence in sequential actions at different administrative levels.

Those key processes were then used as independent variables with an analysis of water provider management as a dependent variable and qualitative comparative analysis (QCA) was used to determine causal effects of institutions on management changes. Causal mechanisms identified by process tracing above were tested in medium-n cross-case analysis using QCA (Beach and Pedersen 2012). The difference between this and frequentist comparative methods is that frequentist methods make inferences about the patterns of regularity between X and Y, whereas in process-tracing, inferences are made about the presence of causal mechanisms between X and Y.

QCA is particularly useful for identifying institutional conditions that were associated with management changes and learning because it helps to generalize from individual cases (water providers) (Hamidov et al. 2015) by formulating general statements from complex settings, such as whether or not an institution was a factor in a management decision. QCA is a non-probable comparative method that allows qualitative and quantitative data to be merged (Vink and van Vliet 2009). It is ideal for small- to medium-sized (n=5-50) data analysis (Krook

2010, Mollinga and Gondhalekar 2014) because it is case-oriented, making it an appropriate method for this analysis, where traditional statistical methods fall short. QCA uses pairwise comparisons to analyze combinations of conditions that are necessary or sufficient for an outcome to occur. Using Boolean algebra, it analyzes the causal contribution of different conditions to an outcome of interest. QCA starts with the documentation of the different configurations of conditions associated with each case of an observed outcome (Pahl-wostl and Knieper 2014). These are then subjected to a minimization procedure that identifies the simplest set of conditions that can account for all the observed outcomes, as well as their absence (Thomas et al. 2014).

Water provider management changes were evaluated using data from Chapter 2 to develop a simple index to capture the type of learning process each provider underwent. The two types described in Chapter 2 were water providers who made minor adjustments to their management, primarily by increasing resources, and those who engaged in a more adaptive process by including planning and increasing their flexibility. The index used to determine if a provider fell into each of these categories was calculated as follow the sum of the mean change in strategies water provider used by year and the ratio of planning to resource-increasing strategies. Based on expert judgement, a cutoff of 1 was assessed, where water providers with index values greater than 1 were deemed to have changed to ‘adaptive management responses’ and those with index values less than 1 to have not changed their management. While this index is somewhat rudimentary, it provides a basic measure of the types of management changes made, which can be used as a proxy for assessing how their interactions with institutional processes affected learning.

The last step in analysis was to discuss and isolate underlying mechanisms associated with institutions that contributed to changes in management and implications for regional adaptive capacity.

DROUGHT EFFECTS ON INSTITUTIONS IN COLORADO

In Colorado, both formal policy processes and informal learning processes often follow periods of drought, illustrated in Figure 3.1, which shows a timeline of significant state legislative and judicial policy processes from 1930 until 2015. Although there is often a lag period following droughts, it is clear that the system is responsive to stress and adjusts policies after each drought event to better manage future situations. While it doesn't capture all of the learning processes that occurred over time, Figure 3.1 demonstrates that the time following the 2002 drought period had significantly more formal policy changes[16] than following previous droughts, making it an interesting focal point for this study.

The 2002 drought is an example of a crisis where water scarcity was heightened and water managers at all administrative levels recognized that the existing paradigm for water management was insufficient (Pielke and Waskom 2003). As theorized by multiple scholars (discussed above), the crisis presented in the 2002 drought jumpstarted a system that had become stagnant, leading to the cascade of formal policy processes illustrated in Figure 3.1. Although the drought impacts were disastrous, causing $1.6 billion dollars of damage statewide[17], they were not so catastrophic that they led to a system collapse, as they likely would have had the drought continued. Instead, the system adjusted, both as the result of formal policy processes and informal learning processes. To evaluate how this institutional learning took place, the section

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[16] The difference post-2002 could be due to better, digital record-keeping, in addition to an increase in formal institutional changes.

[17] Western Water Assessment Extreme Events Database http://wwa.colorado.edu/climate/extremes/database/

below describes key institutional processes that affected water providers then dissects the specific mechanisms that providers interacted with.

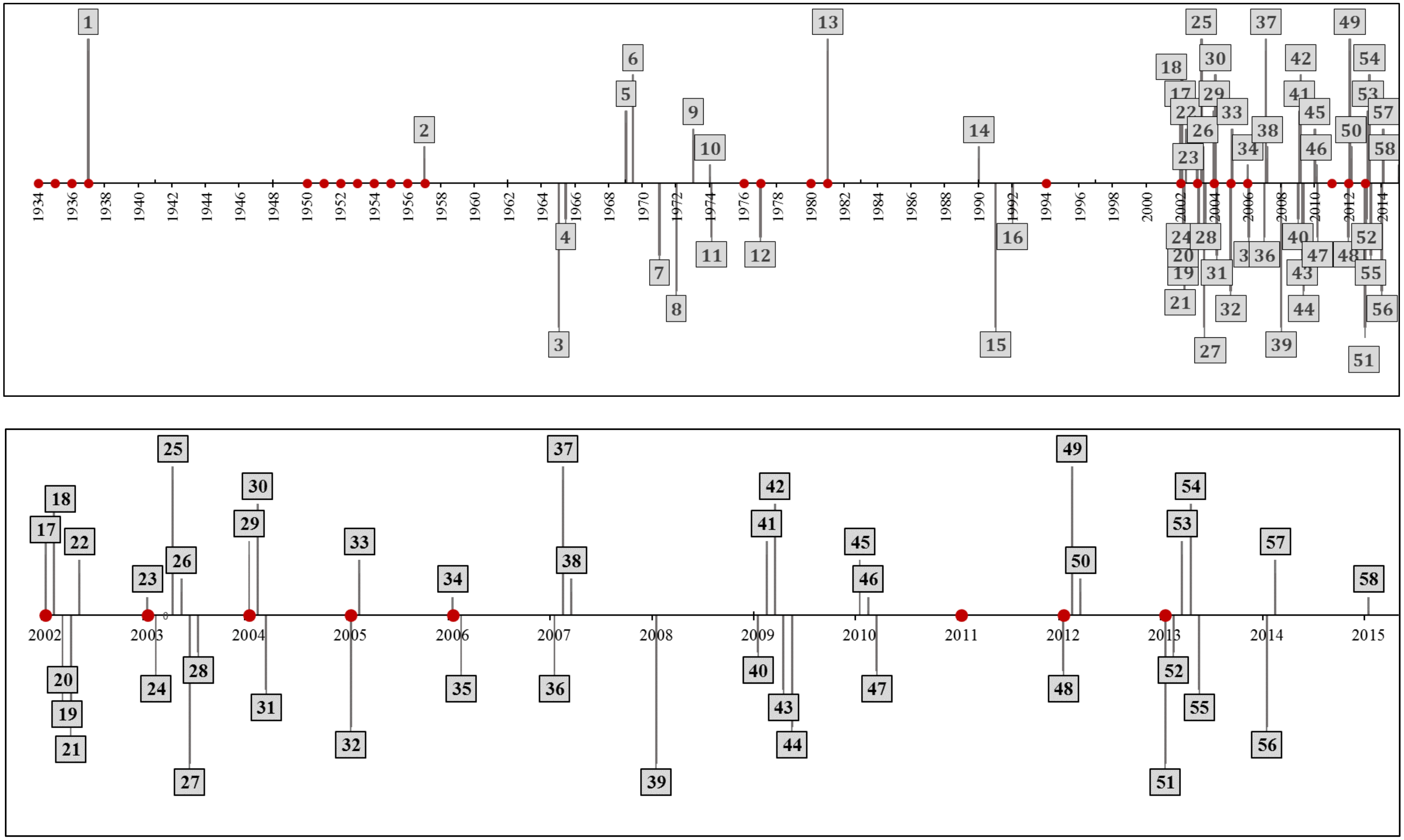

Figure 3.18. Legislative changes (regulatory and statutory) and Colorado Supreme Court rulings relating to water providers from 1935 to 2015 (top) and only 2002 to 2015 (bottom). Data were collected via online searches. Red dots signify drought years. Names corresponding with numbers are listed in Appendix 3.1.

KEY POLICY AND LEARNING PROCESSES FOLLOWING THE 2002 DROUGHT

Because it was not possible to evaluate how all of the changes to formal policy processes (shown in Figure 3.1) affected water management, the study determined the most impactful processes and use these for further analysis. Blomquist et al. (2004) explains that in order to isolate institutional effects from other influences on water management regime, a comparative analysis is necessary. Therefore, the study looked for key institutional processes (formal policy and informal learning) that serve as the independent variables for the next section of this study, where their effects on water management are evaluated.

Based on interviews with state water policy-makers and expert opinion, process tracing was used to inductively isolate processes that were perceived to have high impact on how providers managed water. For additional verification, a causal map was created (Appendix 3.2) for each action taken by each water provider (of those interviewed) between 2000 and 2015 and three key institutional processes were selected for further testing of their impacts on water management: Formal policy processes aimed specifically at increasing management options (e.g., The Water Conservation Act of 2004 (HB04-1365)); formal policy processes that aimed to mitigate drought impacts (e.g., updates to the Colorado Drought and Mitigation Plan (or Water Availability Task Force – WATF)); and informal networks that were created by water providers.

Management Option Increases

As a general rule, the State of Colorado minimally legislates drought or water use, relying instead on water courts and markets to sort out who has the right to use water when supply is scarce, through the prior appropriation doctrine. However, in 1991 the Water Conservation Act was passed (HB-1145) to promote water use efficiency, requiring all "covered entities"[18] to develop water conservation plans prior to receiving any financial assistance from the Colorado

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[18] Covered entities are providers that annually supply over 2000 acre-feet of water to retail customers.

Water Conservation Board or the Colorado Water Resources and Power Development Authority (Colorado Water Conservation Board 2004a).

The 2002 drought led to the realization that water conservation and efficiency are key parts to meeting future demands and requirements of the 1991 Act were ineffective. In 2004, the State Legislature improved upon the Water Conservation Act of 1991 by passing the Water Conservation Act of 2004 (HB04-1365). Key elements of the new act were that it created a grant mechanism to allow water providers to apply for grants to assist them with water conservation and drought planning activities. Water providers covered under the act were given two years to comply with the requirement to submit a conservation plan to the state and revise it every seven years thereafter. The Act allowed the Colorado Water Conservation Board to provide resources to assist providers with creation of their conservation plans, including grants, template documents, and review of old plans.

A number of other laws created during this period shared the goal of increasing water efficiency while promoting flexibility of management options for water providers, including: amending regulations to allow rainwater harvesting; requirements for high efficiency appliances; and streamlining the process of changing surface water diversion points.

Management Impacts

The 2004 Conservation Act successfully achieved its intent to increase water providers who developed formalized conservation plans. Figure 3.2 shows that the number of water providers interviewed in this study with formal plans increased four-fold after the deadline established by the Act (2007).

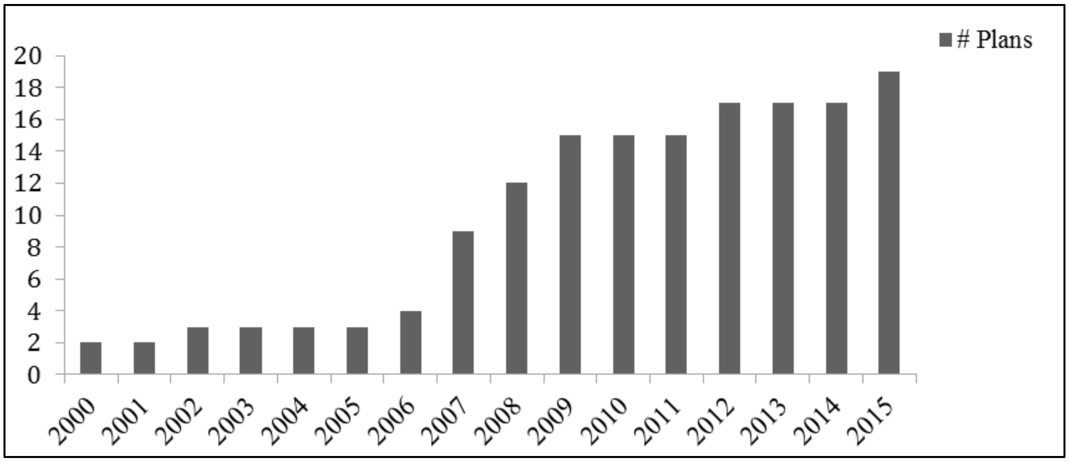

Figure 3.19. Number of water providers (of the 25 interviewed) with formalized conservation plans as of December 2015

Although it caused a substantial change in the number of providers with plans, the Conservation Act also significantly affected the way the 2012 drought was managed. The presence of formalized conservation plans led to a shift in both the type and diversity of strategies used by water providers. Those with conservation plans had a broader range of management alternatives to draw from during the 2012 drought than they did in the 2002 drought. During the 2002 drought, most providers did not have any formalized plans in place and primarily relied on mandatory restrictions or finding ways to increase supply, strategies that had been sufficient in previous droughts, but were inadequate due to the duration of the shortages.

The Conservation Act required plans to contain certain minimum elements, including: a profile of the existing system, profile of water demands and historical demand management, integrated planning and water efficiency benefits and goals, selection of water efficiency activities, and an implementation and monitoring plan. Fulfilling the necessary elements warranted an introspective evaluation of their water system's capacity and future needs, as well as the ability to utilize alternative strategies to fulfill management objectives. Although the 2002 drought had recently tested the supply and demand capacities and management strategies of many providers, some reported that the process of revisiting their conservation plans jumpstarted their thinking about the longevity of their supply and led them to become more forward-thinking with their planning, and shift their focus to preemption rather than reacting to water shortages after they had begun.

Water providers identified their largest areas of water use and water savings goals and were then required to evaluate potential methods to reach those goals. Considering the appropriate conservation strategies to meet their objectives was a multi-step process that involved identifying existing programs and evaluating the feasibility of measures from a list of programs[19]. Additionally, the state contracted with Colorado WaterWise to develop a Guidebook of Best Practices for Municipal Water Conservation in Colorado (Colorado Waterwise and Aquacraft 2010) which many providers used to augment their list of potential conservation measures. Once a list of strategies was compiled, the plans outlined whether the program was already being used or whether it would be implemented in the future. This decision was justified, usually based on a cost/benefit assessment as well as justification for its effectiveness or appropriateness to the community.

Interview data pertaining to reasoning associated with the use of particular management techniques revealed that development of these plans directly resulted in many water providers implementing a larger number and more diverse suite of conservation and water shortage strategies (see Appendix 3.2). Most water providers began implementing new conservation measures during the 2002 drought. For example, some providers continued using summer water

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[19] HB04-1365 provided a list of minimum measures and programs that could be considered, which includes: water-efficient fixtures and appliances; low water use landscapes and efficient irrigation; water-efficient industrial and commercial water-using processes; water reuse systems; distribution system leak identification and repair; dissemination of information regarding water use efficiency measures, including by public education, customer water use audits, and water-saving demonstrations; water rate structures and billing systems designed to encourage water use efficiency in a fiscally responsible manner; the department of local affairs may provide technical assistance to the covered entities that are local governments to implement tiered billing systems; regulatory measures that encourage water conservation; and incentives to implement water conservation including customer rebates.

restrictions annually, after the 2002 drought, finding that it not only helped stretch their supply, but additionally it kept water conservation at the forefront of customers' minds, making it easier to promote further conservation efforts when needed. Similarly, public education programs that began during the 2002 drought continued in perpetuity because they were made a core requirement of conservation plans. Although water providers may have developed and implemented new conservation policies during the 2002 drought, they were codified in their conservation plans, making them easier to draw from when droughts returned. This resulted in the use of more diverse management techniques (in number and type) during the 2012 drought, and thus a more robust response. However, some providers acknowledged the potential downside of increasing overall efficiency being that if a system uses water conservation measures to meet growing demand, there are fewer options to reduce demand when supply is compromised, such as during droughts (a phenomenon called 'demand hardening').

Drought Impact Mitigation

During and following the 2002 drought state officials realized that more could be done to monitor and reduce the impacts of future droughts. A statewide Drought Mitigation Response Plan (DMRP) was in place (created in 1981), but it had never been tested before and was unusable, resulting in a complete overhaul and restructuring of the response mechanisms to be more effective. The original DMRP was designed to provide an effective and systematic means for the State to recognize and reduce the impacts of water shortages (Colorado Water Availability Task Force 2003). Believed to be the first comprehensive plan of its type in the nation, the original plan consisted of monitoring, assessment, mitigation, and response (Colorado Water Conservation Board 2013), carried out by a Water Availability Task Force (WATF). The WATF is a group of water supply specialists, emergency management professionals, land managers, and climatological experts who meet regularly to monitor drought conditions (Colorado Water Availability Task Force 2003). If they believe conditions are in a state of decline, the WATF is required to notify the Governor and request activation of relevant Impact Task Forces (ITFs). (See Figure 3.2 for Task Force diagram). ITFs are sector-specific (agriculture, energy, municipal water, and wildlife) and convene on an as-needed basis (when activated by the WATF) to determine existing or potential impacts within specific sectors. In early versions of the DMPR, the ITFs reported to agencies and an inter-agency coordinating group (Colorado Water Conservation Board 2010), making up a "spaghetti diagram that no one could follow and required an engineering degree to figure out" (unpublished interview).

According to state officials, two decades of unusually wet conditions led to "the DMRP sitting on a shelf from its creation until 2002." During that drought policy-makers knew it was there but that it was largely ineffective, so it wasn't utilized. Following the crisis, state officials knew that they needed to update the plan if they wanted the state to engage more effectively to monitor and respond to future droughts, so in another formal policy process the plan was revised in 2007 and completely overhauled in 2010. One of the major additions was to create a Drought Task Force (DTF)[20], comprised of directors of executive agencies and chairpersons of the WATF and ITFs, that reviews reports from the WATF and ITFs, develop recommendations for drought response, and make reports to leadership, the media, and response agencies. The DTF is the primary forum in which drought-related information (climate and water supply) exchange occurs from state to local actors. Combined, the task forces make up a web of monitoring (WATF), sector-specific impact assessments (ITFs) and general assessment and response (DTF) (Colorado Water Conservation Board 2013).

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[20] The DTF was added in a 2007 DMRP update and further streamlined in the 2010 update.

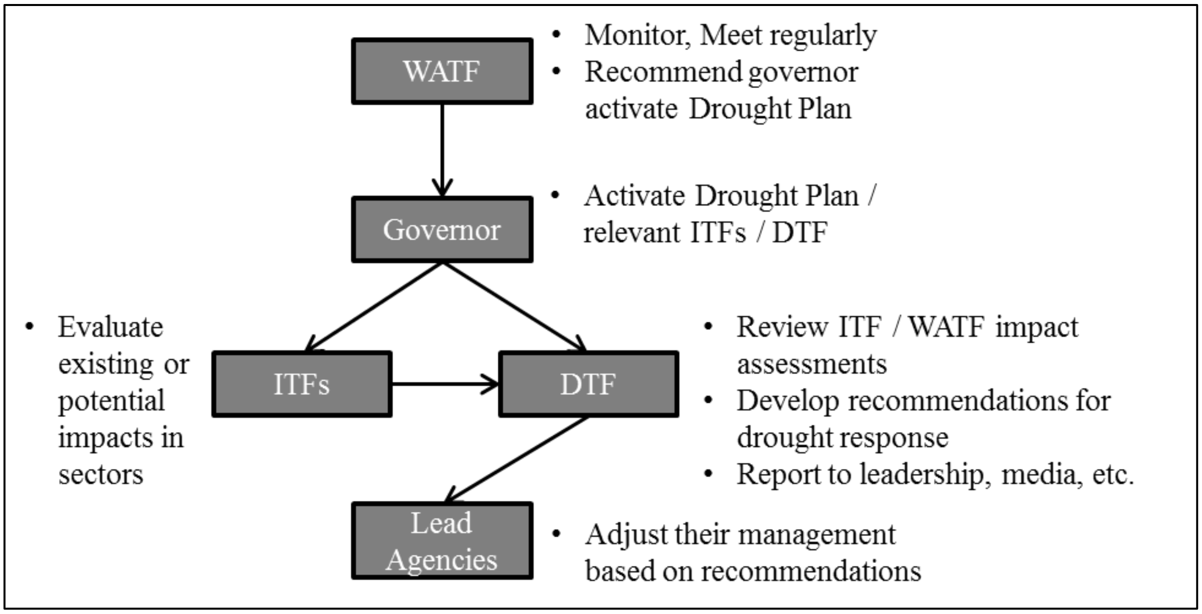

Figure 3.20. Drought response structure, established in the 2010 DMRP

The 2007 plan expanded mitigation aspects and incorporated a study of statewide water supply study to provide an effective and systematic means for the state to reduce the impacts of long-term water shortages. In 2010, the DMRP underwent a significant revision, which included development of a comprehensive drought hazard vulnerability assessment by region and sector, modernization of response elements, development of additional tools and resources to support local drought planning efforts, and evaluation and updating the indices used for drought monitoring.

Management Impacts

Alterations to the drought impact mitigation processes were designed to specifically help water providers in two ways: the continuous monitoring of the WATF would to ensure that a drought didn’t surprise water managers again; and the Municipal ITF would serve as an interface between municipal water providers and state agencies by evaluating on-the-ground impacts and communicating them back to state officials who could then develop responses to mitigate those impacts and relay changing conditions to the local communities. Although the process of updating the DMRP began shortly after the 2002 drought and was based upon that experience, it was not finalized until 2010 and was used in the subsequent drought. State officials reported that it worked as designed, and few updates were made following the drought in a 2013 update. Water providers reported mixed interactions with DMPR mechanisms in the 2012 drought.

Many of the providers interviewed described that impacts in the 2002 drought were worsened due to a delayed response and there was citizen confusion about their local conservation measures and restrictions (e.g., people in Aurora would hear about Denver Water restrictions on the news and not understand that their local conservation measures were different). Therefore, goals of the DMRP and DTF became to coordinate messaging and help manage early action. Most major water providers reported attending the WATF meetings on a monthly basis and are engaged with the Municipal ITF, but few others had direct interaction with these mechanisms. However, major providers typically have a reach that extends to smaller ones because they either provide water for those communities through service agreements or they interact with them on local management issues. Therefore, they can (and do) act as nodes to other providers who are less engaged.

The most reported influence on management of the 2012 drought was that once it began, the DTF reached out to them to find out how they were managing shortages and developed a website (coh2o.co) where citizens could look up local restrictions. State officials said that they are always trying to develop tools and resources to help with drought response at the local level. This proved to be a highly effective tool because many providers listed that the 2012 drought response was greatly improved because of better region-wide communication and coordination as well as early response (some reported that the response was almost too early and robust).

Informal provider networks

During the 2002 drought and immediately after, many water providers started working together more closely to cope with the effects and learn from one another. This coordination existed in some form prior to the drought, but became more pronounced and in some cases transitioned from informal communication to formalized arrangements during and after the drought. The types of coordination that existed are quite diverse and resulted in a network of informal learning networks that increased the robustness of water management regionally. The informal learning networks can be lumped into three groups (described below): ad hoc gatherings during extreme stress; coordination on infrastructure projects; and coordinated informal emergency responses. These groups are interconnected, often with water providers being members of multiple groups or with an informal group leading to a formalized partnership.

In the wake of the 2002 drought, water providers in the Denver metro area and those north of the Denver area formed sub-regional, informal groups to discuss their water supply issues and strategies they were using to cope with severe shortages. They met semi-regularly (some reported meeting monthly, others recalled quarterly meetings), and discussed specific topics at each meeting, but the primary purpose of the meetings was to coordinate messaging, communicate problems they may be having, and generally check in. Attendance and group membership were based on existing relationships and not formalized, but multiple interviewees reported that they attended the meetings, in person or over the phone, and that they were helpful in coping with the drought and revising their plans after. The meetings dwindled once drought conditions subsided, but all providers who were involved reported an expectation that they would start back up when scarcity issues return (unpublished interviews). These ad-hoc groups represent informal learning processes.

The drought brought awareness that existing water supplies were insufficient for future demand and stress, so some groups of water providers collaborated on infrastructure projects during and in the aftermath of the drought. Organizations throughout the region teamed up to build new reservoirs because the cost and regulatory burden was more than they could manage independently. For example, Tri-Districts[21] joined up with the City of Greeley to purchase gravel pits to store water following the 2002 drought. Similarly, the Little Thompson Water District partnered with the Central Weld County Water District to convert a gravel pit into storage, reporting that they could build a bigger reservoir in one location that could serve both districts. By partnering and sharing a location, not only would their impact be smaller, but they reported the benefit of sharing administrative and financial loads.

While these arrangements are examples of formal policy processes, similar informal examples exist, where water providers coordinated affluent dumping (e.g., coordination between Lafayette and Boulder as well as between Genesee Water and Sanitation District and Evergreen) so there would be sufficient return flows for downstream use and water could be reused without excessive treatment costs. Many collaborations were ad-hoc and served as an emergency response during shortages. Most water providers interviewed reported informal arrangements with neighboring providers who will provide emergency supplies, if needed. These are often through existing emergency connections of infrastructure, but also were arranged by hauling water in. Although rarely used, this was listed as an emergency supply option by many water providers. One water provider, Pinewood Springs Water & Sanitation District hauled in water daily from a neighboring city during the worst parts of the drought. Similarly some providers indicated that during the worst periods of drought, they coordinated return flows with up/down-

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[21] North Weld County Water District, East Larimer County Water District, and Fort Collins Loveland Water District make up “Tri-Districts”. Although they are independently managed water districts, they share infrastructure and staff and collaborate on multiple projects.

stream neighbors so there would be surface-water available during hours it was needed (e.g., Genesee and Evergreen). Other unique cases involved cities swapping water with local ditch companies so water at treatment plant intakes was high enough volume and quality (Fort Collins).

Management Impacts

Ultimately the developments of these arrangements are manifestations of trust building and cooperation that occurred during this period. Trust lubricates collaboration (Pretty and Ward 2001) and according to Olsson et al. (2004a), all cases of successful co-management involve long periods of trust building. Most water providers (15/25 of those interviewed) reported that they engage with others locally to manage droughts and that it positively influenced their water management going forward, with effects as diverse as the collaborations themselves. Overall the interactions affected providers by: 1. introducing new management strategies due to awareness of what others were doing and learning lessons from their experience; and 2. Changing the culture of water managers due to regional pressure.

The north Denver ad-hoc groups disbanded shortly after the drought, when there was no longer a need to meet. In the time between the droughts, some members continued meeting to strategize on projects and management. Others formalized partnerships and studies were born out of the meetings, including a group looking at how climate change will affect water providers and their preparation to deal with associated challenges. During the 2012 drought, many of the groups resumed, but with a different objective than the previous drought. In 2002, the main purpose of the group was to communicate management and restrictions to geographically similar customers to avoid confusion, a role that was filled by mechanisms the DTF developed. Providers who were part of these groups conveyed that they were able to learn from others and replicate successful management techniques. Some providers mentioned that attitudes of their board and managers had shifted due to regional pressure because there had been a culture shift and some practices were no longer acceptable to partners.

Similarly, formalized partnerships were born from informal, local collaborations. Water providers in the South Metro area use non-tributary groundwater as their primary source, so they were uniquely unaffected by the drought. However, after the drought many also began teaming up to develop reservoirs to diversify their supplies. Because they have a 'drought-proof' source, they also were part of a collaboration launched by Aurora, Denver Water, and the South Metro Water Supply Authority (which is made up of ten south metro water providers). The Prairie Waters Project is a water trading agreement designed to utilize available resources to benefit each participating water provider by sharing supplies and infrastructure capacity to reduce groundwater reliance and bolster renewable supplies to the South Metro area while maximizing the use of existing water assets belonging to Aurora and Denver Water[22].

Informal emergency response collaborations (see above) had little effect on management following the drought period, other than to serve as assurance for backup supply during worst-case-scenarios. Communities with such agreements did not report additional interactions or actions taken after the initial agreements were made, with one exception. One water provider reported a severely compromised intake system during the 2012 drought due to sedimentation from fires in the watershed. They initiated a water swapping agreement with a neighboring agricultural ditch company who had alternative cleaner water sources and could use the sedimentous water. Following the crisis, the partnership blossomed to a regional working group with other local water providers, researchers, and non-profits to investigate potential for future water swapping agreements.

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[22] http://southmetrowater.org/wise-partnership/

EFFECTS OF INSTITUTOINAL PROCESSES ON WATER PROVIDER MANAGEMENT

The two objectives of this study were to evaluate how institutional processes responded to a severe drought and how these processes facilitated learning among water providers, reflected in changes in their water management. As outlined above, during water provider interviews they outlined each management action along with why those decisions were made, providing a causal map of decision-making. While all of the institutions investigated in this study affected management in some ways, the objective of this study was to investigate how managers interacted with formal and informal learning processes to understand specific mechanisms that affected their management.

As described above, each water provider's management strategies were evaluated to determine if their changes represented a significant change in management, towards an 'adaptive' style, or whether actions they took were refinements of existing strategies. The full table of results can be found in Appendix 3.3. Next, to elucidate if their interaction with institutional processes affected their management, a crisp-set qualitative comparative analysis (csQCA) was employed. Performing a csQCA involves creating a binary data matrix with each case as a row of true or false (0/1) values, assigned for each variable (Kent 2008, Schneider and Wagemann 2010). Therefore, if the water provider indicated that they engaged with an institutional process, they were scored as a 1. The processes were: formal processes to increase management options (M); formal drought impact mitigation processes (D); and informal provider networks (I).

A means of quantifying adaptive behaviors toward drought and responses following drought is testing causal relationships between conditions and outcomes. The analysis of necessary conditions to achieve a change in management among water providers interviewed in the SPRB tells which institutional processes (or combinations) water providers *must* interact with in order to have changed their management. To identify causal relations between conditions and outcomes, QCA uses two tests: necessity and sufficiency. Necessity and sufficiency are asymmetrical relationships that can be tested analytically (Seate et al. 2015). *Necessity* is when the cause must be present to produce the outcome, but presence of the cause doesn't always ensure the outcome's presence. This type of relationship is described by Ragin (2000, 2008) as indicative of the outcome being a subset of the cause (e.g., episodes of rain are a subset of episodes of clouds. You can have clouds but no rain but not rain without clouds.), or more simply, if the outcome is present, the condition is always present. In practice, conditions are identified that are shared by cases with the same outcome (Ragin 2008, Kane et al. 2014). Figure 3.3 illustrates a hypothetical example where condition X is a necessary condition for management to change because all cases with condition X are also members of the set of cases where the outcome is present (Kane et al. 2014). *Sufficiency* is when cause A produces outcome Y, but the outcome can be produced by other causes as well — If A is present, Y is present (or A is a subset of Y) or if the condition is present, the outcome is present. Seate et al. (2015) gives the example that plants outside in the rain are a subset of plants that are watered, but they could have been watered in other ways. So plants that are outside in the rain is sufficient for plants to be watered. Figure 3.3 shows that multiple and different combinations of conditions can produce the outcome in question. Schneider and Wagemann 2010) explain that a condition is sufficient if always when the condition is present, the outcome is also present, making the condition a sub-set of the outcome. Differing is a necessary condition, where if the outcome is present, the condition is always present, making the necessary condition a super-set of the outcome (Ragin 2000).

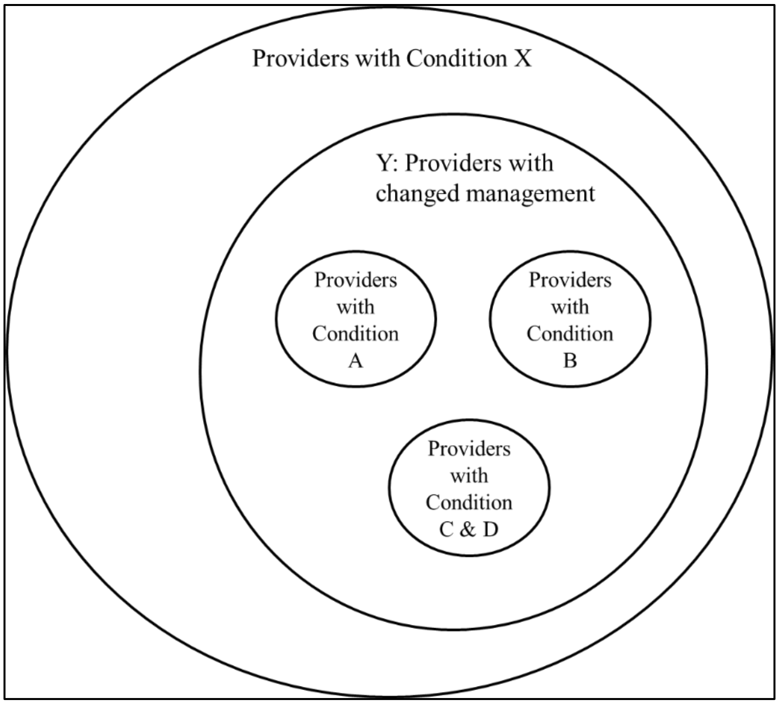

Figure 3.21. Necessary and sufficient conditions for set-theoretic relationships (adapted from Kane et al. (2014))

Each of these tests yields two parameters of fit: consistency and coverage. Schneider and Groffman (2006) explain that, although not entirely analogous or mathematically similar, the consistency value is conceptually similar to the significance value of inferential statistics and coverage values share some characteristics with r^2 values in regression analysis. *Consistency*, ranging from 0-1, is the degree to which the data support the set-theoretic claim. It can be thought of as the proportion of cases that with the given causal combination and the outcome set (Seate et al. 2015). Ragin (2000, 2008) suggests that for a cause to be necessary, the consistency score should be as close to 1 as possible, but scores above 0.90 are acceptable and for sufficiency, consistency scores greater than 0.80 provide acceptable evidence that the cause is a subset of the outcome. *Coverage* represents the proportion of cases with the outcome are represented by a particular causal condition, or the conceptual equivalence of the 'total variance explained.' When coverage of a causal pathway is high, the more common the solution is and the more the outcome is accounted for by the pathway (Kane et al. 2014). There is often a tradeoff between consistency and coverage that must be balanced. A causal combination with high consistency and low coverage means that high proportion of cases with causal combo have the outcome but it isn't a very high proportion of the overall cases (e.g., when I drink a martini, I get drunk most of the time, but I don't often drink martinis). This solution isn't very compelling because it doesn't describe many cases. In contrast to a causal combination with low consistency and high coverage, indicating that a high proportion of the cases have the causal combination, but the outcome doesn't occur often enough to make a strong causal argument (e.g., I often drink martinis, but I rarely get drunk, so it is difficult to determine if it is because of the martinis).

Consistency and coverage were calculated using the R package, QCA (Thiem and Du 2013). For this study, a consistency score of 0.80 was used as a threshold for accepting a condition as being necessary (Emmenegger 2010, Hamidov et al. 2015). Results indicated only one condition, involvement in informal provider networks yielded a 'significant' consistency score to be deemed as a necessary condition for a provider to shift to a more adaptive form of management on its own (displayed in Table 3.2). Interpretation of this score means that, of water providers who changed their management between the drought periods, most of them were involved with some form of a provider network. However, a lower consistency score means that, although most providers who were involved with informal networks changed their management, there was only a moderate proportion of providers who engaged with this process.

An additional pathway that did not meet the cutoff for consistency, but had a high coverage score was involvement with BOTH processes to increase management options AND drought impact mitigation processes. This pathway can be interpreted as many water providers engaged with both formal processes to increase management options, but a change in management didn't occur often enough to make a strong causal argument.

Table 3.4. Analysis of necessary conditions

Conditions tested	**Consistency**	**Coverage**
(I) Informal provider networks	0.833*	0.667
(M * D) Processes to increase management options AND drought impact mitigation processes	0.667	0.889
* indicates conditions with consistency > 0.80		

Sufficiency analysis was also performed to determine which individual conditions or combination of conditions would be sufficient for achieving the outcome. It is possible that simultaneous occurrence of the conditions might be sufficient for the presence of the outcome, so combinations of conditions using logical AND / OR (displayed as * symbol for AND, + symbol for OR).

Results of the analysis also revealed the same two causal pathways that were sufficient for the outcome to be present: engagement with informal provider networks; and interaction with BOTH formal policies to affect management AND drought impact mitigation (see Table 3.2, below). The solution[23] coverage of 0.688 indicates the proportion of providers that changed their management that have either of the two configurations, so most providers who changed their management were involved with one of the two causal pathways. The solution consistency of 0.917 gives the proportion of providers with either configuration that obtains the outcome of a highly effective intervention, indicating that almost all providers who were involved with those mechanisms changed their management. Interestingly, the mechanism M*D had a much higher

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[23] Solution consistency and coverage are metrics that measure the overall consistency and coverage scores for cases interacting with either causal pathway. Raw consistency and coverage are for individual mechanisms.

consistency score (1.000) but the solution I had a much higher coverage score (0.833) (see Appendix 3.4 for the truth table, showing full causal combinations for all water providers). This tells us that while more providers who changed to adaptive management styles interacted with provider networks, of those who did engage with management option mechanisms and drought impact mitigation, all switched their management.

Table 3.5. Sufficiency Analysis

Solution	**I**	**+**	**M * D**	**↔**	**Management Δ**
Covered cases	4, 9, 12, 16, 17, 18, 23, 1, 5, 14, 20, 7, 2, 15, 21		25, 2, 15, 21		
Ray consistency	0.667		1.000		
Raw coverage	0.833		0.333		
Solution coverage		0.688			
Solution consistency		0.917			

Sufficiency analysis tells us if a water provider interacted with a given institutional process (or combinations of processes), that can essentially be interpreted as a proxy for change in their management. However, having two causal pathways, one with high coverage / low consistency and the other low consistency / high coverage is an unsatisfying result. Chapter 2 grouped water providers into clusters, based on the types of changes they made to their drought management. To fine-tune the analysis and look more specifically at *how* interaction with these institutions affected management, sufficiency analysis was repeated for each of the groups from Chapter 2. To summarize the primary strategy choices by the different types of group: Group 1 primarily augmented their planning-related efforts, relying on ‘softer’ approaches; Group 2 focused on securing their water supplies and promoting active demand management; Group 3 exclusively built new reservoirs; and Group 4 did nothing (and was thus excluded from this analysis because QCA cannot be performed with an empty table). Table 3.3 shows that all Group 1 providers who altered towards adaptive management interacted with informal provider networks. While this result is unsurprising, since the primary management changes performed by this group were to become more adaptive through planning-related efforts, it does show a relationship between the two processes. More interestingly, two causal pathways led to management changes for Group 2: Interaction with drought impact mechanisms AND interaction with mechanisms to increase management options (particularly the Conservation Act) as well as interaction with drought impact mitigation AND informal networks. Both of these pathways reveal a significant interaction with drought impact mitigation, discussed more below. Lastly, neither provider in Group 3 switched their management but one did report collaborating with other water providers informally, revealing that for this group that alone does not lead to changes in management.

Table 3.6. Provider group sufficiency analysis

Solution	**I**	**+**	**M * D**	**+**	**D* I**	↔	**Management Δ**
	Group 1		Group 2		Group 2		
Consistency	1.000		1.000		0.750		
Coverage	0.875		0.750		0.750		
Group 3			I			≠	**Management Δ**

These results reveal that there were likely a number of different mechanisms underlying these institutional processes that caused them to affect management differently. The discussion of reasoning associated with management changes allowed for a qualitative assessment of how institutions affected management, and isolation underlying mechanisms that contributed to those changes in management.

ROLE OF POLICY AND LEARNING PROCESSES ON WATER MANAGEMENT

While the first objective of this study was to evaluate key institutional processes (formal policy and informal learning) that affected drought management of water providers following the 2002 drought, the second objective looked at how providers who changed to adaptive management styles interacted with those processes, revealing that different types of providers interacted with the processes differently. By investigating how providers engaged with the institutional processes differently, a better understanding of the interplay between formal policy processes and informal learning processes led to an overall increase management resilience the SPRB following the 2002 drought.

Most Group 1 water providers who altered their management also reported a high rate of interaction with informal provider networks, revealing that this to be a significant institutional pathway to achieve more forward-looking water management. Many of these water providers reported that their actions ‘institutionalized a culture of conservation’ among water users who, prior to the drought expected reliable water delivery, but after became accustomed to conservation due to restrictions and education efforts. Figure 3.5 is a stylized sequence of events between the creation of the institutional processes evaluated above and their effects on water management, showing how this pathway led to management changed through cultural changes[24]

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[24] A culture shift wasn't measured, but was mentioned by several water providers as an outcome of the drought effects and permanent conservation measures that were implemented after. They were drawing comparisons from water use and management prior to the 2002 drought. The 1980s and 1990s were a wet period, with above average snowpack and rainfall. Coupled with lower populations, there was abundant supply for high per capita demands. Anecdotally, since there was no severe drought in recent memory and much of the population growth was not from western states, many water users had never been required to conserve water. Additionally, many water providers had 'increasing block' rate structures, based on economies of scale, which incentivizes more water use. Following

of water users as well as among water providers themselves, due to regional pressure. As discussed above, the informal collaborations that led to formal partnerships and supply-augmenting projects was also a unique characteristic of Group 1 water providers.

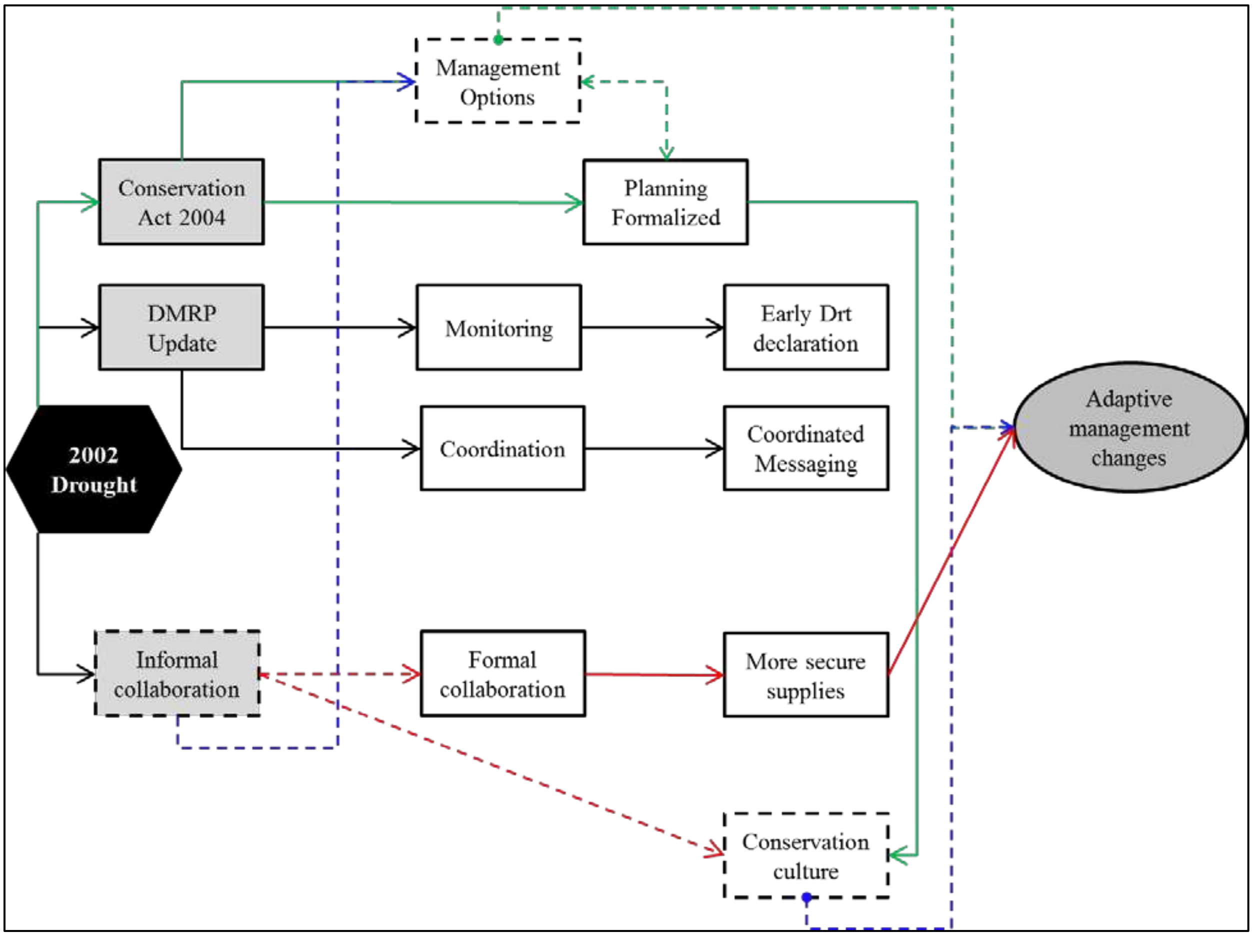

Figure 3.22. Stylized institutional processes and their effects on water providers. Grey boxes represent processes specifically investigated in this study. The three key processes each led to two mechanisms water providers reported affecting their management. Formal policies to increase management options resulted in: more management options and formalized plans, both of which helped created a local conservation culture among water users. Drought impact mitigation processes led to increased monitoring and coordination. Solid lines represent formal policy processes and dashed lines represent informal learning processes. Line color represents pathways used by different water provider groups. Red is Group 1; Green is Group 2; Blue is both Groups 1 and 2; and Black was not described by either.

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the drought, demand did not rebound, which water providers attribute to a new 'culture of conservation,' where water users understand the scarcity of the resource and conserve when necessary and water managers promote efforts to conserve.

Water providers who changed their management in Group 2 tended to interact differently with the institutional processes. A significant portion reported that formal policy processes designed to increase their management options, specifically the Conservation Act of 2004, led to a shift in their drought management (as is illustrated in causal maps in Appendix 3.2 as well as the QCA). Although it wasn't entirely the intent of the bill, drought management was largely formalized due to requirements of the Conservation Act of 2004. The experience that water providers underwent during the near catastrophic 2002 drought served as an impetus for the shift towards conservation, but the requirement to formalize conservation plans institutionalized the strategies where they would be accessible for later use. This formalization also led to more management options to draw from in subsequent droughts, also leading to a change in culture reported among users.

These two separate pathways help understand the role of formal and informal processes in the different institutional mechanisms that led to change in water provider management. A leading assumption of Pahl-Wostl et al. (2013) was that higher levels of learning that lead to adaptive and transformative management require informal settings, but are only effective when they are connected to formal processes (Pahl-Wostl 2009). Berkes (2007) concurs, cautioning that the social memory only lasts about 20 years individuals, however if events are encoded in "institutional memory" through the creation of new, formal policies, they will be longer lasting. Culture changes were created due to formalization required to meet HB04-1365 requirements, but a culture change among water managers was also created through informal learning processes, established within informal provider networks. The formation of informal actor networks plays an important role in the early phases of change (Olsson et al. 2006) because informal settings provide space for experimentation, which can lead to the revision of assumptions and paradigms (Pahl-Wostl et al. 2013). Greater interaction among providers created a sort of peer pressure to use more adaptive management techniques. Additionally, the formalization of sub-regional processes that sprung up from informal provider networks caused a shift towards more regional cooperation and forward-looking management. Informal institutions were changed and permeated the decision-making landscape, so that water providers' paradigms about water management were changed, having a greater impact than the changed landscape of strategies available. The interaction between formal and informal processes demonstrates that both led to and were perhaps needed to create positive management outcomes because they each provided agility and learning following the 2002 drought.

In a similar analysis of the 2002 drought in the Yampa White River Basin, in northwestern Colorado, McNeeley (2014) found that local social capital prevented curtailments of water rights due to trust and cooperation that was present at the time. The author describes that, 'social capital is the informal relationships and social networks, agreements, flows of information and features of social organization such as trust, norms, and networks that facilitate coordinated actions' (Adger et al. 2003) and cooperation through strong social capital built through relationships and trust is a central component of adaptive capacity (McNeeley 2014). Due to decades of high population growth, competing interests, and sufficient supplies this social capital was either missing or dormant in the SPRB. However, examples demonstrate how social capital was developed during and after the 2002 drought, then called upon during the 2012 drought.

Overall the formal drought impact mitigation policy processes did not have a strong impact on water management, but it is attributed by some to an improvement in regional coordination and early response. It serves as an outlet for cross-scale communication between federal, state, and local governments, as well as between experts / academics who sit on the task forces and water managers. Although it doesn't have a perfect reach, it is an improvement to regional coordination issues, and more importantly, it has a mechanism for refinement through a requirement for regular updates. However, the awareness brought on by the drought and collaboration among water providers as well as efforts by state processes to improve drought impact mitigation increased physical capital available to manage droughts. Ellis (2000) outlines the role that institutions play in shaping the strategies used by individuals (or organizations) to manage crisis, much of which is mediated by access to capital. The drought impact mitigation efforts improved coordination and access to information, which is an asset that increases adaptive capacity.

INSTITUTIONAL BARRIERS

Although these are examples of institutional success, where they acted as drivers to change, analysis revealed significant institutional barriers for some water providers. Water providers who were closer to the Denver metro area and served larger communities were targeted by all of these institutional changes and received the benefits of improved management through participation. While these institutional mechanisms worked to improve drought management for water providers in Groups 1 and 2, this wasn't the case with all types of water provider. One Group 3 provider also collaborated closely with others, but did not change their management.

The creation of formalized water conservation plans did affect those who did them, but some water providers who do not fit the definition of a 'covered entity' did not create conservation plans and didn't see the benefits they provided. These water providers were primarily those that are very small (they sell less than 2000 AF annually) and they had the exact opposite effect of those that created the conservation plans, they did not change their water management at all after the 2002 drought, further confirming that the plans did affect water management. Interviews with providers and state officials also revealed a lack of interaction between the drought impact mitigation mechanisms and rural providers, largely due to a lack of capacity to attend or call in and being disconnected from the metro area.

While the reasoning for the exclusion of small providers from this requirement was to ease the regulatory burden on entities that do not have the capacity to create these plans, it is these small, rural providers who also are less likely to be involved in with the formal policy or informal learning processes, making them potentially more vulnerable. In the future including smaller and rural water providers in legislation to bring them up to regional expectations, while providing resources would reduce their vulnerability to droughts.

Although the cultural shift of both water users and managers towards conservation proved to be an asset in the 2012 drought, in a study of drought preparedness of water providers in Arizona, Engle (2013) presents a similar phenomenon as a barrier to adaptive capacity because it provides little incentive to transform. The author concludes that there is a prevailing perception among providers that a conservation ethic is sufficient to address long-term problems and needs, but this attitude could limit them from responding quickly and changing course when droughts become intense beyond previous experiences.

> *"While they are well prepared for current droughts and have built the adaptive capacity to weather these events, lock-in may prevent them from moving beyond a culture of conservation and towards a culture that is well prepared for climate change"* (Engle 2013).

If not provided appropriate incentives to look forward and plan for all future scenarios (not just based on past experiences), the culture of conservation mentioned as an asset by many SPRB water providers could be an institutional barrier as well.

CONCLUSION

Because the SPRB is expected to undergo significant future changes, exacerbating current water management challenges, evaluation of institutional changes that improved drought management following the 2002 drought offers useful lessons for incentivizing more adaptive water management and provides a better understanding of levers to pull to enable more robust system transformations in the future. Assessment of how existing institutions were altered after the drought and their effects on management revealed the most significant underlying mechanisms were: formalization of management strategies, better mechanisms for communication and monitoring drought conditions, and informal collaborations that led to a culture change among water providers and the communities they serve. Informal mechanisms provided learning opportunities for water providers to change their management to be more agile and responsive to subsequent droughts, but interactions with formal institutions also create learning opportunities, revealing that variety in institutional mechanisms is needed to reach such a diverse group of water providers

These findings tell us that while much of the burden of drought preparedness still falls on operational management, state agencies play a significant role as well in preparing for future stress and institutions, both formal and informal, facilitated more robust drought management. While water providers were still scrambling to help their systems rebound, State agencies were able to do robust assessments of drought impacts, and the drought response that most providers would have been unable to do. They used this learning to help make coordination and response systems more robust, which worked to both improve information water providers had, and the relationships that they had with the state. Additionally, legislative actions to mandated efficiency, forcing water providers to reassess their management, learn from the past and try to understand their future vulnerabilities.

Both of these efforts, as well as the experience of the drought itself shifted the risk perception of water providers (and users), leading to a 'culture of conservation.' As pointed out above, a culture that promotes conservation can be a double-edged sword, allowing water providers to stretch their supplies further, but attitudes that efficiency is sufficient may prevent them from taking more drastic measures if future droughts and shortages are more severe or present themselves differently than the past.

While many water providers have efficiency plans in place and are certainly thinking about drought management, when asked, most water providers did not have official drought plans in place and do not consider climate change in their drought planning. As a next step, state agencies could advance drought preparedness by promoting more coordinated efforts for drought-specific response focusing on future scenarios of population growth and climate change. Additionally, efforts to work with the small group of water providers who were neither required to develop a conservation plan nor interacted with the DTF, would help ensure a more even drought preparedness regionally.

Although there is an improved understanding of how policies improved water management response during droughts, the methodology was imperfect because the two drought periods were not entirely comparable. While the 2012 drought was severe, it was what is considered a 'flash drought,' an extraordinarily dry period that comes on very quickly. The 2002 drought was only in the most severe stages for the same length of time, but the region had been abnormally dry for two years leading to the drought, causing reservoir levels to dwindle. This difference means a one-to-one comparison is not possible, which is why overall effects were discussed generally and mean impact scores over the two time periods were not compared.

Generalizing findings from this study should be done cautiously. Although the nested comparative case study design was entirely appropriate for this study, analysis was performed within the context of the SPRB and findings may not be generalizable to other regions or even other basins within the same region (e.g., findings from the McNeeley (2014) study were not comparable to this basin because of quite different contexts in which the two river basins lie). Although efforts were made to get a representative sample, only a subset of water providers were interviewed, so there are gaps in the coverage of water provider types and a response error is likely because those more invested in management were more likely to accept interview requests.

Additionally, while the IAD is a useful tool for accounting for multiple levels of decision-making, it does have some weaknesses. Despite its account for multiple levels of decision-making, Kadirbeyoglu and Özertan (2015) note that the framework neglects the impact of power distribution among users, which is an important factor for resource management generally, but is a central factor governing the use of water in Colorado, particularly.

Within Colorado, water providers are still trying to learn from these events and improve upon their management. This study is useful because the 2012 drought provided an ideal opportunity to test management techniques established and engage in adaptive learning. However, few providers or policy makers have the capacity to perform that type of evaluation, therefore highlighting policies that led to better management and more sustainable cultures that will help direct policy-makers in the future.

The field of institutions and adaptation is still in theoretical infancy. This study adds empirics to the field and tests theory on the role institutions play in fostering adaptation. They are responsive to crises and transform system by formalizing coping strategies into adaptations that are available in the future. In this way, crises, such as droughts, can actually be used as tools to catalyze adaptation and increase resilience.

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CHAPTER 4: CHARACTERISTICS OF DROUGHT CONDITIONS IN THE SOUTH PLATTE RIVER BASIN UNDER FOUR FUTURE CLIMATE SCENARIOS

INTRODUCTION

Assessments of climate impacts in the United States say that drought may become more frequent and severe in the coming decades (Christensen et al. 2007, Morgan et al. 2008, Coles and Scott 2009, Western Water Assessment 2011b, Gordon and Ojima 2014). A study by Gordon and Ojima (2014) on climate change vulnerability in Colorado shows a trend towards more frequent soil-moisture drought conditions over the past 30 years and says ‘projections more clearly indicate droughts becoming more frequent and intense by mid-century’. In 2011, the Western Water Assessment conducted a similar study on Colorado’s climate preparedness, finding that ‘droughts are likely to become more common and more intense as regional and seasonal patterns change’ (Western Water Assessment 2011b).

While this provides water managers and planners with an understanding that water supplies that are available today may be less reliable in the future, there remains a vague understanding of how drought conditions could change (e.g., will the most severe drought on record occur with more frequency, or will droughts remain the same in severity be last longer?). Interviews with water planners (see Chapter 2) show uncertainty about whether they should plan for future droughts that are unimaginable or if planning within the range of variability historically experienced will be sufficient, a range that encompasses planning paradigms.

Drought is a frequent visitor to Colorado (Mckee et al. 2000), with single season droughts occurring most years in the state. Mckee et al. (2000) found that droughts with a SPI-3 (see explanation below) value of -1 or lower (the equivalent to a moderate precipitation deficit) historically occurred 90% of years in any given location in the state. However, historically, droughts are relatively short, with multi-year droughts occurring infrequently.

Since a severe drought occurred in the SPRB in 2002, Colorado has revised its drought monitoring and planning to better prepare water managers for future droughts (Colorado Water Conservation Board 2004b, 2010). New mechanisms were established to monitor water supplies and multi-sector drought response protocols were developed (see Chapter 3 for details). However, limited information remains about the potential frequency or severity of future drought conditions, adding difficulty to planning responses to such events.

The objectives of this study were to investigate the characteristics of historical and future droughts and, using univariate and multivariate analysis, evaluate how they may change in future scenarios. Univariate analysis was used to calculate drought characteristics for return periods during future and historical climate periods. Copula functions were then used to calculate multivariate probabilities drought characteristics will exceed historically extreme thresholds.

METHODS

Scenario planning

Scenario planning serves as a tool for resource managers to understand potential climate change impacts and uncertainties and plan for a range of plausible conditions (Fisichelli et al. 2016b). Organizations who use the past to understand how the future will unfold or focus solely on incremental changes to develop long-term strategic plans may find themselves caught off guard, however scenario planning is a process to help organizations make sense of potential changes coming their way (Lorenz et al. 2016). The process doesn’t aim to predict the future, but instead develops a series of plausible futures and encourages participants to deliberate how they can best prepare for each of the futures. Thinking strategically about what future challenges may exist allows organizations to develop a long-range strategic plan, and develop strategic, actionable decisions that can be refined as needed (Star et al. 2016). Scenarios help managers plan for low probability, high consequence events (e.g., multi-year droughts where the watershed has been severely compromised by fire) and plan around those. It is useful for planning around stress events before they occur, allowing managers to perform contingency planning and orchestrate deployment of assets more effectively, rather than reactively.

Scenario have been used by governments and commercial for over 50 years and are becoming a regular and accepted part of climate change adaptation planning due to their value in situations of high uncertainty (Star et al. 2016). For example, in 2016 the Department of Defense (DoD) released a report outlining their process (in one of the most expansively publicly-released efforts to date (The Center for Climate and Security 2018)) for developing scenarios of sea-level rise that can be used for coastal risk management. Because the U.S. military infrastructure depends on climate and coastal stability, changes to climate and sea-level may become strategic vulnerabilities due to risks to coastal military infrastructure and could affect their ability to deter enemies, defend interests, or support allies (Hall et al. 2016). To adjust to the ‘rapidly changing’ theater, five global sea-level rise scenarios were created during three future time horizons (2035,2065, and 2100) for 1,774 DoD sites globally (Hall et al. 2016). From these scenarios, the plausible range of risk for coastal managers was evaluated, from which decision-makers were able to ‘game out’ key decisions to be made. The National Park Service performs similar scenario planning activities with park managers to assess how park resources may be impacted under climate scenarios. Using these scenarios, park managers develop adaptation strategies that mitigate harmful effects. National Park Service (2013) provides guidance on using global climate models (GCMs) to develop scenarios that capture the range of uncertainty affecting resource responses to climate change. This study uses these scenario planning tools to evaluate the probability of drought conditions in future periods in Colorado's South Platte River Basin (SPRB).

Standard Precipitation-Evapotranspiration Index

Droughts are sometimes referred to as "creeping" disasters that are difficult to understand, prepare for, or respond to. It is difficult to forecast their onset or duration, as droughts are not distinct events with a recognizable start or end. Many variable and complex factors determine droughts, but they generally begin with a "meteorological drought" (a period without rain) that is followed by a "hydrologic drought" (shortages) (Grigg 2005). Indices have been developed to assimilate precipitation, temperature, streamflow, and other measures of water supply into a single number that helps determine meteorological drought characteristics in a way that is useful for decision-making (Hayes et al. 2007). A number of indices exist – each with its own merits and limitations, which have been debated by drought scholars –the Standardized Precipitation-Evapotranspiration Index (SPEI) is used in this study to determine characteristics of drought periods.

SPEI is a multi-scalar drought index, based on precipitation and potential evapotranspiration (PET), that is used to determine wet and dry periods in a given location (Vicente-Serrano et al. 2010). The inclusion of temperature makes SPEI particularly well suited for evaluating combined effects of changes in warming and precipitation. Index values are determined by calculating a climatic water balance, the accumulation of deficit/surplus at various timescales (Vicente-Serrano et al. 2010). SPEI has an intensity scale in which positive and negative values are calculated, identifying both dry and wet periods: where values of zero indicate average moisture balance, positive values signify above-average wetness, and negative values represent drier than average conditions. Similar to its predecessor, the SPI, SPEI uses a probabilistic approach, requiring long-term precipitation and temperature records, typically at least 30 years (Vicente-Serrano et al. 2010).

Calculation of SPEI is based on the original Standardized Precipitation Index procedure, where monthly difference between precipitation and PET is the input data (the difference is the climatic water balance). A number of methods exist to calculate PET, the amount of evapotranspiration that would occur if a sufficient water source were available (e.g., Penman-Monteith, Thornthwaithe, Hargreaves). Because of the limited number of climatic variables available for global climate models, the Thornthwaite equation was used to calculate historical and future PET (Thornthwaite 1948, Buytaert and Bievre 2012). Once the value for PET is obtained, the difference (D) between precipitation (P) and PET for the month (i) is calculated:

$$D_i = P_i - PET_i$$

providing a simple measure of the water surplus or deficit for the analyzed month (Li et al. 2015). The values for D are aggregated at different timescales, discussed below. SPEI variables are then standardized using a log-Logistic distribution function so that mean values are 0 (Vicente-Serrano et al. 2010, Vicente-Serrano and National Center for Atmospheric Research Staff 2015). For this analysis, both PET and SPEI were calculated using the R package SPEI, which was developed by the creators of the indicator (Beguería and Vicente-Serrano 2017).

Because relevant timescales differ among processes (e.g., processes affecting agriculture happen on the order of a couple months vs processes affecting the rates that reservoirs dry up occur over several months to years), the SPI (and consequently SPEI) was designed to be adjustable to the user’s timescale preference. It can be calculated for time steps from 1 to 48 months (timescales can indicate the effects of drought differently and the period selected should be on the order of what is appropriate for decision-making). So while SPEI-3 measures rainfall conditions over a 3-month period, and is useful for studying impacts on soil water conditions or agricultural production, SPI-24 would measure rainfall conditions over two years and would be useful for showing effects of prolonged wet and dry periods on groundwater or large bodies of water. For this study, the 6-month SPEI (SPEI-6) was selected because it is consistent with the timeframes in which water providers consider droughts to be significant and it matches timeframes used to evaluate water provider decision-making in Chapter 2.

Study Area

The SPRB experiences moderate droughts regularly and severe droughts about once every 20 years, on average (see Figure 4.6). While the focus of this entire dissertation is on the SPRB broadly, this analysis focuses on a central and significant location within the region, Greeley, CO (see Figure 4.1). Greeley was selected because of its central location in the basin as well as its proximity to the South Platte River and its prominence as the agricultural center of the region. The location has a mean temperature and precipitation similar to the regional mean, making it a suitable proxy for the basin, when doing analysis of a single area.

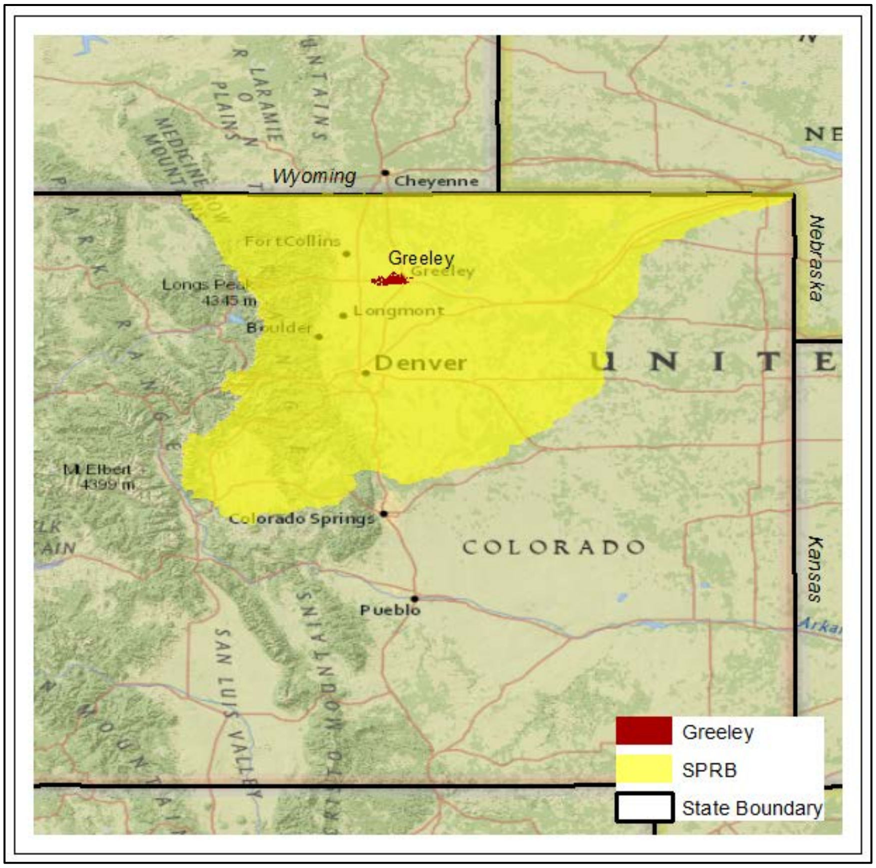

Figure 4.23 South Platte River Basin in Colorado. Greeley (in red) is used as the location where climate data was derived for use in this study

Climate Data

CMIP5 climate data (daily precipitation, maximum temperature, and minimum temperature) were obtained from the Multivariate Adaptive Constructed Analogs (MACA) gridded dataset, available at 1/24 degree (~4km) resolution (Abatzoglou 2011). The MACA downscaling process is a statistical downscaling method based on the assumption that when daily weather is processed over a period of time, long-term climate trends emerge, and if climate is processed long enough, climate changes will occur. This technique enables modelers to process the core determinants of climate change, rather than imposing a statistical correction on monthly data. Due to its use of a historical library of observations and a multivariate approach, this method has been shown to be preferable to direct daily interpolated bias correction in regions of complex terrain (like those in the SPRB) (Abatzoglou and Brown 2012).

MACA climate data were downloaded for all grid cells touching Greeley boundaries and averaged (see Figure 4.1), based on two warming-climate scenarios (decreased future greenhouse gas emissions Representative Concentration Pathway (RCP) 4.5 and a business as usually, high emission, RCP 8.5 (Fisichelli et al. 2015)) and 20 global climate models. Climate data were analyzed for three time periods, historical (1950-1999), near future (2025-2055) and far future (2070-2100). Typically, it is preferable to use the same length of time for both the reference period and the future scenarios; however 50 years was chosen for the historical period due to the intervals between wet and dry periods. Using a 30-year reference period between 1950-1980 would have captured two significant droughts (in the 1950s and 1970s), drawing the mean SPEI down (average SPEI 1950-1979 is -0.09), while using the latter 30 years of 20th century (1970-1999) captures two historically wet decades (1980s and 1990s), showing a higher than average SPEI of 0.06. SPEI guidance (Vicente-Serrano and National Center for Atmospheric Research Staff 2015) recommends using a long base period (30-50+ years) that samples the natural variability, therefore applying a 50-year reference period smooths out those fluctuations, allowing future scenarios to be compared to an average SPEI close to zero[25]. Combined with the two time periods, this creates four future scenarios, two for mid-century (Near Future, RCP.45 – NF-45, Near Future, RCP.85 – NF-85) and two for end-century (Far Future, RCP.45 – FF-45, Far Future, RCP.85 – FF-85). Models were averaged for the scenarios.

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[25] SPEI is a measure of wetness/dryness. Zero indicates the mean balance between precipitation and evapotranspiration for a given area. Positive values signal above-average wetness and negative represent above-average dryness.

Estimating drought characteristics

Drought events were identified using SPEI values that were continuously below a certain truncation value (Shiau and Shen 2001). Negative SPEI values signify conditions that are drier than average, however to be considered a 'drought' conditions need to be significantly drier than average, so a truncation level of -1 was selected to mark a drought event. The "theory of runs," proposed by Yevjevich (1967) was used to determine characteristics of each drought event. Once drought events were identified for each period and scenario, drought characteristics – duration, severity, and intensity (peak) – were calculated for each event (see Figure 4.2). Drought duration is the number of consecutive months during which SPEI is below the truncation level. Peak is the minimum SPEI value during a drought event (or maximum drought level), and severity is the cumulative SPEI value below the truncation level for the duration of the drought event. The frequency of drought events, referred to as the "interarrival time" is the length of time (in months) between the start of one drought and the start of the next (Yevjevich 1967, Shiau and Shen 2001, Yang et al. 2009).

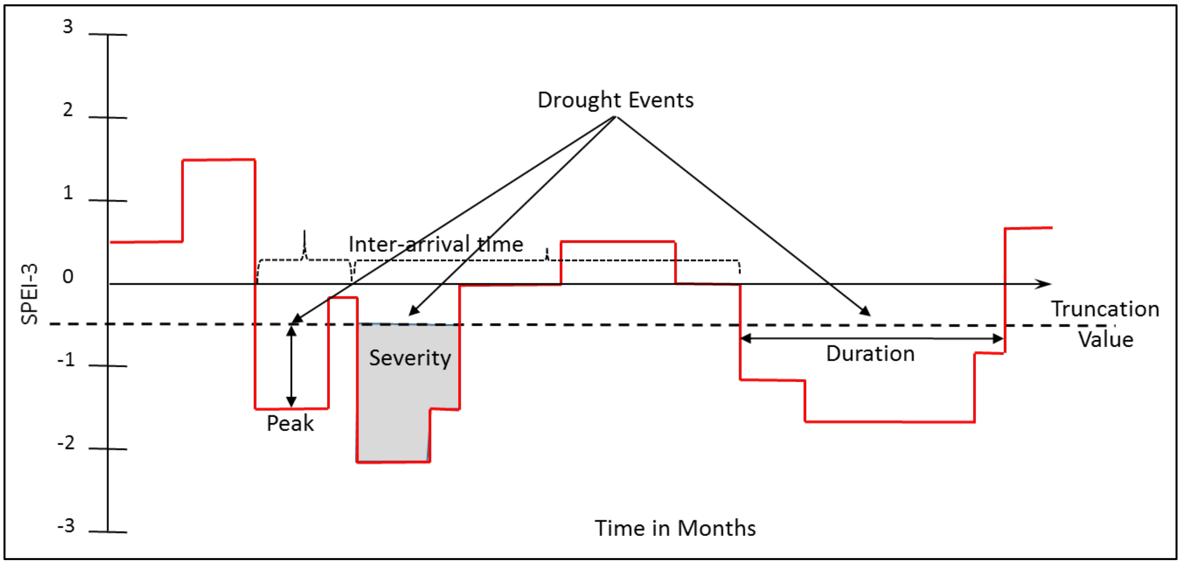

Figure 4.24. Drought characteristics defined by 'runs.' Adapted from (Shiau and Shen 2001).

Univariate and multivariate analysis

Return period calculation

Return periods are often calculated for extreme hydrologic events to meet design objectives for hydrological and hydraulic structures. A recurrence interval (return period) of a hydrologic event is described by (Haan 1997) as the 'average elapsed time between occurrences of an event with a certain magnitude or greater.' However, because droughts can last multiple years or may not occur in a given year, recurrence intervals are considered as the mean interarrival time of drought events (Shiau and Shen 2001). The interarrival time, illustrated in Figure 4.2, is defined as the time between the beginning of one drought event and the beginning of the next (Shiau and Shen 2001, Shiau 2006) and is estimated from observed droughts.

Shiau and Shen (2001) theoretically derive return periods for drought characteristics as a function of the expected drought interarrival time and cumulative distribution function of the drought characteristic, so the univariate return periods are calculated using the following equation:

$$T = \frac{E(L)}{1 - F(c)} \tag{4.1}$$

where T indicates the return period (in years) for the relevant drought characteristic, F(c) represents the cumulative marginal distribution function of the drought characteristic – duration, peak, and severity – and E(L) is the expected drought interarrival time (Shiau and Shen 2001, Janga Reddy and Ganguli 2012, Ekanayake and Perera 2014, Thilakarathne and Sridhar 2017).

Univariate analysis was used to calculate drought associated with 20-, 50- and 100-year return periods for the drought characteristics for the four scenarios: the two climate emissions scenarios, RCP 4.5 and RCP 8.5, during two time periods near future (2025-2055) and far future (2070-2100). For the observed historical period (1950-1999) and these four future scenarios, interarrival time was estimated and the characteristics were calculated for each drought event. Three commonly used discrete marginal distributions for duration (Poisson, negative binomial, and geometric) and four commonly used continuous distributions for peak and severity (Weibull, gamma, exponential, and lognormal) were selected as candidate distributions. The characteristics were then fitted to distributions using maximum likelihood estimation method and to obtain the cumulative distribution function and shape parameters were estimated. The best-fitting distribution was selected using Cramer-Von Mises test (Berg 2009) (see Appendix 4.1).

Joint distributions

Because drought characteristics are typically correlated (e.g., duration is correlated with severity), reporting estimates of drought return periods based solely on their marginal distributions can be misleading (Yang et al. 2009). Copula functions offer the advantage of effectively combining multiple marginal distributions into a joint distribution by constructing the dependence structure between variables when their marginal distributions are distinct (Thilakarathne and Sridhar 2017). Copulas offer the advantage of providing a methodology to model multivariate distributions by dealing with the marginal and respective dependence structure separately (Yang et al. 2009).

The joint distribution structure was modelled for the five periods (historical, near future / RCP 4.5, far future / RCP 4.5, near future / RCP 8.5, and far future / RCP 8.5) using five copulas[26] that are often good fits for modeling hydrological and extreme variables. The parameters of the copula function were estimated using the maximum likelihood method using the R package VineCopula (Schepsmeier 2015). Again, the Cramer-Von Mises test (Berg 2009)

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[26] Copulas tested were: Student t copula, an elliptical copula that is widely used to model hydrological extremes; Clayton, Frank, and Gumbel copulas from the Archimedean family and are also often a good fit for hydrologic variables; and the Joe copula.

was employed to assess the goodness of fit for the copula functions. The Joe copula was chosen for all joint distributions, except far-future / RCP 4.5, where the Frank copula was the best fit.

From this, the bivariate joint occurrence probability was calculated using an equation derived by Shiau (2006). The conditional distributions for the drought variables were derived from the bivariate copulas, where the conditional distribution of drought duration (D) given drought severity (S) exceeding a certain threshold, s’ is expressed as:

$$\begin{aligned} P(D \leq d | S \geq s') &= \frac{P(D \leq d, S \geq s'}{P(S \geq s')} \\ &= \frac{F_D(d) - F_{D,S}(d, s')}{1 - F_s(s')} \\ &= \frac{F_D(d) - C[F_D\,(d), F_S\,(s')]}{1 - F_S(s')} \end{aligned} \tag{4.2}$$

Constructing this conditional drought distribution allows for the probability that drought duration and severity will simultaneously exceed certain thresholds (e.g., the probability that a drought will exceed both the observed severity and duration of the 2002 drought).

RESULTS AND DISCUSSION

Changes in climate variables among scenarios

Because drought estimates using SPEI rely on temperatures and precipitation patterns, evaluation of how these climate variables shift under the future scenarios is important to understanding the underlying drivers in changing drought characteristics. Figure 4.3 shows the mean monthly precipitation in the study area. The month of May historically received the highest rainfall, averaging 60 mm. Future scenarios show an earlier peak in maximum monthly rainfall, demonstrating a future seasonality shift that may alter future water use (e.g., irrigation may be needed by mid- or early-summer, resulting in a potential mismatch with cropping needs). Future scenarios also show increased winter precipitation, particularly late winter. Traditionally this time of year is when most of the snowpack is accumulated, which could be beneficial for streamflow and filling reservoirs, unless coupled with warmer temperatures during this shoulder season, which could result in more runoff and water lost from the system. Comparisons between future scenarios show similar trends, but diverge in the amount and timing of summer precipitation decline.

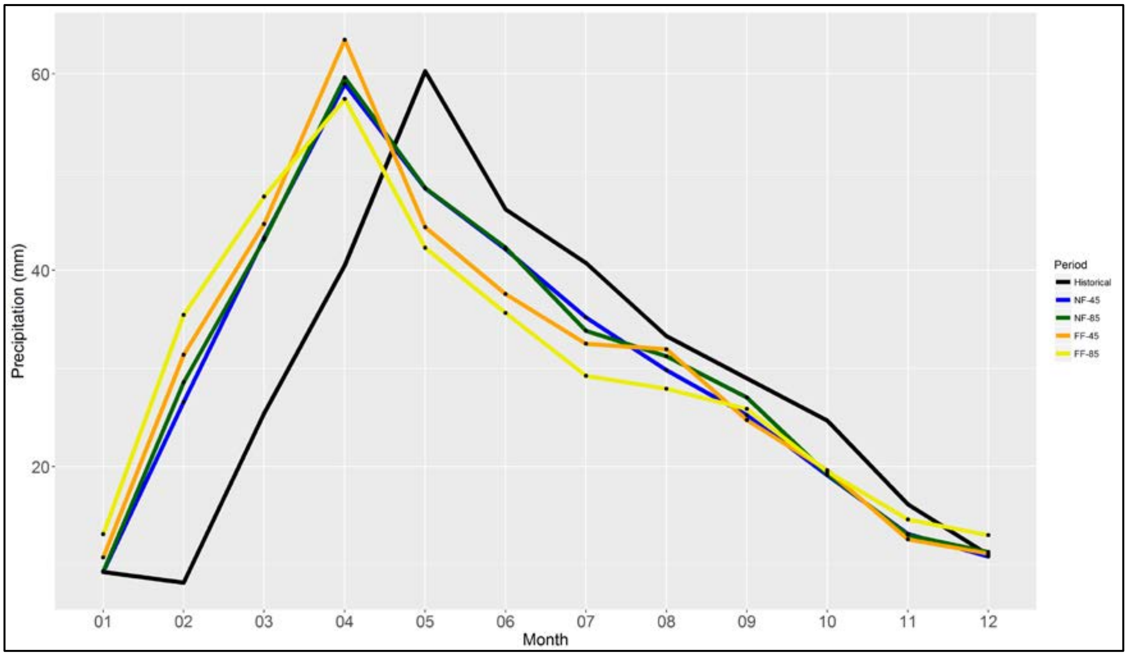

Figure 4.25. Mean monthly precipitation for historical period and scenarios. Scenarios: NF-45, near future, RCP 4.5; FF-45, far future, RCP 4.5; NF-85, near future, RCP 8.5; FF-85, far future, RCP-85.

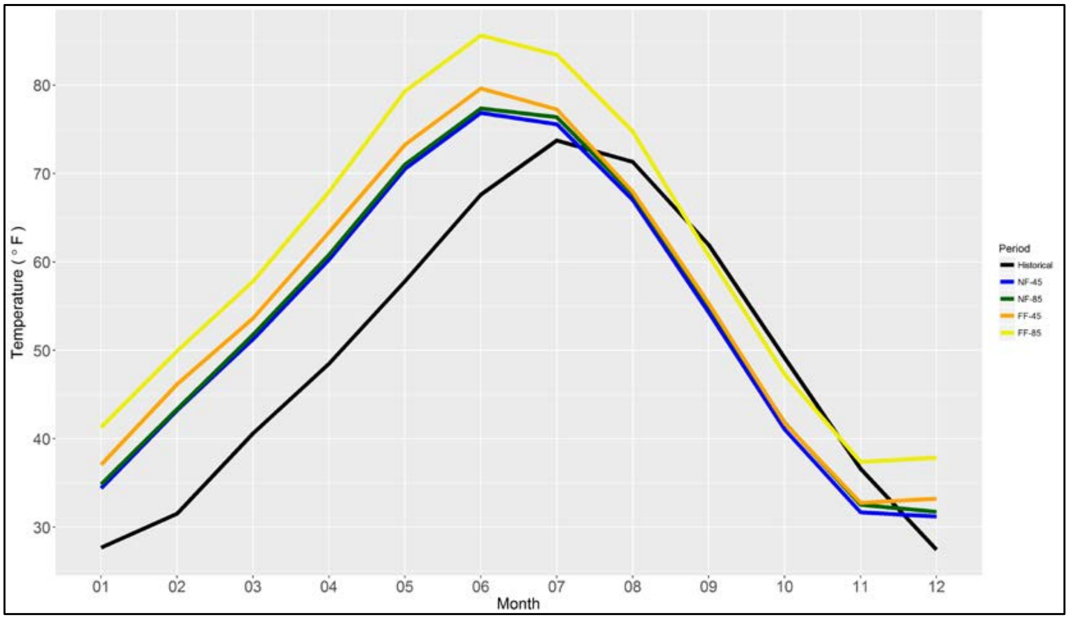

Figure 4.26. Mean monthly temperature for historical period and scenarios.

Differences between the scenarios and historical temperatures show a similar shift in seasonality. Winter and spring temperatures for all future scenarios are warmer by an average of 10 °F, but the warmest period is shifted from July and August in historical period to June and July in all future scenarios. The warmer temperatures could result in earlier peaks in agricultural irrigation and residential water use. Additionally, warmer late winter and spring temperatures could result in earlier snowmelt and lead to the gains in precipitation during that period to runoff sooner. On the other hand, all future scenarios show a decline in late summer and fall temperatures. Comparison between future temperatures shows a similar trend between all except FF-85, which is significantly warmer year-round.

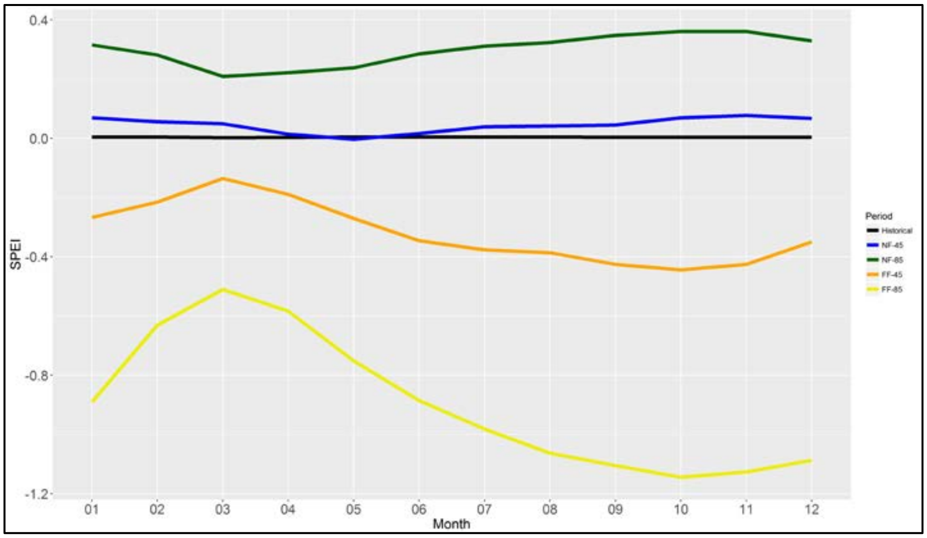

Figure 4.27. Mean monthly SPEI for historical period and scenarios

The combined effects of temperature and precipitation result in significant divergence between SPEI (drought) trends in future periods, illustrated in Figure 4.5. SPEI over the historical period averages to monthly values that are near zero because the period encompasses both extreme droughts and abnormally wet periods (discussed above), causing the monthly average to negate any differences. This is not unexpected for a long reference period of an indicator where 0 represents an average value.

However, future trends in temperature and precipitation result in divergent monthly SPEI averages with a high variability. Although precipitation is relatively similar for all future scenarios, FF-85 shows the lowest SPEI values (worst drought conditions), demonstrating that temperature has a greater effect on SPEI values than precipitation. What is important to note here is that the average SPEI for each of scenarios is shifting enough to change the whole distribution.

Marginal distribution of drought characteristics

Because SPEI is a calculation of a change in ‘wetness’ (0 indicates average moisture, positive results indicate unusually wet conditions, and negative results indicate unusually dry conditions), averaging SPEI provides minimal utility for drought planning. Most values are near zero, and long time periods wash out variation, resulting in averages near zero (as seen with historical average in Figure 4.5). SPEI calculations are useful when evaluating extremes and changes in distributions. However, analysis of extreme events during this period brings more clarity to how the droughts may shift. Table 4.1 shows drought characteristics for the historically significant droughts of the 1950s, 2002, and 2012.

Table 4.7. Drought characteristics for historically significant droughts (1950s, 2002, and 2012), compared to other droughts during the historical period (average).

	Average	**1950s**	**2002**	**2012**
Duration (months)	3.03	2.83	4.08	3.38
Severity	-4.34	-3.92	-6.27	-4.64
Peak	-1.18	-1.20	1.21	1.08

The first step in calculating return periods was to identify the marginal distribution for each of the three drought characteristics for each scenario. After the 6-month SPEI was calculated, drought events were identified using a truncation value of -1. Figure 4.6 illustrates the calculated historical SPEI and drought periods identified as ‘significant’ by values less than the truncation (worse droughts). Then the mean interarrival time (e.g., frequency) of droughts estimated from the observed data was: Historical – 16 months; NF-4.5 is 19 months; FF-4.5 is 12 months; NF-8.5 is 39 months; and FF-8.f is 8 months.

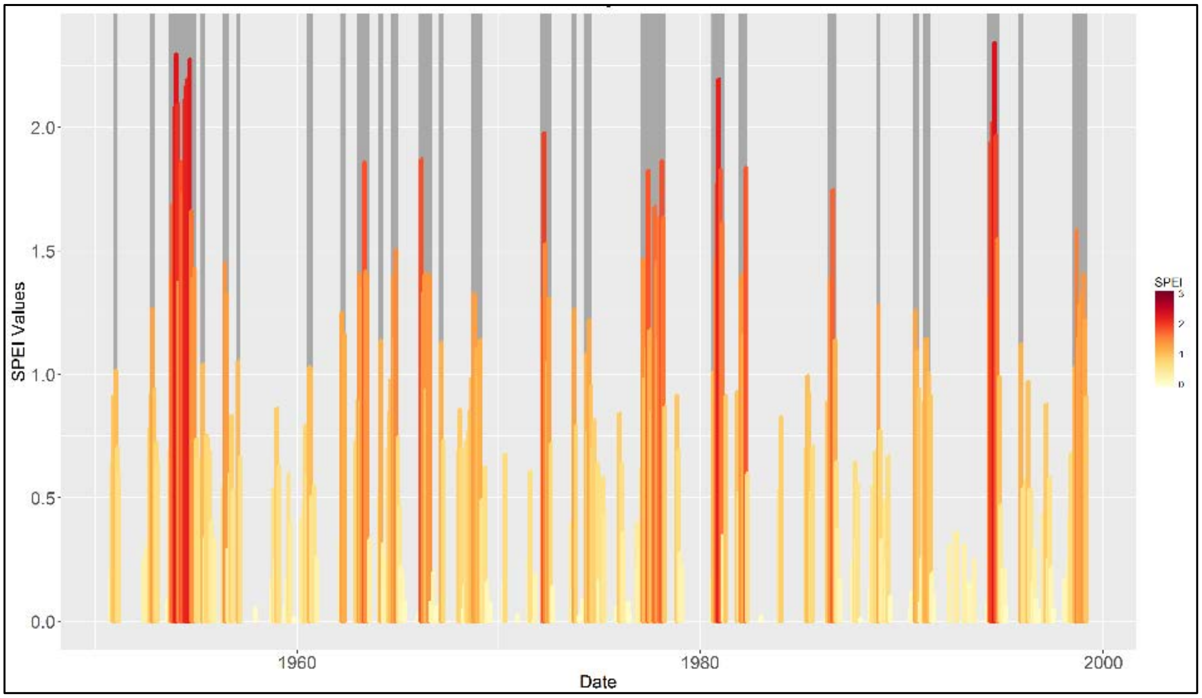

Figure 4.28. Historical 6-month SPEI values. Grey areas are those with truncation values -1.

The drought duration, severity, and intensity (peak) were abstracted from each of the observed drought events and univariate analysis was performed. Once the appropriate marginal distribution was identified, the parameters were estimated (proved in Appendix 4.1). Figure 4.7 to Figure 4.9 illustrates the observed values for each drought characteristic for each period.

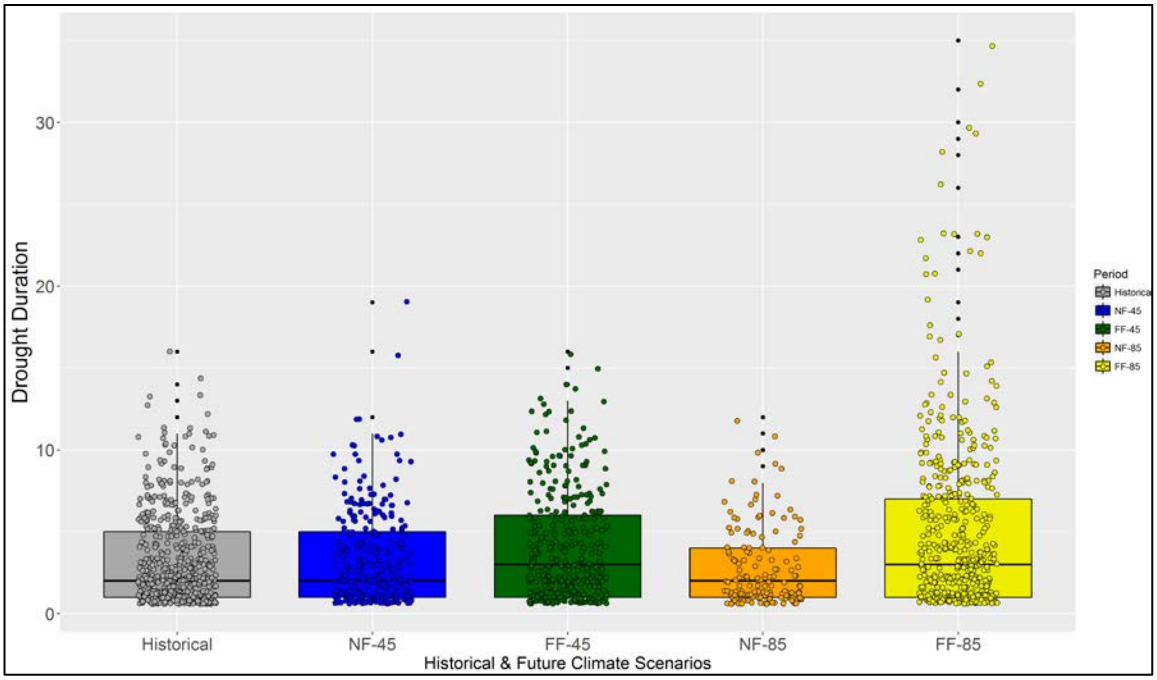

Figure 4.29. Duration (in months) of drought events in historical and future scenarios

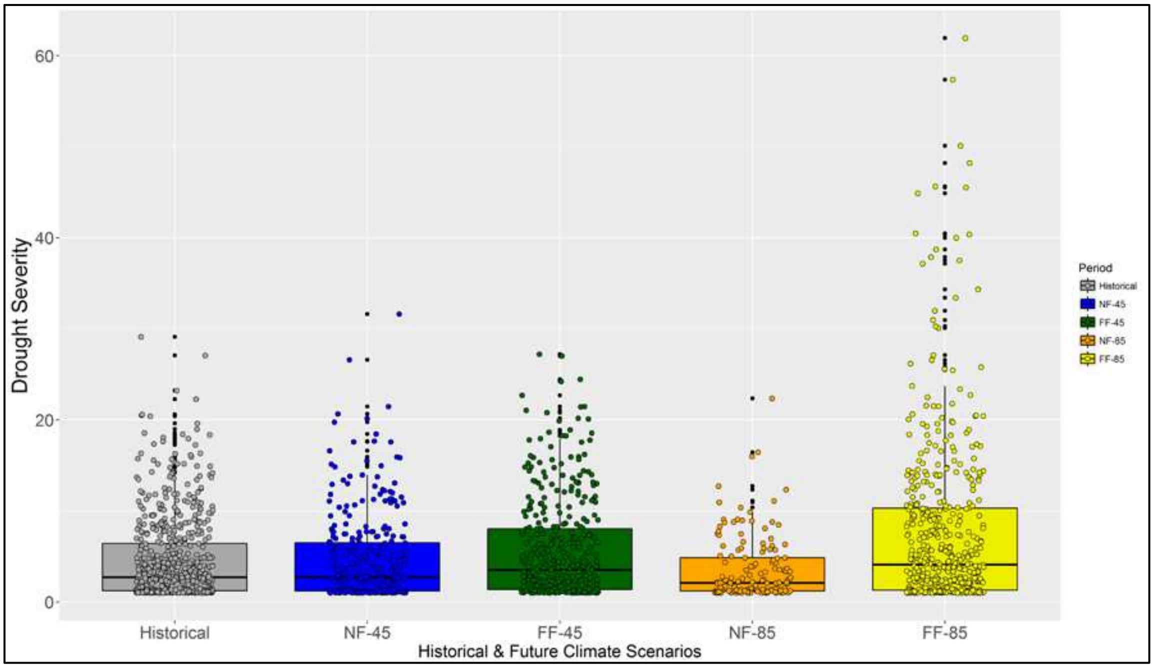

Figure 4.30. Severity (duration * -SPEI values) of drought events in historical and future scenarios

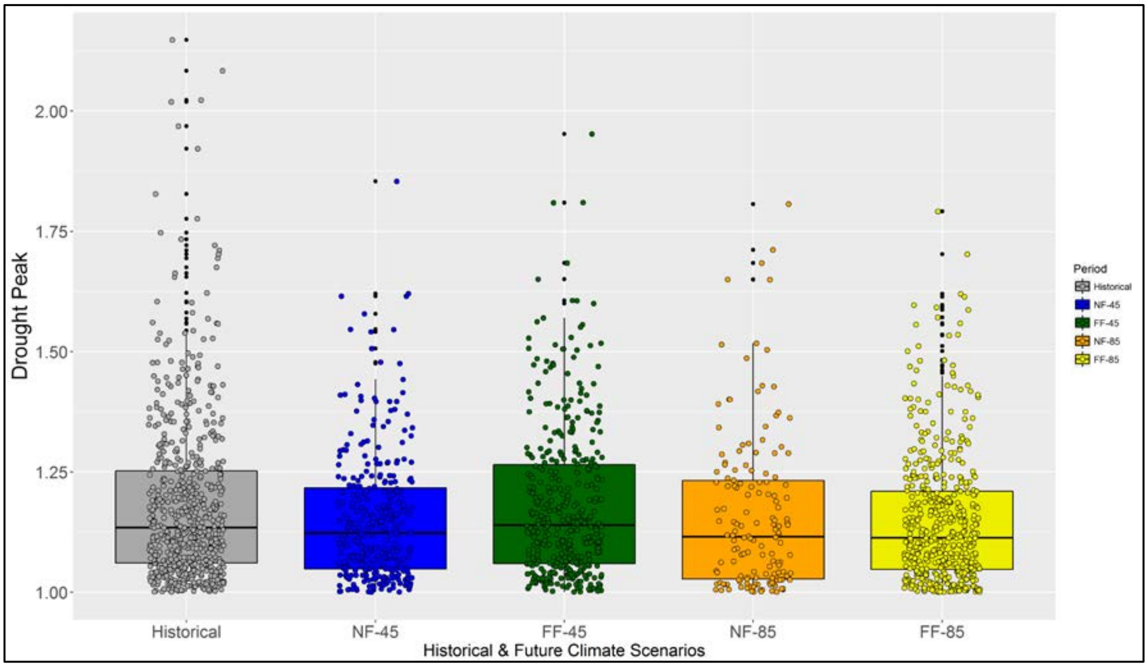

Figure 4.31. Peak (- max SPEI value) of drought events in historical and future scenarios

<u>Univariate return periods</u>

Using the interarrival times and parameterized cumulative density functions, the recurrence intervals (return periods) of periods of 20, 50, and 100 years were estimated using Equation (4.1). Table 4.2 defines the single-variate return periods for drought duration, severity and peak.

Table 4.8. Return periods for drought characteristics

Drought Characteristic	Return	Historical	RCP 4.5 NF	RCP 4.5 FF	RCP 8.5 NF	RCP 8.5 FF
Duration	20	9.00	9.00	12.00	7.00	18.00
	50	13.00	13.00	16.00	10.00	24.00
	100	15.00	15.00	19.00	13.00	27.00
	Return	**Historical**	**RCP 4.5 NF**	**RCP 4.5 FF**	**RCP 8.5 NF**	**RCP 8.5 FF**
Severity	20	11.62	7.44	17.09	7.62	31.21
	50	17.11	9.47	22.29	11.00	47.50
	100	22.08	10.93	26.23	13.97	63.06
	Return	**Historical**	**RCP 4.5 NF**	**RCP 4.5 FF**	**RCP 8.5 NF**	**RCP 8.5 FF**
Peak	20	0.94	1.15	0.88	1.04	0.89
	50	0.69	0.89	0.67	0.70	0.68
	100	0.55	0.73	0.54	0.50	0.54

For all characteristics, near future condition remain similar or even slightly improve compared to those observed historically. However, far future duration and severity worsen significantly, particularly under the RCP 8.5 scenario. This is expected when using global climate models, where RCPs do not begin to diverge substantially across different emissions scenarios until mid-century. Table 4.3 shows the percent change for 20-year return periods, illustrating a mix between scenarios where characteristics improve or worsen.

Table 4.9. Percentage change for median 20-year drought characteristics (normalized with respective historical value). Red indicates scenario that is worsening, blue represents scenario that is improving.

Drought Characteristic	Scenario	Change
Duration	RCP 4.5 NF	0.00
	RCP 4.5 FF	3.00
	RCP 8.5 NF	-2.00
	RCP 8.5 FF	9.00
Severity	RCP 4.5 NF	-4.18
	RCP 4.5 FF	5.47
	RCP 8.5 NF	-4.01
	RCP 8.5 FF	19.59
Peak	RCP 4.5 NF	0.21
	RCP 4.5 FF	-0.05
	RCP 8.5 NF	0.10
	RCP 8.5 FF	-0.05

Joint distribution

According to Shiau (2006), droughts are considered (at least) bivariate events characterized by duration and severity, therefore it is more useful to estimate reoccurrence of bivariate distributed hydrologic events as joined and conditional events. This analysis estimated the conditional probabilities of drought severity, given duration because Table 4.3 did not show heightened drought intensity for future scenarios. We can assume that severity is increase is due to an increase in drought duration (rather than peaks), making the two characteristics correlated, and an appropriate application of copula joint distributions. Therefore, peak was dropped and the multi-variate distribution, which only models the combined dependence structures of duration and severity.

Using Equation (4.2), conditional drought distributions were derived from the bivariate drought distributions. Figure 4.10 and Figure 4.11 illustrate the conditional drought duration distributions given that the drought severity exceeds certain thresholds of S' for near- and far-future periods under RCP 4.5. The 2002 drought event led to significant shifts in water management and understanding of droughts in the SPRB (See Chapters 2-3), which were tested during another severe drought in 2012. Therefore, the drought conditions of those events were calculated from observed climate records in Greeley. The period that the 2002 SPEI was below the -1 truncation level drought duration was 4.08 months, it peaked at -1.21 SPEI, and the total severity was -6.27. The 2012 drought conditions lasted 3.38 months, peaked at -1.08 SPEI with a total severity of -4.64. Conditional probabilities of droughts exceeding these thresholds were plotted against the joint probability.

The derived conditional return period of duration and severity can be used to evaluate risk that water supply systems will be insufficient to meet demand under situations that drought duration exceeding 4 months given drought severity exceeding 5. Based on the derived conditional distributions, water resource managers could be informed that the probabilities that drought severity less than X, given drought duration exceeding Y are equal to Z. For example, the below plots show the probability, under each scenario, that a given drought event will have conditions similar to the 2002 and 2012 droughts. The probability for both are relatively low in NF-45, but increase in scenario FF-45. The shallower probability curves, like those in NF-45, represent drought longer, less severe droughts, whereas steeper curves like FF-45 represent a drought regime with more severe, flashier droughts, which is why the probability for a flash drought, similar to 2012, becomes more likely under the FF-45 scenario. This information is useful in evaluating the water supply capability and needed auxiliary water resources during severe droughts for particular water supply systems.

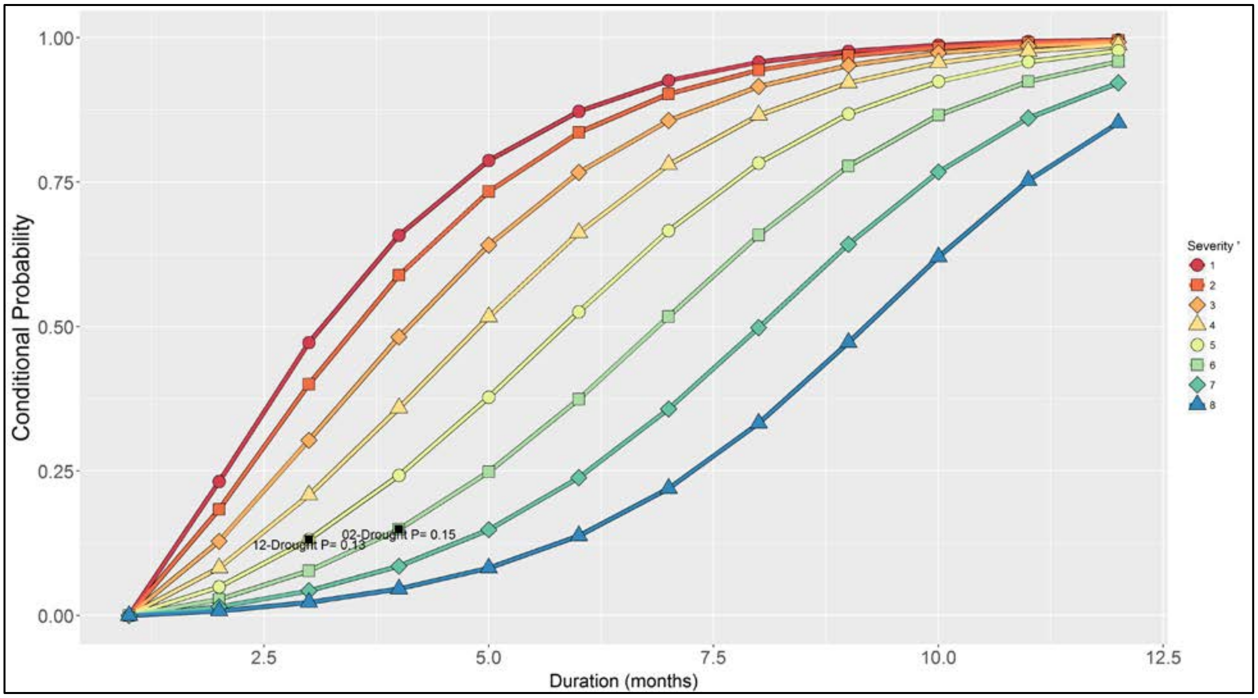

Figure 4.32. Conditional distribution of duration given drought severity exceeding S' in the Near Future- RCP4.5 scenario

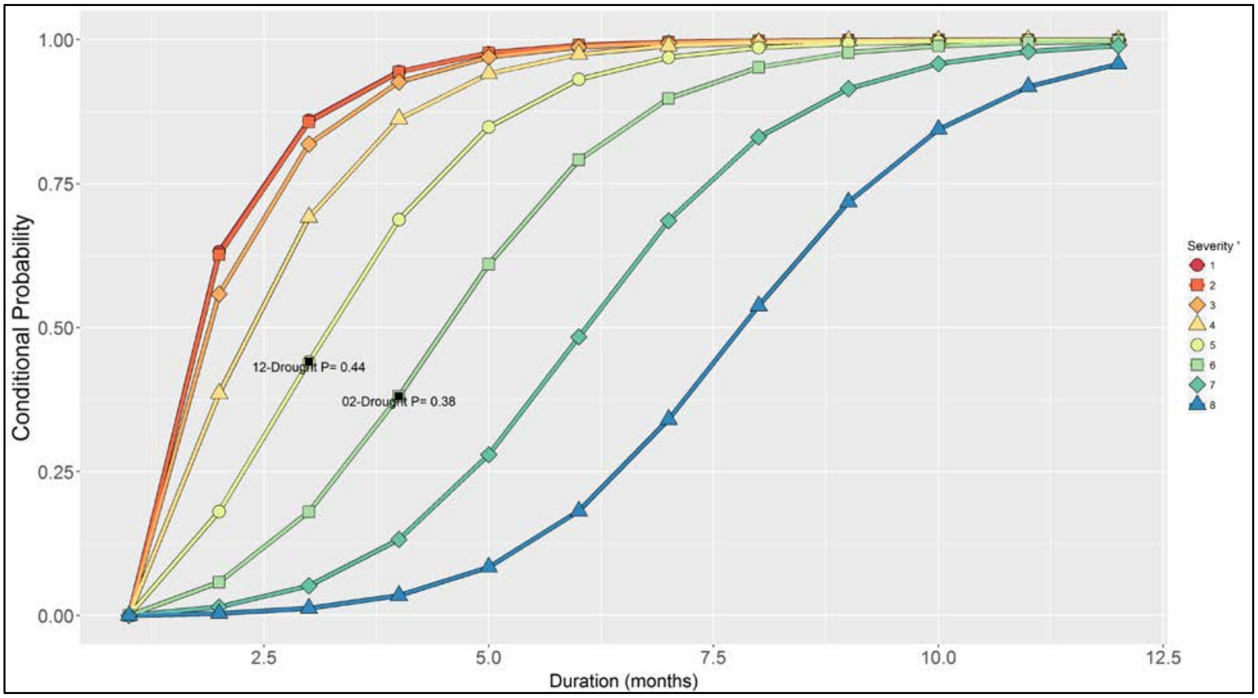

Figure 4.33. Conditional distribution of duration given drought severity exceeding S' in the Far Future- RCP4.5 scenario.

CONCLUSION

This study identified drought characteristics using the 6-month SPEI for historical period and future scenarios. Results for all scenarios show that severity and duration may be elevated, but peak will likely remain similar. Drought characteristics will likely be similar in the near future scenarios, but could be much more extreme by end of the century. The findings for all scenarios except FF.45 show that drought severity will increase, while intensity may remain the same or decline signifies that droughts will likely last longer. The consequences of this finding for the SPRB may be that fewer "flash droughts", like that experienced in 2012, occur[27]. However, when droughts do occur, they will remain moderately severe for longer. A shorter interarrival time shows a trend towards more frequent droughts as well.

This finding is interesting for two reasons. First other chapters in this dissertation (Chapters 2-3) found that gradual changes allow adaptation to occur and actually help foster climate adaptation. However, if drought conditions lessen towards mid-century then become more severe abruptly, there will likely be inadequate water supply to serve the rapid population growth that is projected to occur during that time period and systems will have insufficient time to adapt. This will spell disaster for a region that is already stressed and will need decades to develop water projects needed to meet the end of century supply/demand gap this scenario would present.

Secondly, as previously mentioned, other studies (Chapter 2) analyzing past droughts in the SPRB showed that one reason that impacts of the 2012 drought were less consequential than the 2002 drought was that, while the 2012 peak was similar, the duration was shorter. Water systems in the region are well prepared to deal with flash droughts, even those quite severe.

[2727] A flash drought is a relatively short period of warm surface temperature and anomalously low and rapidly decreasing soil moisture (Mo and Lettenmaier 2016)

However, when they last beyond a year, reservoirs become severely stressed. As Chapter 2 states, many water providers surveyed said that if the 2002 drought had lasted longer, they would have run out of supplies. The far future scenarios project drought durations significantly longer than the 2002 drought, so if additional supplies or storage for existing supplies is not increased, these longer droughts could have more severe impacts.

While this methodology provides useful insights about future drought conditions that may occur in the 21st century, they are based on imperfect climate projections and downscaling methodologies, so they are only estimates with a moderate degree of uncertainty. Additionally, the drought index used, SPEI, is an estimated based on precipitation and temperature. The water system in the SPRB relies heavily on snowmelt for supplies, so SPEI does not tell the whole story and better measures of drought conditions exist (SWSI, PDSI). However, they were not used in this study because they can be overly-complicated to run with future climate projections. While SPEI does not measure snowpack and storage, it does provide useful estimates of drought duration and severity, characteristics that greatly affect storage and snowmelt.

This methodology can be useful for vulnerability assessment and understanding probability of drought severity during future periods. Future studies could improve on this methodologies by doing similar analysis with other, more regionally relevant drought metrics or analyzing spatial variation throughout the region, similar to Thilakarathne and Sridhar (2017). This would be particularly useful in alpine areas, where warming winter temperatures could be particularly consequential for snowpack. However, caution in selecting downscaling methodology should be taken because downscaling in mountainous areas, where microclimates can vary significantly.

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CHAPTER 5: IMPLICATIONS OF WATER PROVIDER ADAPTIVE CAPACITY ON REGIONAL VULNERABILITY

My primary goal for conducting this research was to contribute to the global change and adaptation communities' understanding of the relationships between stress, adaptation, and vulnerability. To do this, I situated the research in the context of water resources in a region experiencing multiple stresses – climate change and rapid population growth – and evaluated how the adaptive capacity of a specific stakeholder group – water providers – changed throughout the course of 15 years and two droughts. This case study was analyzed within a social-ecological framework to investigate decision-making of key stakeholders to understand drivers of shifts in their adaptive capacity, and potential changes to future drought conditions.

In Chapter 1, I presented theoretical challenges with typical adaptive capacity assessments that either evaluate the presence (or absence) of indicators as a proxy for adaptive potential or studying past adaptations with the assumption that future adaptive capacity will function similarly. I suggested this challenge could be resolved by using a decision-making approach to evaluate when and why adaptation occurred to better understand its underlying mechanisms so it could be mobilized and expanded to meet future challenges. This dissertation was a case study that used this approach to evaluate how water providers' adaptive capacity changed and potential vulnerabilities. It was conducted in three parts, with three general research goals to help achieve the primary objective:

1) To introduce a methodology to evaluate the adaptive strategies of a particular stakeholder group by assessing elements that underlie their ability and motivation to adapt to environmental stress;

2) To examine multi-scale learning and institutional changes made in response to extreme stress to characterize how governance, management, and institutional approaches contributed to change in water management;
3) To investigate the characteristics of past drought events that have led to adaptation and evaluate how future drought characteristics may manifest similarly or differently, as a means of understanding how the drivers of adaptation may shift.

In the next section, I review the major findings and contributions from each chapter. I then tie these findings together and evaluate potential vulnerabilities of different types of water providers. From this, implications for regional vulnerability is discussed, and I close with broader recommendations and thoughts regarding future of adaptation research.

FINDINGS AND CONTRIBUTIONS

Chapter 2 serves as the methodological foundation upon which Chapter 3 was created. The objective of the chapter was primarily to provide a methodology to evaluate adaptive strategies employed by diverse stakeholder group to be able to draw conclusions what that means for their adaptive capacity and vulnerability to future chages. It utilized a mixed methods approach, combining the rich data analysis that comes from "bottom-up" studies with ability to extrapolate to larger groups that a "top-down", quantified analysis provides. This study was then able to discuss potential regional vulnerabilities by assessing how stakeholders were affected by drought in the past, adaptations they made to their systems following the drought, and characteristics of those who took different strategy pathways that would make them more or less adaptable to future stressors. From this, potential areas for maladaptation and vulnerability were derived from an understanding of the underlying decision-making process.

Qualitative analysis revealed that the impacts of the 2002 drought were varied among providers, ranging from those who completely ran out of water, to others who were minimally affected. The 2012 drought had minimal impacts on all providers, a finding that was confirmed by a quantitative comparison of impacts. Analysis of management ability showed that all providers ability to meet their water demand requirements improved from 2002 to 2012, and performance was actually better during the subsequent drought than during the period just before, showing that the adaptive strategies used improved adaptive capacity. Results of specific response strategies, using an Event History Calendar revealed a shift in the overall number of strategies used and their distributions between the two drought periods. While demand management strategies still made up the majority of management decisions, there was a large shift wards using policy-related strategies and a large decline in emergency-related strategies. To capture common management changes and begin to understand motivations behind adaptive decisions, water providers were divided into groups based on strategies they used to manage the droughts and how they altered their strategies.

Further investigation into specific strategies revealed a shift away from reactive, demand management approaches to forward-looking, policy-centered approaches made up the majority of transitions and served as an underlying reason most providers attributed to their change in attitudes. The qualitative comparative analysis typology revealed that the primary reason water providers adapted can be attributed to their risk perceptions. Determinants of their perceived risk was due to a perception of reliable water supplies, or because they were not heavily impacted by the drought conditions. In a region that is expected to undergo significant demographic, economic, and environmental changes in the coming decades, this has the potential to present novel vulnerabilities if systems degrade or change slowly and are hit by another severe drought.

This study augments existing knowledge of vulnerability of stakeholders and the region because it provides an understanding of successful adaptive capacities but also sheds light on types of water users and attributes of systems that could create vulnerabilities to worsening drought conditions or water stress.

Findings revealed that most water providers were not heavily impacted by the 2012 drought, largely because the drought ended when it did, but the strategies employed have not completely absolved them from vulnerability to multi-year droughts. It can be expected that those who employed strategies to increase their flexibility and monitoring would fare better than those who only employed strategies to increase their resources if drought conditions become longer and more severe than in the past. This research indicates that most of the water providers who were adaptive were severely impacted by the 2002 drought, but re-organized their management and, therefore, were less impacted by the subsequent drought, suggesting that some level of stress could actually spur a shift away from unsustainable paths and make water providers more resistant to future stress.

The original intent of the chapter was to use a sampling technique that would facilitate the creation of a typology of water providers so adaptive capacity could be extrapolated to other providers in the basin. However, the assumption that water providers' experiences would be similar was naïve. Their circumstances and strategies was so unique, it was difficult to extrapolate their experiences and adaptive capacity to a larger group. The intent of using a typology to understand all water providers' adaptive potential and thus regional adaptive capacity was the primary reason this particular methodology was chosen, but was ultimately impossible. The original study design included a survey to be sent to all water providers in the basin, that would facilitate in creating a typology, however this tool was abandoned for two reasons: 1. The response rate from interview requests was lower than anticipated, so it was doubtful that a survey response rate would provide any additional benefits for extrapolation purposes; and 2. the sample would be taken from the same population from which the interviews were drawn from, a design flaw that would result in sampling error. While the results from the study paint a more complete picture of adaptation to drought in the region than previous studies, it falls short of the original intent.

Chapter 3 built off of these findings to evaluate institutional processes that arose from a severe drought and how those affected water provider management. The research provided empirical evidence supporting the theoretical argument that multi-level learning occurs from stress events. Results showed that the crisis presented in the 2002 drought jumpstarted a system that had become stagnant, leading to the cascade of changes. Because it was not possible to evaluate how all of the institutional changes affected water management, the study determined the most impactful processes and use these for further analysis. Based on interviews with state water policy-makers and expert opinions, three processes were perceived to have high impact on how providers managed water and are discussed below: formal policy processes to increase management options; formal drought impact mitigation processes; and informal networks that were established by water providers. Qualitative comparative analysis was used to elucidate which of these processes water providers who changed their management between the two droughts interacted with, revealing two key pathways: interactions with informal provider networks OR formal policy processes to increase management options AN D drought impact mitigation processes. Repeating analysis on specific groups from Chapter 2 (that were split based on types of adjustments made to management strategies following 2002) revealed that the groups interacted differently with the institutional processes. Group 1 (large providers with relatively secure supplies) management change primarily due to cultural changes and formal arrangements that increase supply security, both stemming from informal provider networks. Group 2 providers interacted more with formal policy processes to increase their management options, a pathway that led to formalization of their conservation and drought planning which helped to shift their culture as well and gave them more strategies to draw from during the subsequent drought. Group 3 interacted with other providers but didn't change their management, showing that the pathway alone is not sufficient.

Key mechanisms that proved effective for improvement management were that they caused a shift in culture surrounding water use, they increased access to capital available for water providers, and they formalized drought management. This region is expected to undergo significant changes in the future, so assessment of institutions that led to successful management adjustments provides useful lessons for incentivizing more adaptive water management in Colorado in the future and will improve theoretical understandings of institutional arrangements that lead to more robust systems. Additionally, knowledge of drivers and barriers of system change, provides a better understanding of levers to pull to enable more robust system transformations in the future.

Adaptive capacity of water providers increased, at least in part, because of their interactions with institutional processes. While Chapter 2 showed that stress can actually lead to adaptation, this chapter revealed that it also leads to multi-level learning because it spurs adaptation across levels. Interactions between formal and informal policy processes confirmed theoretical findings that a mix of both types is needed to build adaptive capacity. While informal processes affect management the most by allowing for agile institutions, if these processes aren't formalized through policy, they may not be long lasting. Interactions with other providers as well as formalizing drought plans as well as the drought itself shifted the risk perception of water providers (and users), leading to a ‘culture of conservation.’ However, a culture that promotes conservation can be a double-edged sword, allowing water providers to stretch their supplies further, but attitudes that efficiency is sufficient may prevent them from taking more drastic measures if future droughts and shortages are more severe or present themselves differently than the past. While this really is a case study of things that were done right, there is still a gap where institutional mechanisms don’t reach rural, small water providers, who may be particularly vulnerable to future droughts.

The study design was conducted as a single case study of “SPRB institutions” with embedded units of analysis, water providers, serving as data-points to analyze how institutional processes affected their management. An inductive approach was used for the first part of the analysis, to determine the most significant institutional changes that resulted from the 2002 drought. The rest of the study used a deductive approach to test the theory that institutional changes altered management. Key institutional changes became independent variables and whether a provider altered its management (determined from Chapter 2) was the dependent variable. While sticking with more qualitative, inductive methods of conducting institutional analysis is more common and perhaps more robust and eloquent, I had considerable difficulty approaching the research question without taking a more structured approach. This process taught me that conducting qualitative, institutional research well requires a type of creative and abstract thinking that I am lacking.

Chapter 4 took a different direction from the previous two chapters. Aside from being located in the same study area and results used to draw conclusions about vulnerability and adaptation, the chapter is largely a stand-alone piece of work. It evaluated the characteristics of historical and future droughts (duration, severity, intensity, and frequency) and evaluated how they may change under four scenarios: near future RCP 4.5, near future RCP 8.5, far future RCP 4.5, and far future RCP 8.5. Because SPEI relies on temperature and precipitation inputs, the study began by evaluating how these climate variables shift under future scenarios, finding a shift in seasonality in temperature and precipitation. Precipitation projections do not change much, but peaks shift to earlier in the year, during late-winter / early-spring. All scenarios show temperature to increase, with the same shift, showing warming occurring most dramatically in late-winter, early-spring, potentially having combined negative effects on snowpack. Estimation of drought characteristics showed that near future conditions remain similar or even slightly improved compared to those observed historically, however far future duration and severity worsen significantly, particularly under the RCP 8.5 scenario. The copula joint distributions used to estimate joint probabilities of drought severity given duration showed a tendency towards longer, less severe droughts mid-century, but droughts that are long and very severe late-century.

Findings revealed that drought characteristics will likely be similar in the near future scenarios, but could be much more extreme by end of the century. The findings for all scenarios except end of century, RCP 4.5 show that drought severity will increase, while intensity may remain the same or decline signifies that droughts will likely last longer. The consequences of this finding for the SPRB may be that fewer "flash droughts", like that experienced in 2012, occur. However, when droughts do occur, they will remain moderately severe for longer. A shorter interarrival time shows a trend towards more frequent droughts as well. Chapters 2 and 3 found that gradual changes and stress allow adaptation to occur and may actually develop climate adaptation. However, if drought conditions lessen towards mid-century then become severe abruptly, there may be inadequate water supply to serve the rapid population growth that is projected to occur during that time period and systems will not have time to adapt. Additionally, Chapter 2 showed that the system is well-prepared to deal with shorter, ‘flash droughts’, but if droughts become longer and more frequent, reservoirs will become severely stressed, leaving providers who do not have additional strategies without reserves.

The decision to conduct this chapter was made purely out of a desire to conduct a more quantitative study that demonstrated other skills I have gained in other work over the course of my PhD. The methodology used is not novel and has been used extensively to address the same research question in other study areas. However, it augments analysis of how adaptation might manifest in the future by providing data on how droughts could manifest. I thought it was particularly interesting that, while most studies say droughts will become more frequent and severe, the results did not confirm that. It showed that droughts will likely last longer, but other conditions did not show to change with any of the climate models. While drought severity and duration may be elevated, peak will likely stay the same. As with use of any climate projections, big caveats should be placed around results of this study. The climate projections are not predictions of the future and should not be taken as such. However the use of scenarios allows decision-makers to put some bounds around the future to understand what they might need to plan for. The original intent of this piece of research was to be a gridded, spatial model to look at drought characteristics throughout the entire basin. However, computational and time limitations prevented from conducting that analysis, and ultimately using a point in the middle of the basin was chosen.

IMPLICATIONS FOR WATER PROVIDER VULNERABILITY

As discussed in Chapter 1, Grothmann and Patt (2005) found that an appropriate perception of risk (not so much risk that efforts will be futile but enough risk to require action) is necessary for actors to take adaptation action. This risk appraisal is based on perceived probability that they will be exposed to the threat and perceived severity of the consequences of the threat to things they value, if the threat does occur. *If* the actor determines the level of risk requires action, they begin a process of adaptation appraisal, evaluation of their ability to avert being harmed along with the costs of taking an action (Grothmann and Patt 2005).

This framework serves as a good basis for understanding how misalignment between perceived probability of threat and actual probability of threat can create vulnerabilities. Similarly, Dilling et al. (2015) furthers this idea, concluding that both vulnerability and the ‘ risk landscape’ are fluid and can shift unpredictably, including changes in chronic stress and cumulative effects of more frequent events (Tompkins and Adger 2004). If risk changes go unnoticed, perceptions of risk associated with current (or past) climate variability may not be appropriate for how the system has changed. This presents the potential that perceptions of risk associated with past or current climate may not position stakeholders to adapt to the impacts of future changes. Additionally, adaptations to one set of risks may expose actors to other risks that were not present in the past, when the adaptation was made or to which the system was less sensitive in past conditions (Dilling et al. 2015).

The theme of vulnerability created by potential risk misalignment runs central through this dissertation. Water providers were caught on their back foot in the 2002 drought because so much time had passed since a drought of that magnitude (50 years) that other elements in the system had shifted, creating new, unforeseen sensitivities. However, interviews revealed that many water providers are still basing their water management on some expectation that future conditions will look similarly to the past. One major provider stated”

> *When we're projecting how much water we'll need out in the future, we use the population projections with a conservative per capita use. The reason for that is uncertainties around water supply planning. In our modeling… we don't model climate change. There are so many different variations in that, that instead we take a more holistic approach in just saying, 'let's just plan for a little higher demand and if our supplies are reduced, we'll just match that.'*

Similar positions that future risk will be similar to current or past risk reveals a potential vulnerability of most water providers interviewed, particularly when coupled with results from Chapter 4, revealing that mid-century might bring similar or even less severe droughts than was past experienced, but by the end of the century (when demand is also projected to double at least), drought conditions may shift suddenly to be severe.

Chapters 2 and 3 revealed water providers that may still be vulnerable to the changing conditions predicted in Chapter 4. Chapter 2 revealed that water providers who have been shielded from drought impacts in the past, particularly groundwater users, have not traditionally been at risk and thus have not had to adapt to droughts. Traditionally groundwater smooths out supply, particularly during droughts. However, those with less reliable groundwater supplies and / or high population growth will still be affected by climate (due to dwindling conjunctive groundwater or due to increased demand). Mid-century, when the climate models show drought to become more significant, population growth models also show a peak. Large water providers who were mandated to create conservation plans, but smaller water providers who were not may be caught on their back foot if there is a misalignment between their expectations based on historical conditions and reality. A recent Denver Post article[28] highlighted this already

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[28] https://www.denverpost.com/2017/10/08/colorado-eastern-plains-groundwater-running-dry/

happening, concluding that groundwater users in eastern Colorado have been trying to wean off of groundwater because it has become less reliable, but due to socio-economic factors, have been unable to. Specific climatic conditions that would stress groundwater are persistent reduced precipitation, due to increasing pull on supplies and the more frequent and/or longer droughts (predicted by most scenarios in Chapter 4), due to the lagged recharge time preventing aquifers to properly recharge. What has been used as a buffer against droughts in the past may not be a reliable safeguard in the future.

IMPLICATIONS FOR REGIONAL VULNERABILITY

The potential effects of climate change and population growth on water provider vulnerability is actually somewhat insignificant compared to other users in the basin. At the end of the day *most* water providers have a number of strategies to mitigate impacts of shortages. They can acquire more water and raise their rates to do so (while reducing demand), so the probability of them totally running out of water is quite low. However, their ability to respond plays a bigger role in overall regional vulnerability because these strategies affect other water users in the basin. Water providers are major water users in the basin. When demand exceeds supply, the ‘preferred’ strategy has been to buy water from agricultural users, ‘buy-and-dry’, which as a state policy-maker stated, “Colorado has a drought plan, and that is buying water from agriculture.’ However, the effects of buy-and-dry on agriculture and rural communities are socially and economically undesirable. Therefore, if water providers are able to adapt to changes and have a broader number of strategies to pull from than buying more water from agriculture (particularly ‘softer’ strategies that stretch existing supplies) these effects on regional vulnerability will be reduced.

CONCLUDING REMARKS

While adaptation literature alludes to the link between stress and adaptive capacity, this study provides empirics on the connections and serves as an example where stress can be used to reduce the overall system vulnerability. Environmental stress compounds other persistent pressures, but this study found that stress, with the right institutions in place, can actually build adaptive capacity. Although some water providers are still vulnerable to climate change, this research was ultimately a case study about a system that was responsive to change and built its adaptive capacity. A complimentary study in either another basin in Colorado (with similar institutional processes) or a completely different state with completely institutional processes would be helpful to test these conclusions.

APPENDIX 2.1. EXAMPLE OF EHC FILLED OUT WITH WATER PROVIDERS DURING INTERVIEWS

W = Winter (Oct - Mar) S = Summer (Apr - Sep)

			2000		2001		2002		2003		2004		2005		2006		2007		2008		2009		2010		2011		2012		2013		2014		2015		
		Severe Drought	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W
Management Information	P1	Drought Plan																																	
	P2	Conservation Plan																																	
	P3	Develop triggers for drought-related actions																																	
	P4	Coordination between water and land-use planning efforts																																	
	C1	Communicate - State																																	
	C2	Communicate - Local																			P								P						C
	C3	Formal education and public communication											P		W						R								R						O
	R1	Declare a drought emergency											R		A						E								E						
	R2	Establish water hauling programs											E	H	T						S								S						W
	R3	Restrict / prohibit new taps											S	U	E						I			D					I	D					A
	S1	Rehabilitate reservoirs to operate at design capacity											I	R	R						D			M					D	M					T
	S2	Develop new storage facilities											D	R							E			R					E	R					E
	S3	Use mechanism for storing conserved water											E	I	F						N			P					N	P					R
	S4	Use of reservoir distribution techniques					S						N	C	O						T								T						
	S5	Review water rights for modifications / flexibility during drought					E						T	A	R									2						2					P
	S6	Dry year leasing of water rights from agriculture					P							N							O			0					O	0					L
	S7	Water banks established for the sale, transfer, and exchange of water					T						B	E	2						B			1					B	1					A
	S8	Interruptible water supply agreements											U		1						A			0					A	3					N
	S9	Reuse					1						S		S						M								M						
	S10	Wet year leasing of water rights to agriculture					1						H		T						A								A						
	D1	Voluntary outdoor watering restrictions											R	K	C						E								R						
	D2	Mandatory outdoor watering restrictions											E	A	E						L			U					E	U					F
	D3	Enforcement of watering restrictions											-	T	N						E			P					-	P					I
	D4	Implement, upgrade water metering and water loss control systems											E	R	T						C			D					E	D					N
	D5	Water-efficient fixtures and appliances											L	I	U						T			A					L	A					A
	D6	Low water use landscapes and efficient irrigation											E	N	R						E			T					E	T					L
	D7	Rate structures to influence water use											C	A	Y						D			E					C	E					I
	M1	Monitor water supply components (e.g. snow pack, stream flow, etc.)											T		A														T						Z
	M2	Evaluate effectiveness post-drought and modify plans											E		C														E						E
	M3	Track public perception and effectiveness of drought measures											D		T														D						D
Impacts	A1	Water Delivery																																	
Personal	I1	Age milestones																																	
	I2	Marital and family milestones																																	
	I3	Professional milestones																																	
		Other																																	

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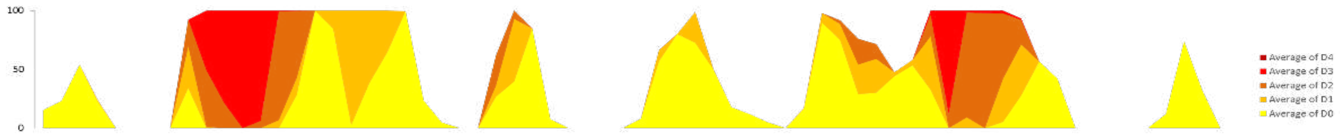


APPENDIX 2.2. SAMPLE INTERVIEW SCRIPT

Intro Statement and explanation of what's going to happen. I'm going to start by asking you a few questions about PROVIDER. Then we'll move on to fill out EHC, the fun part.
Thank you again for taking the time to do this interview. I will be asking you a series of questions about your water system since 2002. The goal of the research is to gain a better understanding of how and why certain management approaches have developed over time, and how the water system managed the 2002 and 2012 droughts.

I know how sensitive discussing these issues can be, so I'm taking a number of steps to ensure confidentiality. First, neither your name nor organization will be associated with the data from this interview. I am analyzing the content of the data and will not link it to any identifying information in my analysis or write-up. Second, the transcript and notes will be associated with a code that only I have access to and no one other than me will have access to the raw data. Hopefully this will ease concerns about speaking candidly.

I have chosen to conduct this interview by using this event history calendar. Tools like this have been shown to be very effective for recording past experiences. I will begin by asking you about your personal history during this period, which is meant to orient you to this particular time period by situating the occurrences in your water system around events that have happened within your life. I have identified other noteworthy events on the calendar to further help with this orientation. I will also ask you to pin-point important local events that have occurred during this period to assist in remembering characteristics of your water system throughout the past decade. My hope is that we can work together to complete this event history calendar as accurately as possible.

Let me run through the layout of the event history calendar. As you can see, these are the categories of questions that I will be asking you throughout the interview (point to rows), and here are the periods over the past decade that each question will pertain to (*point to columns*). I am using summer and winter because climate and management decision are often remembered in seasonal terms, (e.g., 'the drought during the summer of 2001 was a tough one'). Please note the approximate months.

I have chosen to assign to each season (*explain the seasons*). I have identified several prominent events that occurred throughout the decade. Some of these events might have directly impacted your water system; while others are identified because of their ability to orient you to this time period (*explain each of the events*).

First Questions

B1: First of all, when did you start working here at PROVIDER, and what is your background?
B2: How many customers does PROVIDER serve?
B3: Is water primarily municipal, agricultural, industrial/commercial, other?

EHC Questions

OK – Let's start filling in the calendar. Are there any events, climate or other (e.g., large infrastructure installation, local policies or community activities, etc.), that are particularly noteworthy that may help reorient you in this time period? (Record the events at the bottom of the page.)

Excellent – I would like to begin by learning a little about what was personally going on in your life during this time period.

I1. Age milestones: Can you locate any milestone birthdays on the calendar (e.g., when you turned 30, 50, etc.)

I2. Marital family and milestone events: If you are or have been married, I'd like to identify significant events, like when you were married, milestone anniversaries and divorces, if that applies to you. Also, if you have children, were any of them born during this period? Did any of them have milestone birthdays during this period (e.g., turned 16, 21, etc.) or milestone events (e.g., graduate high school or college, get married, etc.)?

I3. Promotions and awards/recognitions: Did you earn any promotions and/or experience career advancements during this period? Did you receive any significant awards or recognitions during this period?

I4. Other: Are there other noteworthy personal events that you would like me to record on this calendar?

(*Take a moment to review the calendar with them for accuracy.*)

Keeping these events in mind, I am now going to turn to questions regarding your water system. The first set of questions relate to approaches you took to manage droughts. We're going to run through each question to identify the emphasis your water system placed on the following approaches.

We'll begin by identifying for each whether it was used at all or not. If it was used, I want you to identify its use as 1-3, or little-moderate-significant (*If ask relative to what, say 'with respect to what you think is physically possible if you had all the resources in the world'*). I am particularly interested in when you feel the status has changed from (e.g., from 0-1 or 1-0). I don't expect you to have done all of these, or for there to necessarily be changes in all of these; you could have been doing them all along, or not at all, or some of them could have changed a lot. My goal is to accurately capture any changes took place. I'll give you a pencil too in case you think it's easier to help with completing the calendar.

[*As they're filling it out, have them discuss why each was used or not or why status changed]*

<u>Policy and Planning</u>

For this first part, we're going to focus on drought and conservation planning.

P1. Drought Plan: When did you have a drought plan in place (*when have plan, not when use plan*). and what time periods of drought have you planned for over this decade (e.g., 5-year drought, 20 year drought, etc.)?

P2. Conservation Plan: When did you have a conservation plan in place?

P3. Develop triggers for drought-related actions: Did you have triggers for drought-related actions (in drought-specific, or master plan)?

P4. Coordinate between water and land-use planning efforts: Did you have any coordination between water and land-use planning? (e.g zoning based on water conditions, restrictions on new taps, density considerations)

Collaboration and Public Communication

Let's think about how you've coordinated with partners.

C1. Collaborate – State: Coordination with state agencies (CWCB, DTF, DOLA, BRT, etc) for drought / water planning

C2. Collaborate – Local: Coordinating with city or county officials / agencies for drought/water planning (e.g., meetings, local planning processes, etc.).

C3. Formal education and public communication: At what point did you start communicating through the public through formal or informal channels (media, inserts in water bills, town hall meetings, etc.). Did you have any avenues for and promoting customer input into your water system's management.

Emergency Response

Here, I'd like to think about when your system experience water supply shortages.

R1. Declare a drought emergency: At what point was a drought emergency declared? If stages of severity were declared, please indicate those times.

R2. Establish water hauling programs: At what point did you truck in water from other sources?

R3. Restrict / prohibit new taps: Did you restrict establishment of new taps or accounts on your water system? When were they allowed to resume?

Water Supply Management

Now we're going to discuss if and when different supply augmentation strategies were used.

S1. Rehabilitate reservoirs to operate at design capacity: Have you evaluated whether reservoirs are operating at design capacity? Has it been considered to rehabilitate reservoirs? Has it been done?

S2. Develop new storage facilities: Have you or have you plans to develop new storage facilities? By how much will this increase your storage capacity?

S3. Develop mechanism for storing conserved water: Is there a mechanism in place to store water that is conserved for drought use?

S4. Use of reservoir distribution techniques: Do you move water around between reservoirs to maximize efficiency or minimize loss during droughts?

S5. Review water rights for modifications / flexibility during drought: Did review your water rights portfolio to evaluate flexibility that might be available during the droughts?

S6. Dry year leasing of water rights: Did you participate in dry year leasing of water rights from agriculture? When?

S7. Water banks established for the sale, transfer, and exchange of water: Did you participate in water banks?

S8. Interruptible water supply agreements: Did you develop or use interruptible water supply agreements?

S9. Reuse: Do you have any water reuse projects?

S10. Wet year leasing of water rights to agriculture: Do you own water that year lease back to agriculture during wet years?

Water Demand Management

Here I'm going to ask you to what extent you used demand management strategies. I expect more of these will have been utilized to various degrees. I'd really like to focus on the degree which they were used and the time periods where that degree changed.

D1. Voluntary outdoor watering restrictions: When did you have voluntary outdoor watering restrictions? Is there a point where it was boosted?

D2. Mandatory outdoor watering restrictions: When did you establish mandatory water restrictions?

D3. Enforcement of watering restrictions: When were programs for enforcing water restrictions more closely monitored?

D4. Implement, upgrade water metering and water loss control systems: Did you upgrade water metering or water loss control systems?

D5. Water-efficient fixtures and appliances: Did you develop programs to incentivize use of water efficient appliances and fixtures?

D6. Low water use landscapes and efficient irrigation: Did you develop programs to develop programs to incentivize water efficient landscaping and irrigation?

D7. Rate structures to influence water use: Did you use a conservation-oriented rate structure, even if it affected your revenues. If so, how have the tiers changed over time (when added 2nd, 3rd, etc.). Follow up: How are the rate structures set?

Monitoring and Evaluation

M1. Monitor water supply components (e.g., snow pack, stream flow, etc.): Over what time periods do you monitor water supply components used to make management decisions? What data do you use (e.g., above).

M2. Evaluate effectiveness post-drought and modify plans: Post-droughts, did you evaluate the effectiveness of your system's response? If so, were plans modified as a result?

M3: Perception of the problem: I want you to track perception of drought (and climate change) as a serious problem (0 = none, 1 = just the water system seeing it as a significant issue, 2 = the water system and your customers seeing it as a significant issue).

Characterizing impacts / adaptive capacity

Now we're going to move to the everyday functioning of your system. Based on your knowledge and experience, please rate the ability of your system to meet its water delivery requirements since 2000. These questions should be answered from (0=none, 1=low, 2=medium, 3=high). I am particularly interested in when you feel the status has changed from (e.g., from 'low' to 'medium', from 'high' to 'low', etc.)

A1. Water delivery: Your water system's ability to high deliver water.

(*Take a moment to review the calendar with them for accuracy*.)

Thank you very much for taking the time to meet with me. Before we end, I’d like to ask if there are any issues or topics that I haven’t addressed that you believe are important items to consider. Lastly, I’d like to ask if you have any questions for me. Thank you again for your time. Your input is invaluable.

APPENDIX 2.3. CHANGES TO STRATEGIES BETWEEN TWO PERIODS

		2002-2003	2012-2013	Percent Change (%)
P1	Drought Plan	14	46	229
P2	Conservation Plant	11	63	473
P3	Drought Triggers	14	38	171
P4	Land-use coordination	9	12	33
C1	State-comms	1	0	-100
C2	Local-comms	1	0	-100
C3	Public ed and comms	42	66	57
R1	Declare emergency	30	4	-87
R2	Water Hauling	3	0	-100
R3	Prohibit taps	12	4	-67
S1	Rehab reservoirs	0	1	1
S2	New storage	2	10	400
S3	Store conserved water	9	8	-11
S4	Reservoir distribution	18	16	-11
S5	Rights flexibility	4	4	0
S6	Dry-year leasing	4	3	-25
S7	water banks	0	0	0
S8	ISAs	5	5	0
S9	Reuse	14	28	100
S10	Wet-year leasing	28	28	0

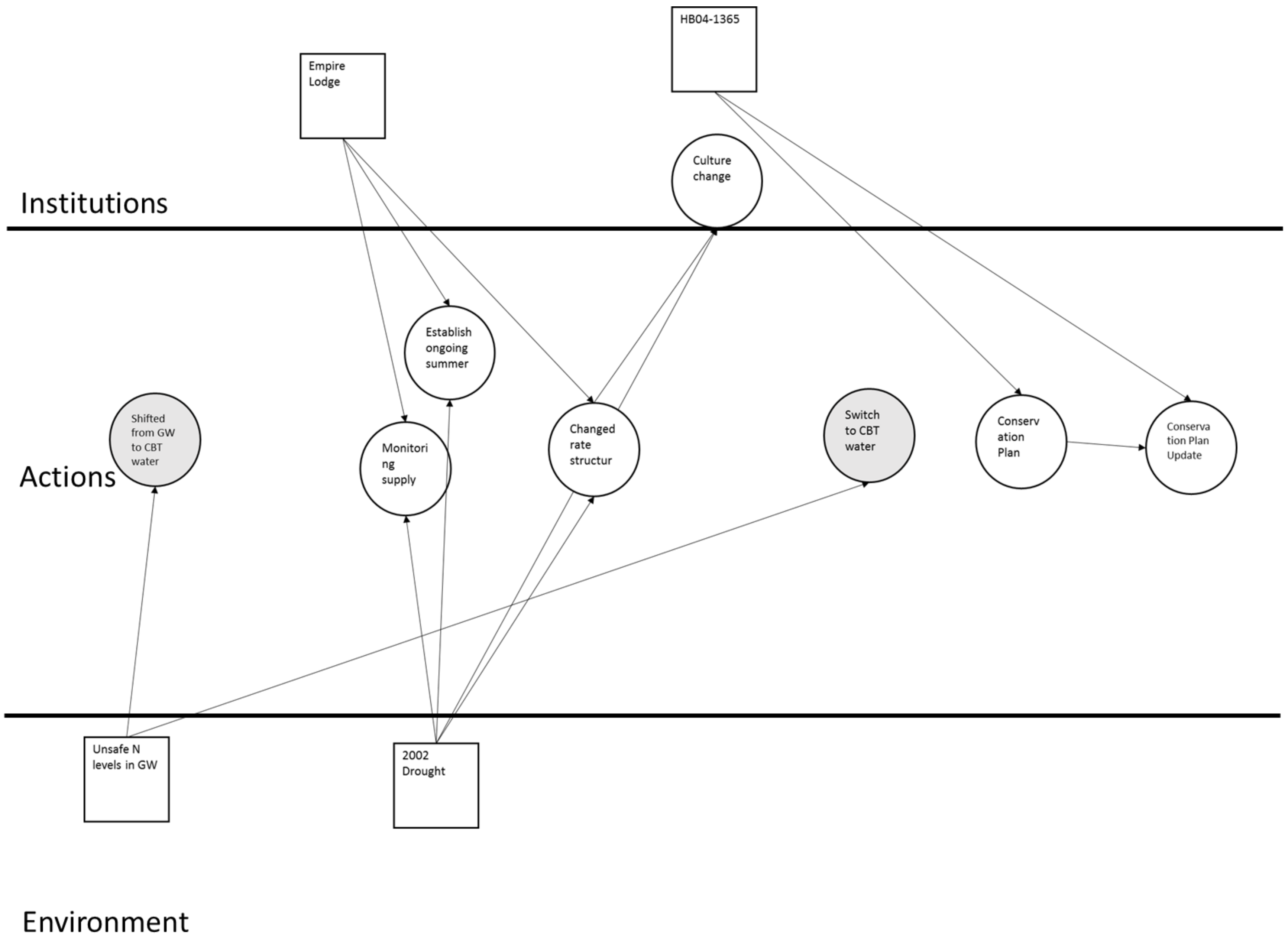
D1	Voluntary restrictions	21	30	43
D2	Mandatory restrictions	54	38	-30
D3	Active enforcement	30	31	3
D4	Water-loss upgrades	26	55	112
D5	Indoor efficiency	15	54	260
D6	Outdoor efficiency	15	60	300
D7	Rate-structures	55	84	53

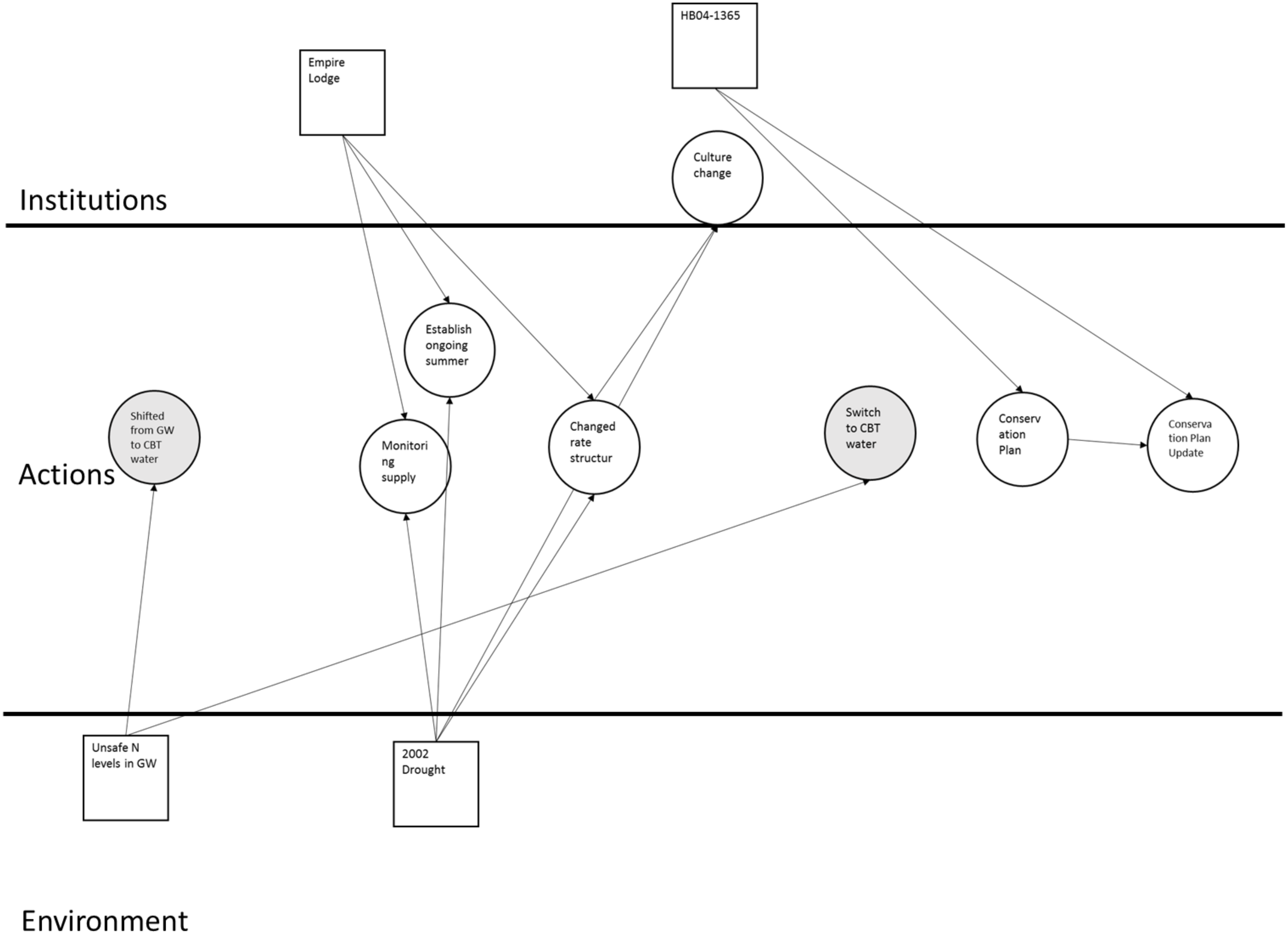
APPENDIX 3.4. COLORADO MAJOR LEGISLATIVE AND STATUTORY CHANGES FROM 1930-2015. NUMBERS CORRESPOND TO THOSE IN FIGURE 3.1

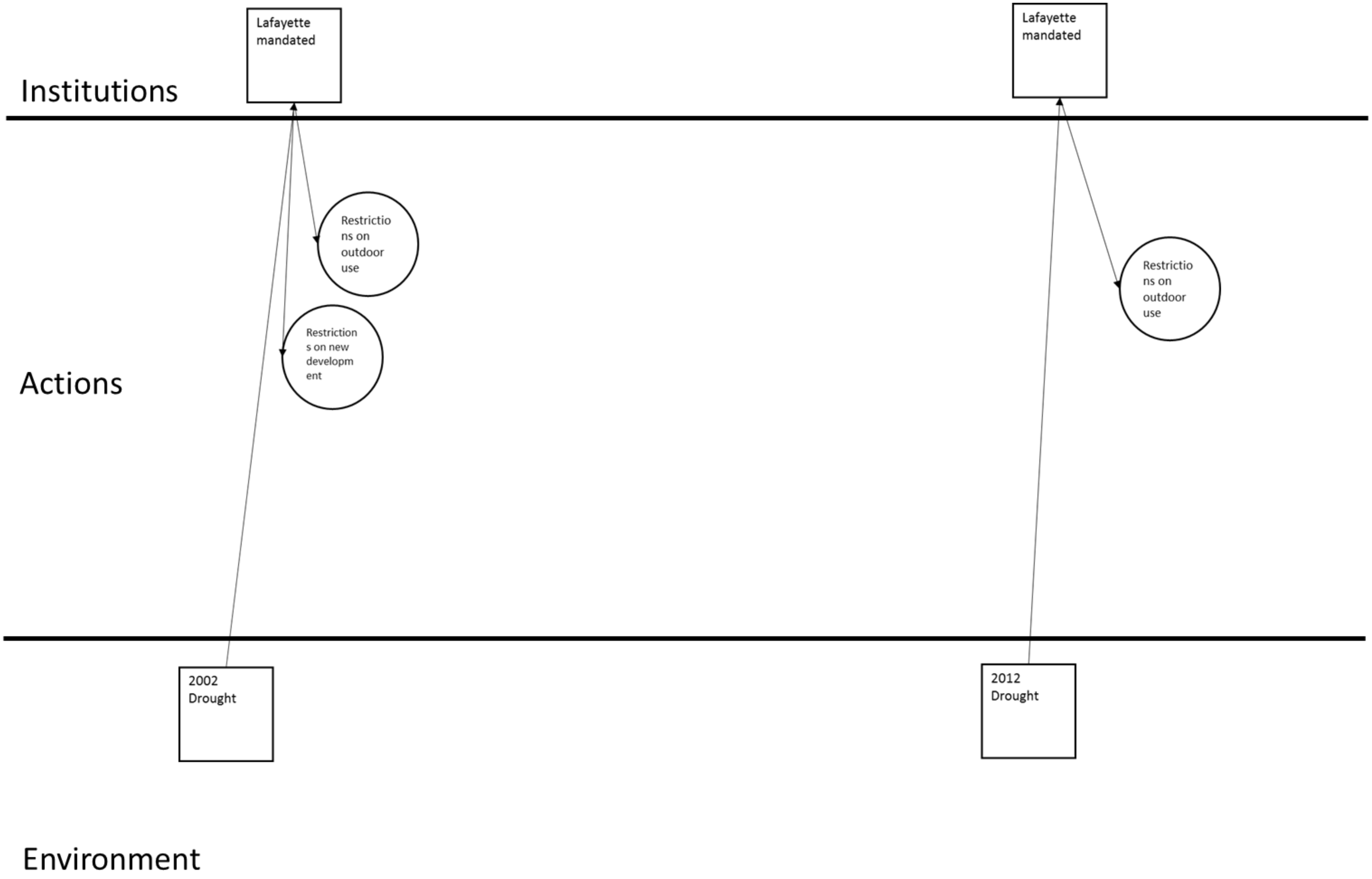
#	Year	Institution	Type
1	1937	1937 Conservancy Law	--
2	1957	Ground Water Law of 1957	--
3	1965	CRS_148-11-22	--
4	1965	1965 Groundwater Management Act	--
5	1969	HB-1066	--
6	1969	CRS_37-92-103	--
7	1971	HB71-1205	--
8	1972	CRS_20-28-133	--
9	1973	1973 ISF and lake level law	--
10	1974	1974 Amended Rules	--
11	1974	CRS_29-20-101	--
12	1977	DMRP 1977	--
13	1981	Colorado Drought Response Plan	--
14	1990	CRS_37-97-101 to 103	--
15	1991	Water Conservation Act of 1991	--
16	1992	Disaster Emergency Act of 1992	--
17	2002	Senate Bill 02S-001	Policy
18	2002	CRS_37-60-121	
19	2002	HB02-1152	
20	2002	HB02-1414	
21	2002	HB02S-1001	
22	2003	CRS_37-80.5-101 to 105	
23	2003	CRS-37-83-104	
24	2002	HB03-1320	
25	2003	CRS_37-92-309	
26	2003	Drought Impact and Mitigation Report 2003	
27	2003	House Joint Res 03-1015	
28	2003	SB03-73	
29	2004	DWSA 2004	
30	2004	SB04-239	
31	2004	HB04-1365	
32	2005	HB05-1177	
33	2005	HB05-1254	
34	2006	CRS 37-92-103(10.6); CRS 37-92-305(3)	
35	2006	CRS_37-60-126	
36	2007	CDWSU	

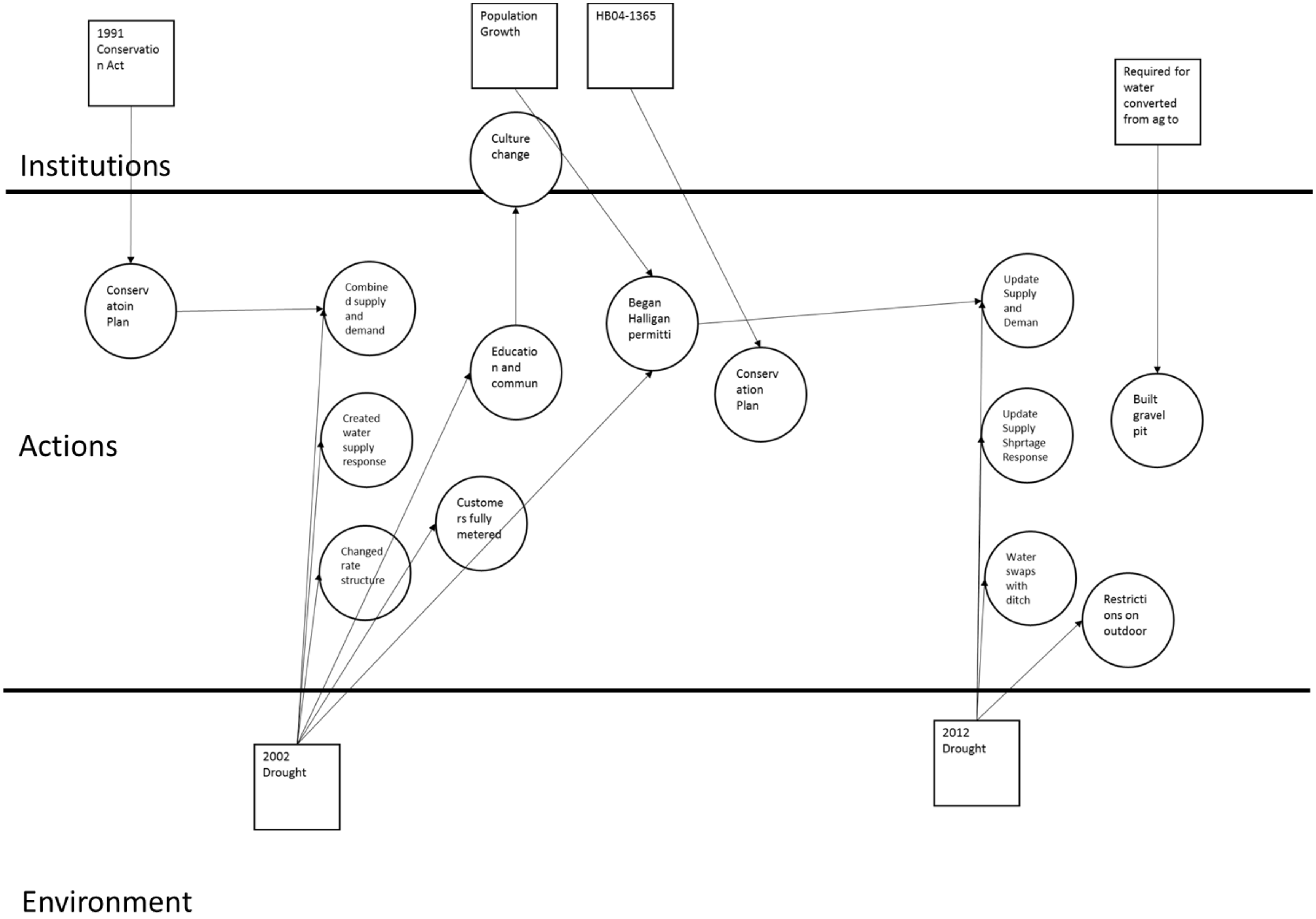
#	Year	Institution	Type
37	2007	DMRP 2007	
38	2007	SB07-008	
39	2008	HB08-1141	
40	2009	HB09-1174	
41	2009	SB09-147	
42	2009	HB09-1129	
43	2009	SB09-080	
44	2009	SB09-165	
45	2010	DMRP 2010	
46	2010	HB10-1051	
47	2010	HB10-1358	
48	2012	CRS_37-38-105	
49	2012	HB12-1278	
50	2012	SB12-097	
51	2013	DMRP 2013	
52	2013	HB13-1248	
53	2013	SB13-041	
54	2013	HB13-1130	
55	2013	SB13-019	
56	2014	SB14-103	
57	2014	SB14-115	
58	2015	State Water Plan	

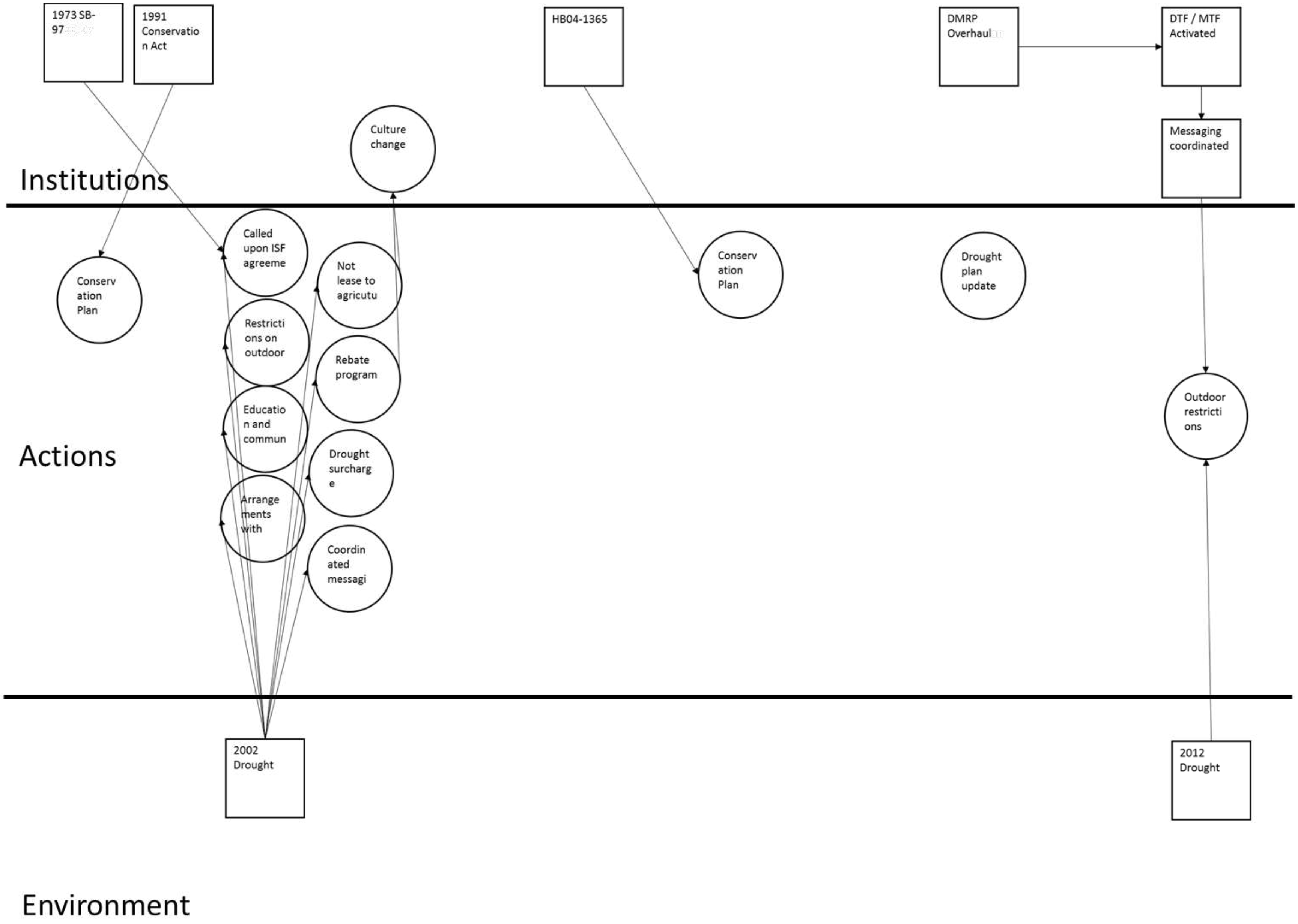
APPENDIX 3.5. CAUSAL MAPS OF WATER PROVIDER ACTIONS MADE BETWEEN 2000 AND 2015. CIRCLES INDICATE ACTIONS MADE BY WATER PROVIDERS. BOXES ARE OUTSIDE INFLUENCES ON ACTIONS. ARROWS REPRESENT INFLUENCE FROM ONE EVENT TO ANOTHER.


HB04-1365
Empire Lodge
Culture change
Institutions
Establish ongoing summer
Shifted from GW to CBT water
Monitori ng supply
Changed rate structur
Switch to CBT water
Conserv ation Plan
Conserva tion Plan Update
Actions
Unsafe N levels in GW
2002 Drought
Environment

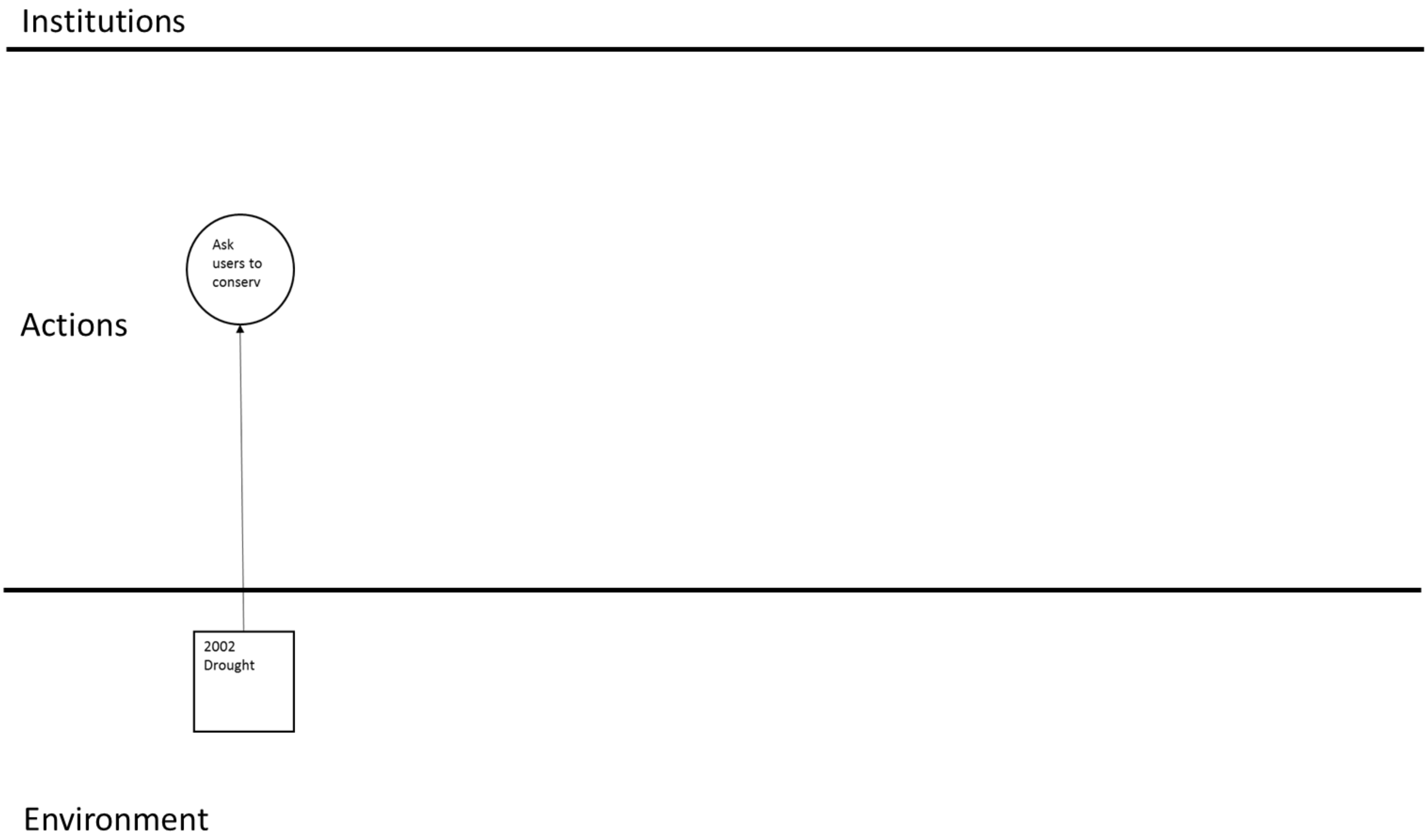

HB04-1365
Empire Lodge
Culture change
Institutions
Establish ongoing summer
Shifted from GW to CBT water
Monitoring supply
Changed rate structur
Switch to CBT water
Conservation Plan
Conservation Plan Update
Actions
Unsafe N levels in GW
2002 Drought
Environment

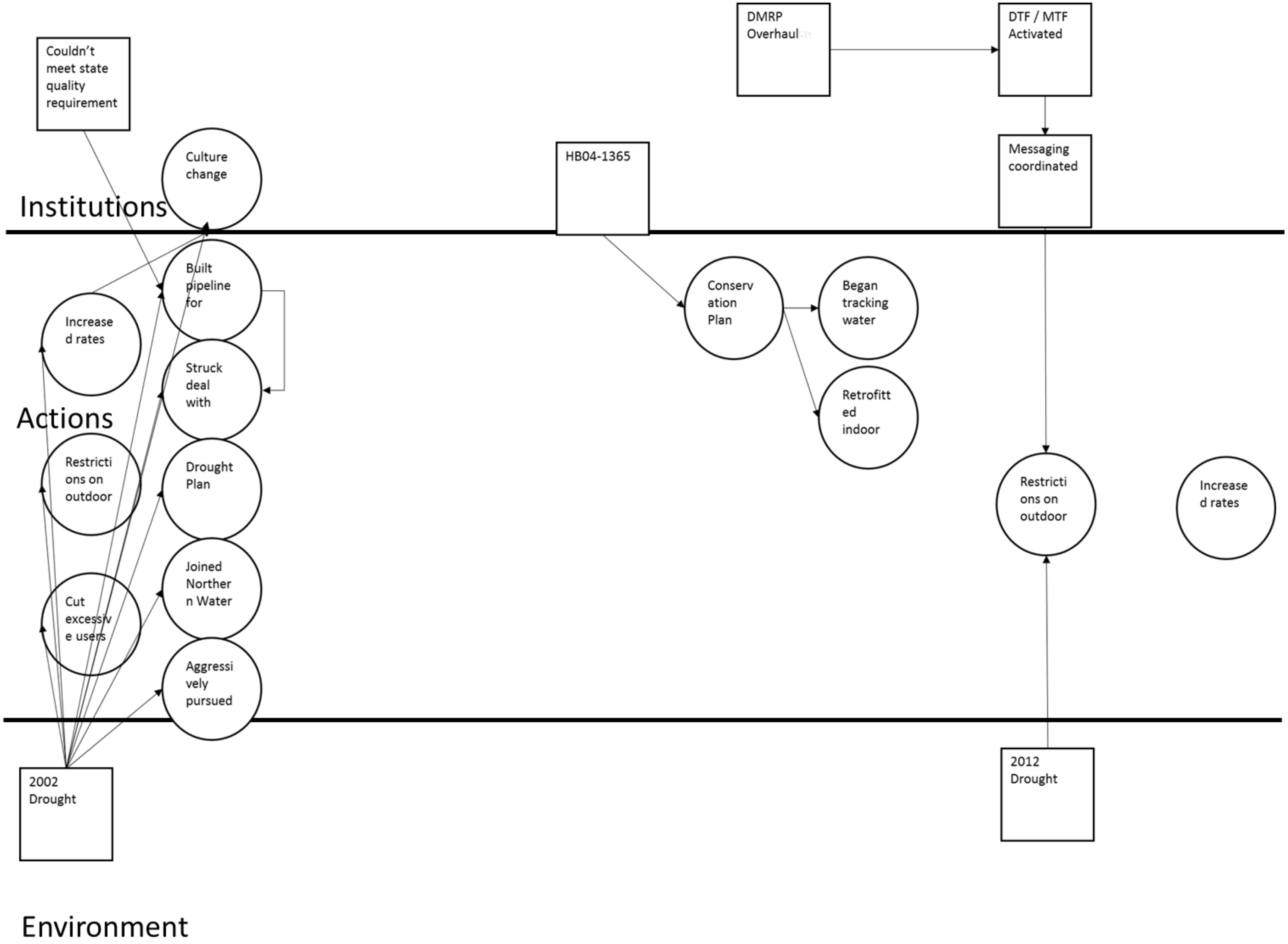

Institutions
Lafayette mandated
Lafayette mandated
Restrictions on outdoor use
Restrictions on new development
Restrictions on outdoor use
Actions
2002 Drought
2012 Drought
Environment

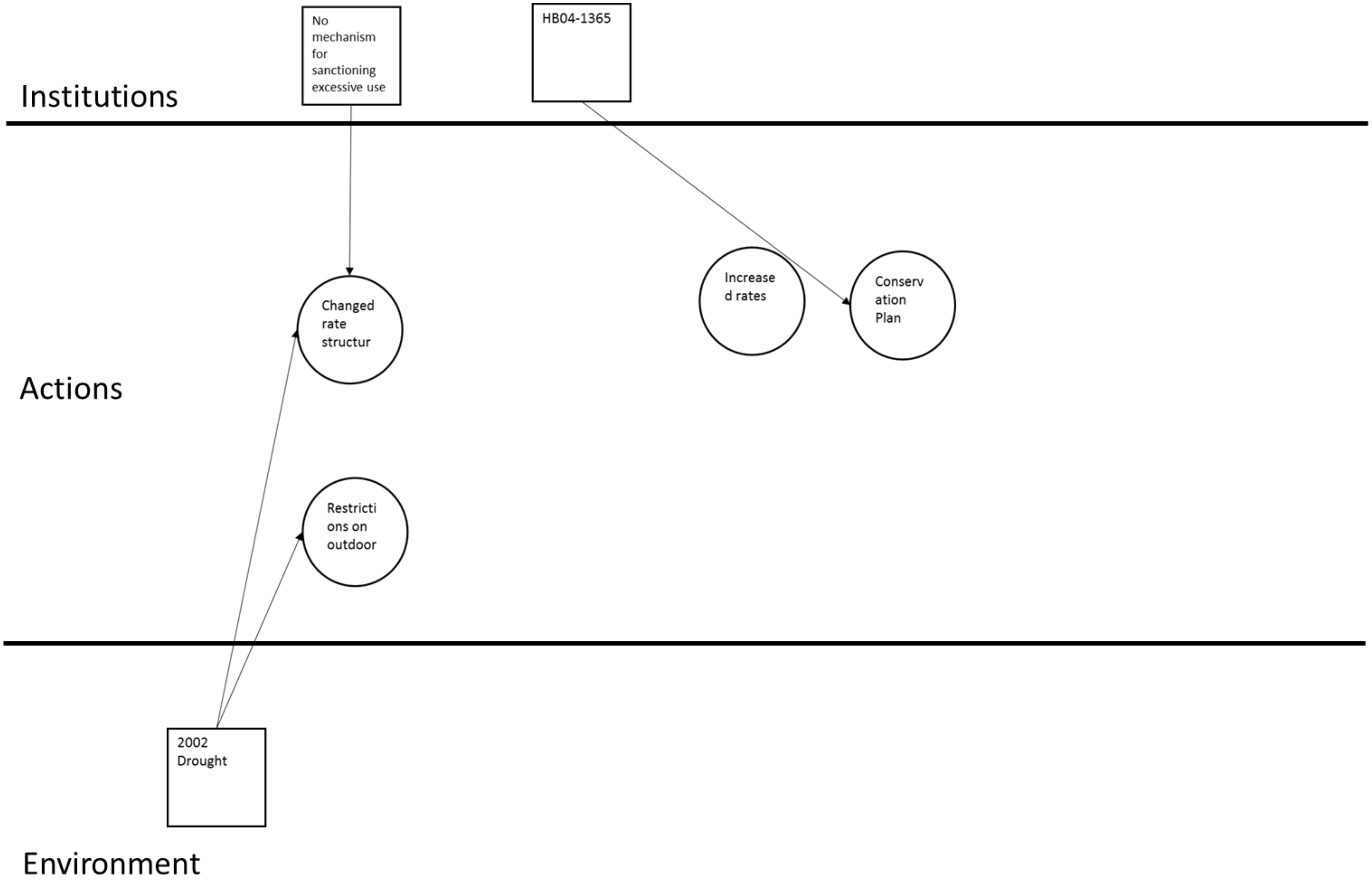

1991 Conservation Act
Population Growth
HB04-1365
Required for water converted from ag to
Culture change
Institutions
Conservatoin Plan
Combined supply and demand
Education and commun
Began Halligan permitti
Conservation Plan
Update Supply and Deman
Update Supply Shprtage Response
Built gravel pit
Actions
Created water supply response
Changed rate structure
Customers fully metered
Water swaps with ditch
Restrictions on outdoor
2002 Drought
2012 Drought
Environment

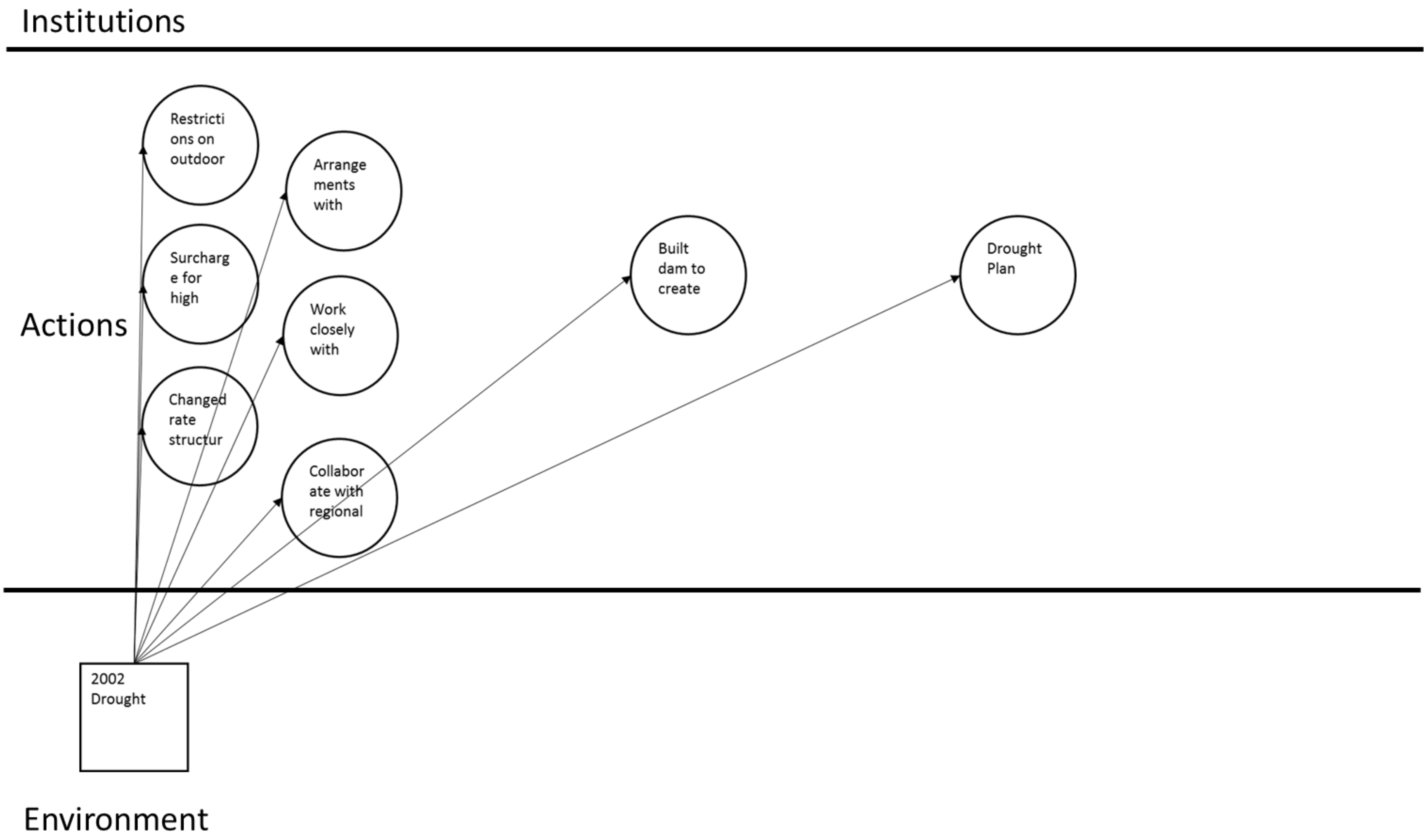


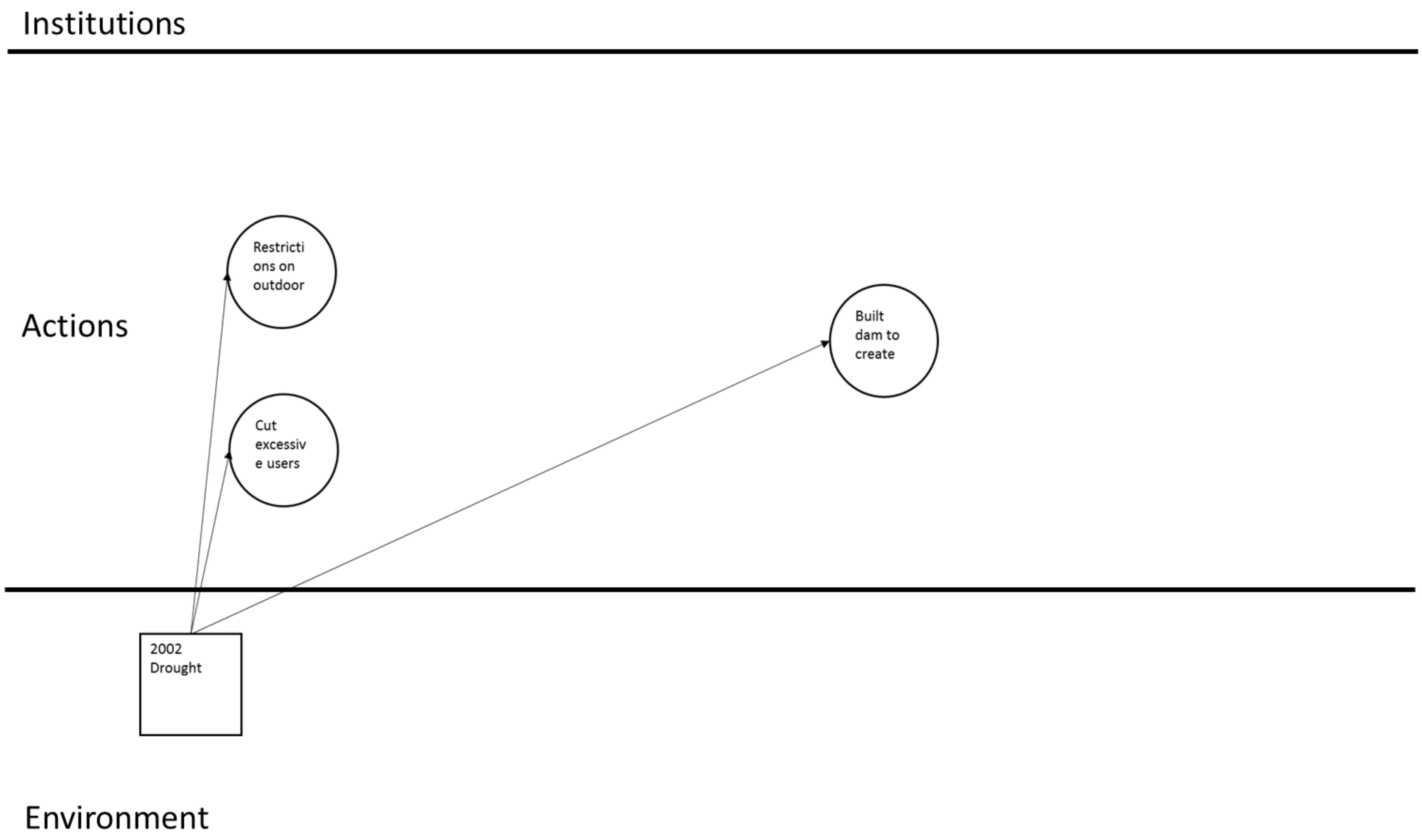
1973 SB-97
1991 Conservation Act
HB04-1365
DMRP Overhaul
DTF / MTF Activated
Culture change
Messaging coordinated
Institutions
Called upon ISF agreeme
Not lease to agricutu
Conservation Plan
Conservation Plan
Drought plan update
Restrictions on outdoor
Rebate program
Education and commun
Drought surcharge
Outdoor restrictions
Actions
Arrangements with
Coordinated messagi
2002 Drought
2012 Drought
Environment

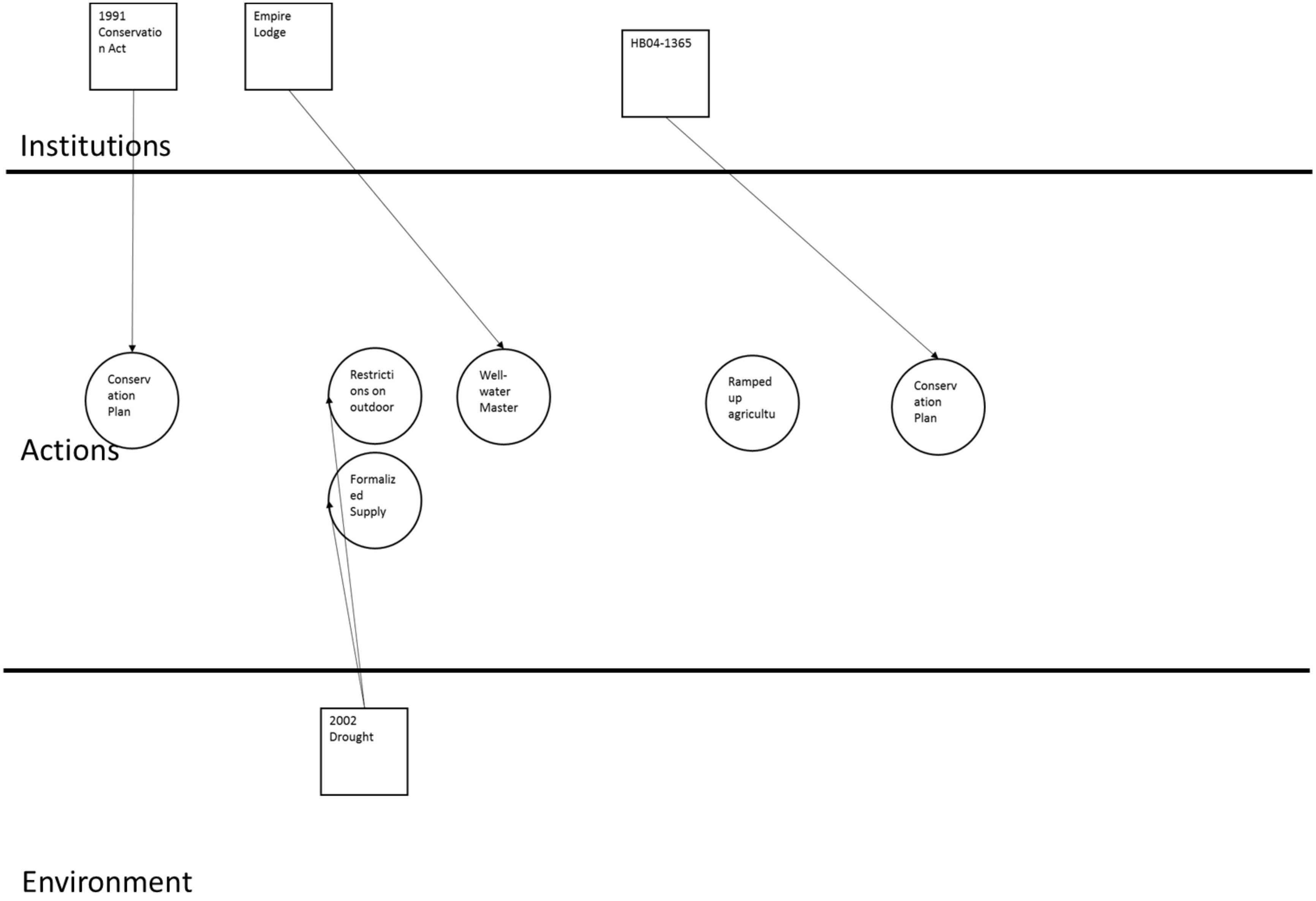

Institutions
Ask users to conserv
Actions
2002 Drought
Environment

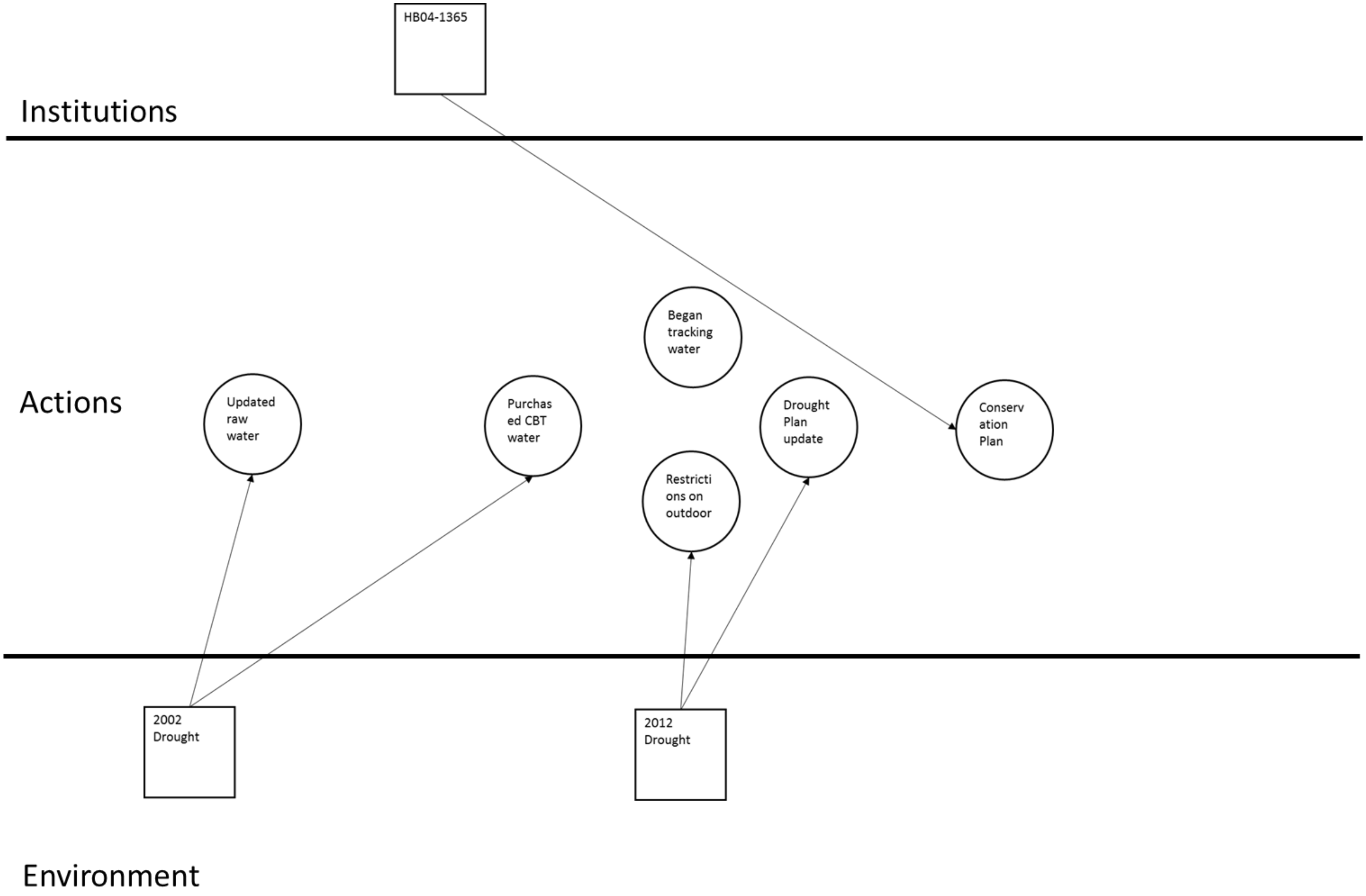

Couldn't meet state quality requirement
DMRP Overhaul
DTF / MTF Activated
Culture change
HB04-1365
Messaging coordinated
Institutions
Built pipeline for
Increased rates
Conservation Plan
Began tracking water
Struck deal with
Retrofitted indoor
Actions
Restrictions on outdoor
Drought Plan
Restrictions on outdoor
Increased rates
Cut excessive users
Joined Northern Water
Aggressively pursued
2002 Drought
2012 Drought
Environment

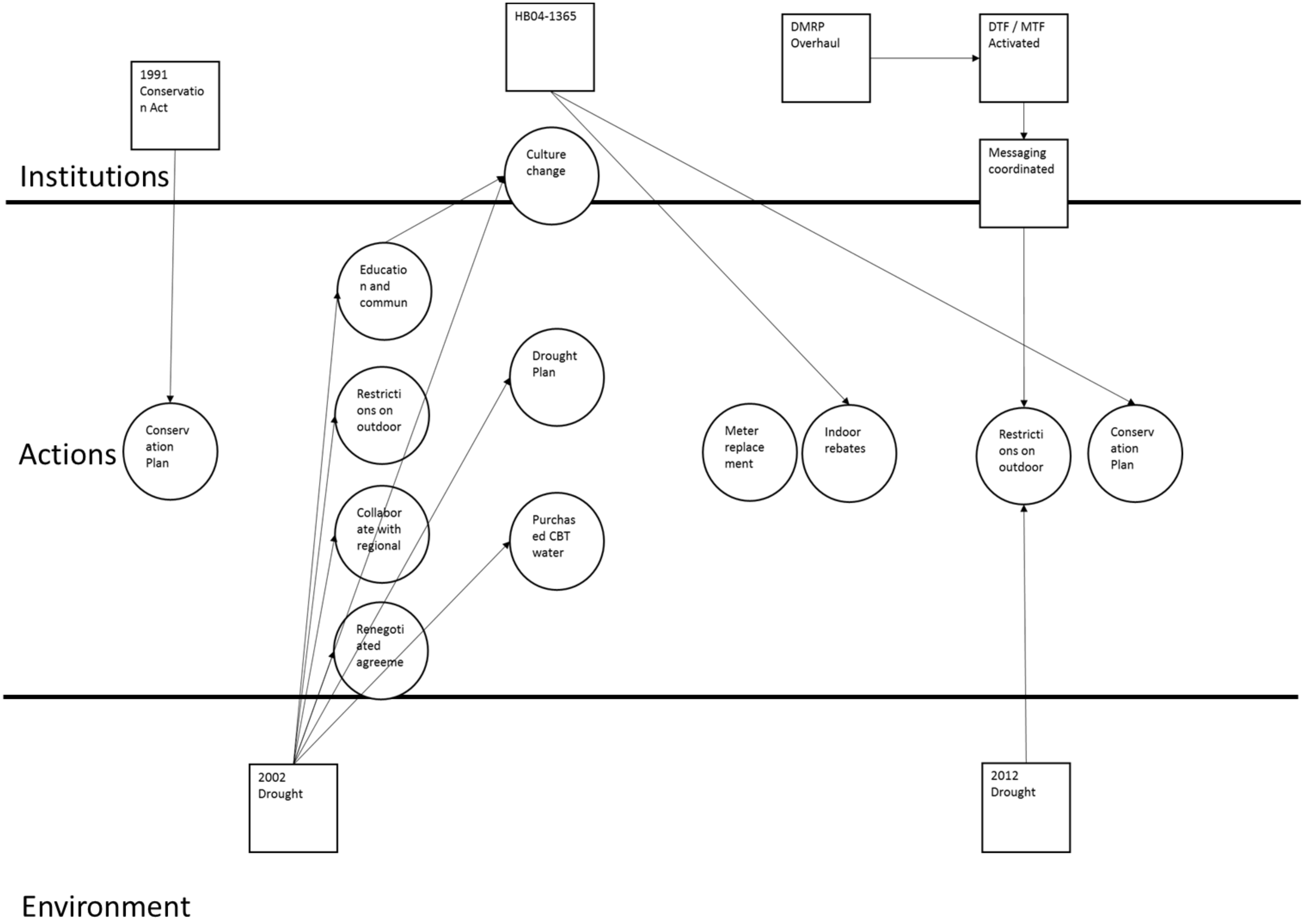

No mechanism for sanctioning excessive use
HB04-1365
Institutions
Changed rate structur
Increase d rates
Conserv ation Plan
Actions
Restricti ons on outdoor
2002 Drought
Environment

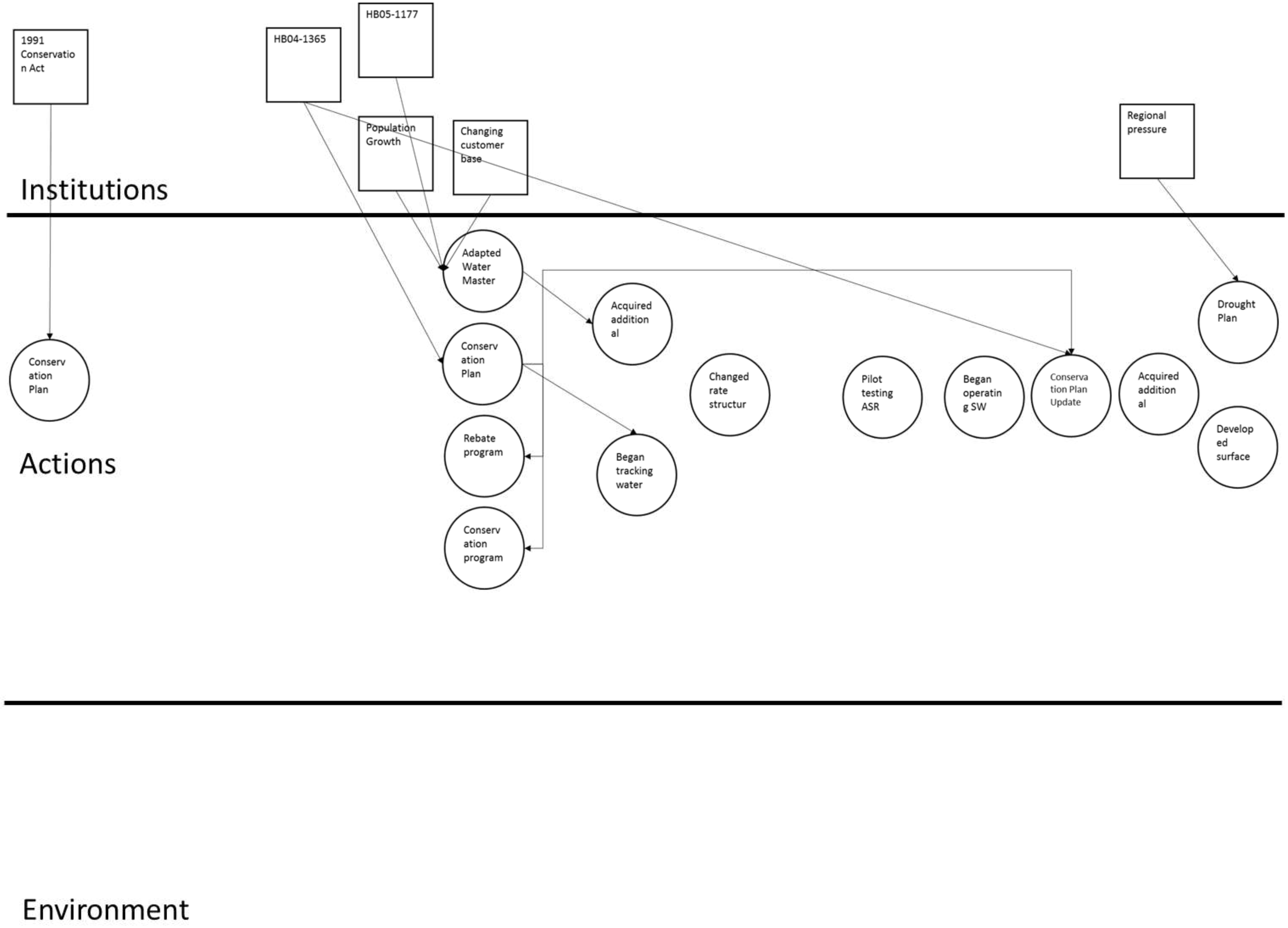

Institutions
Restrictions on outdoor
Arrangements with
Surcharge for high
Built dam to create
Drought Plan
Actions
Work closely with
Changed rate structur
Collaborate with regional
2002 Drought
Environment

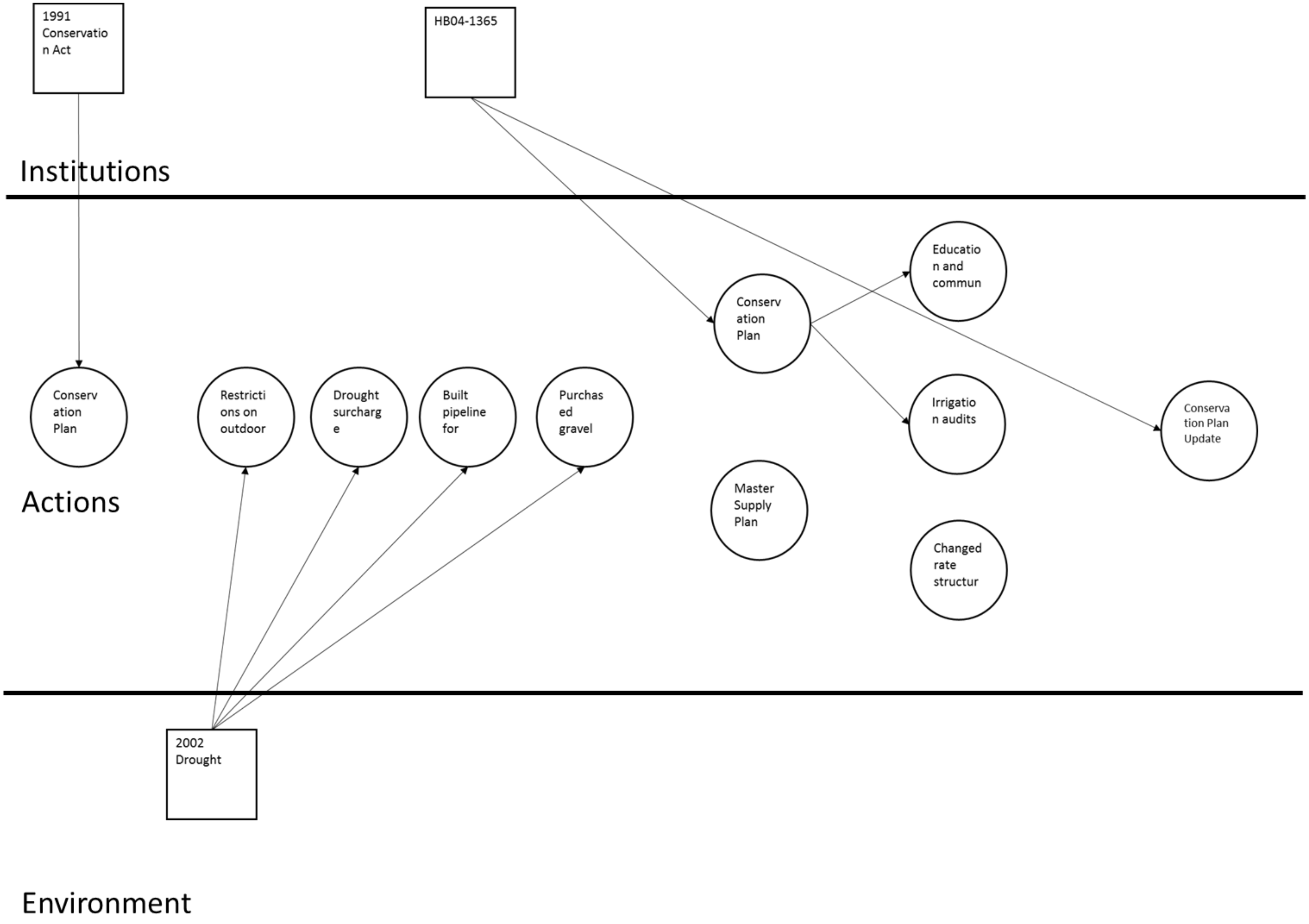

Institutions
Restricti
ons on
outdoor
Actions
Built
dam to
create
Cut
excessiv
e users
2002
Drought
Environment

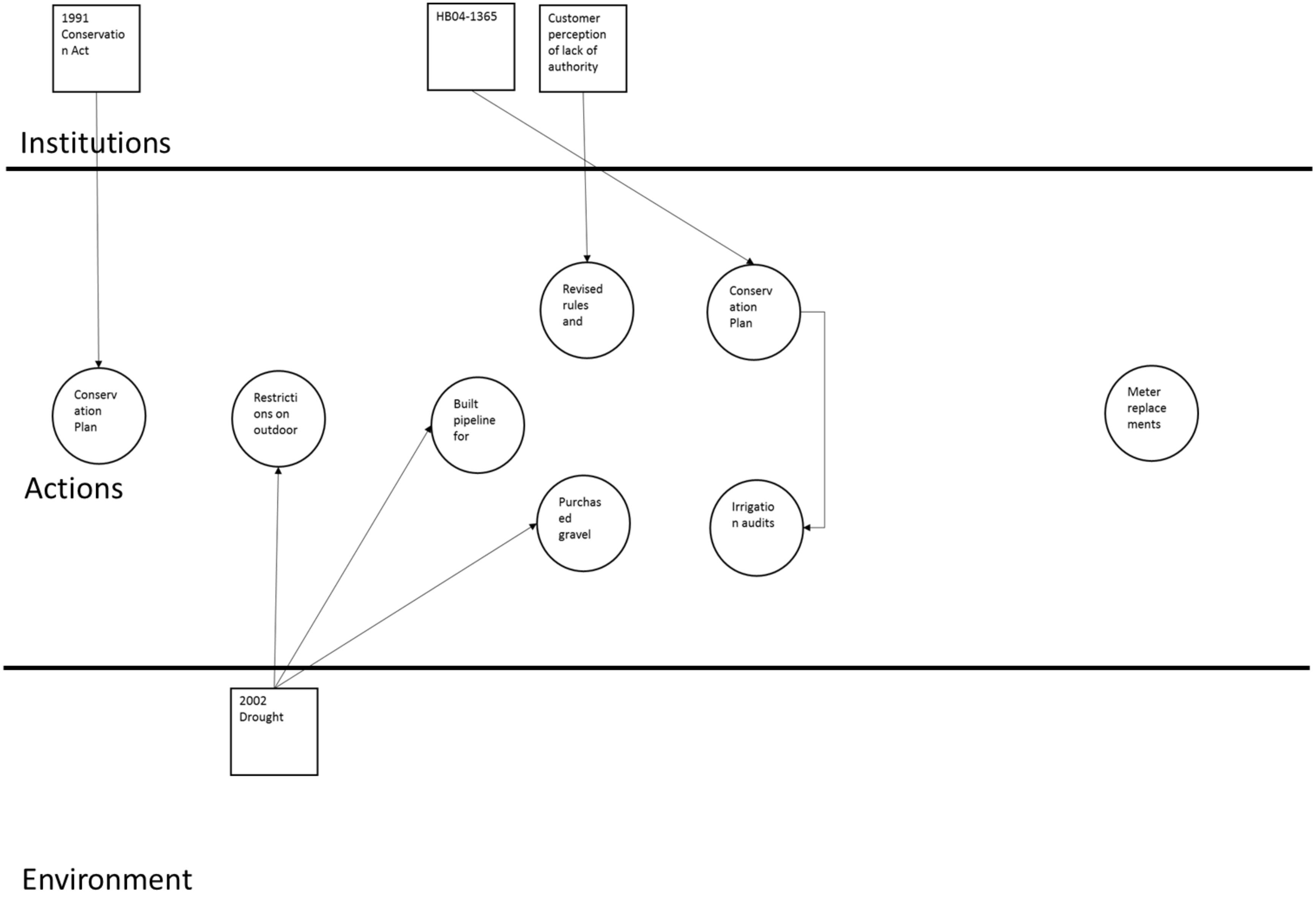

1991 Conservation Act
Empire Lodge
HB04-1365
Institutions
Conservation Plan
Restrictions on outdoor
Well-water Master
Ramped up agricultu
Conservation Plan
Actions
Formalized Supply
2002 Drought
Environment

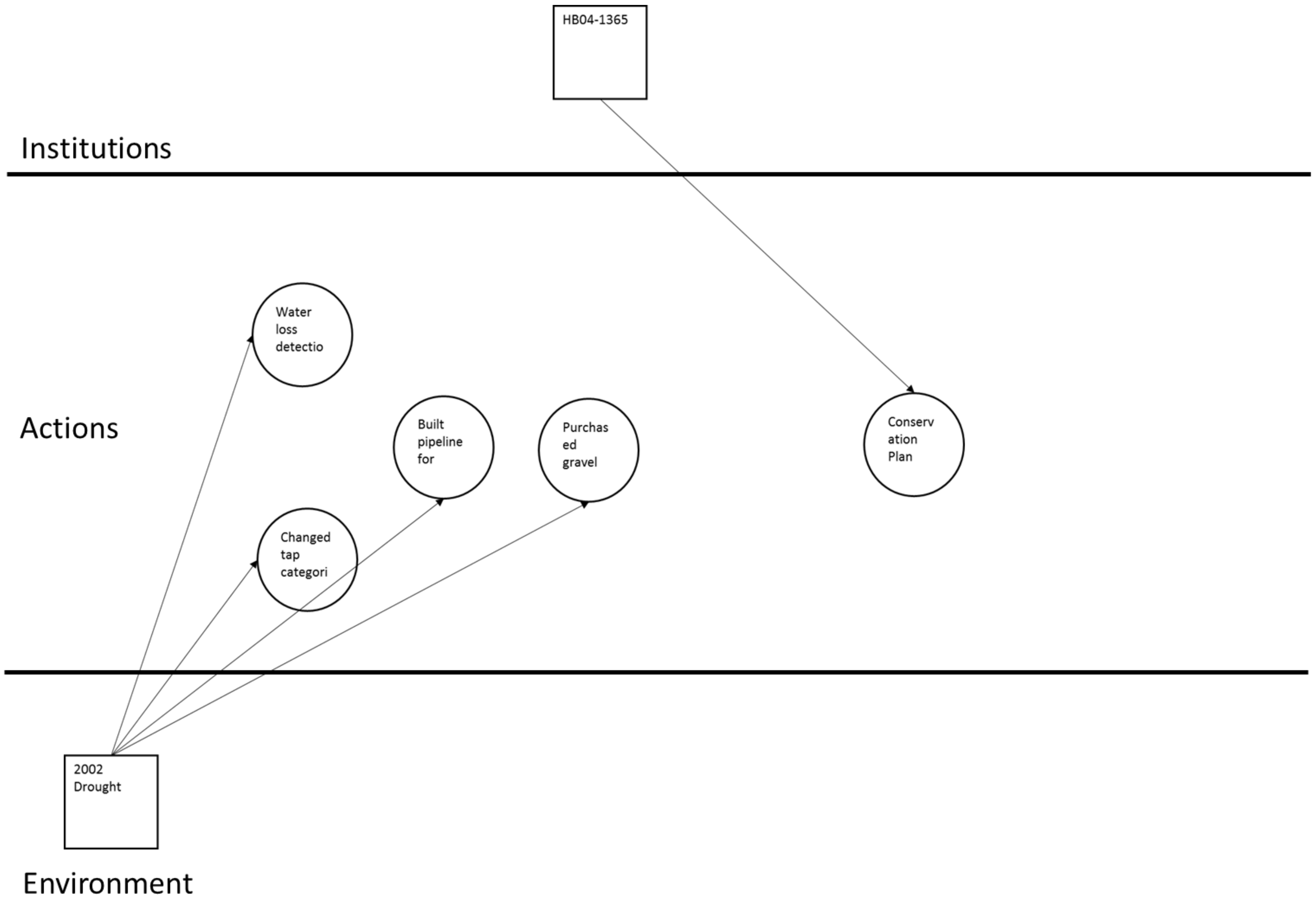

HB04-1365
Institutions
Actions
Began tracking water
Updated raw water
Purchased CBT water
Drought Plan update
Conservation Plan
Restrictions on outdoor
2002 Drought
2012 Drought
Environment

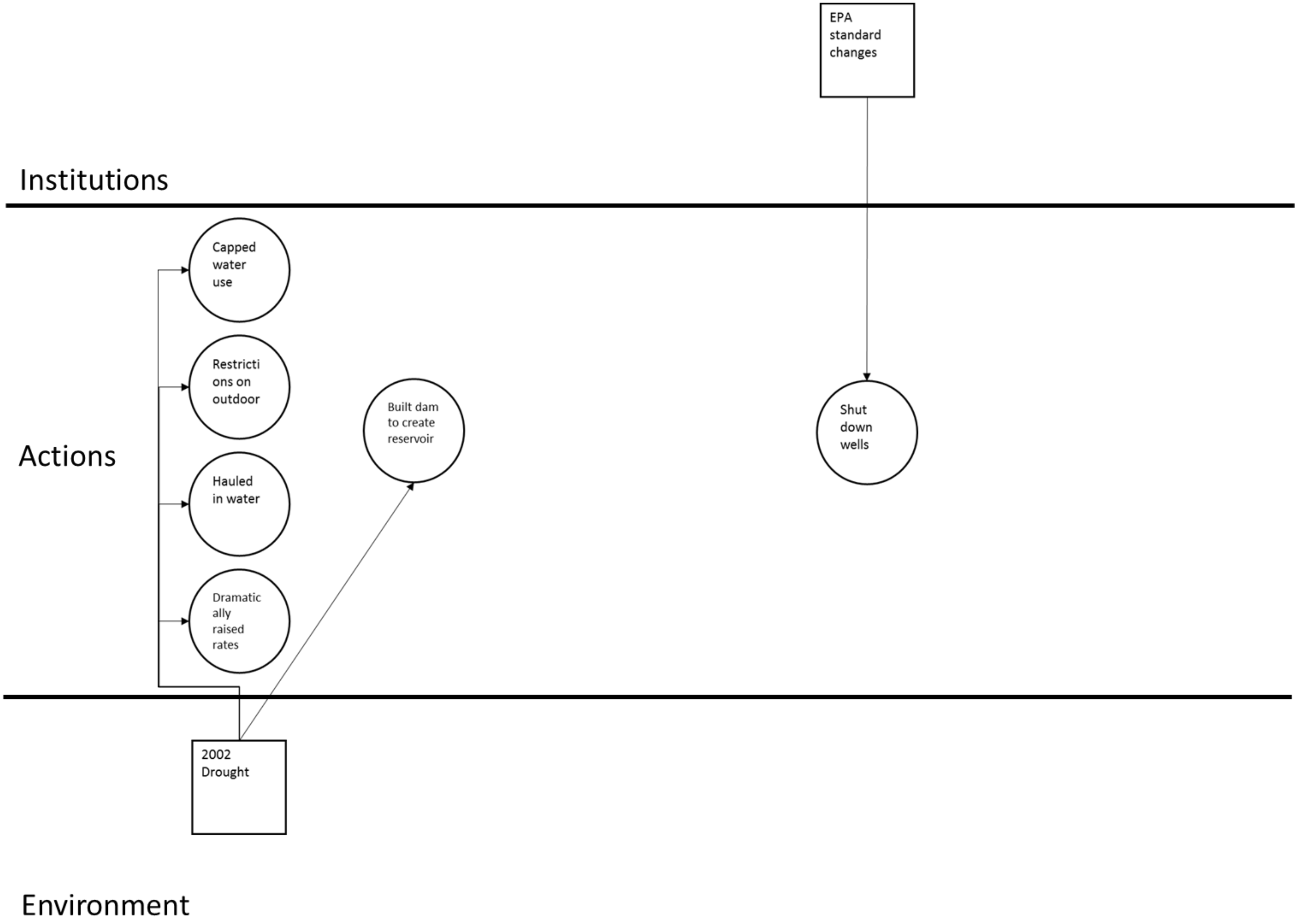

HB04-1365
DMRP Overhaul
DTF / MTF Activated
1991 Conservation Act
Culture change
Messaging coordinated
Institutions
Education and commun
Drought Plan
Restrictions on outdoor
Conservation Plan
Actions
Meter replacement
Indoor rebates
Restrictions on outdoor
Conservation Plan
Collaborate with regional
Purchased CBT water
Renegotiated agreeme
2002 Drought
2012 Drought
Environment

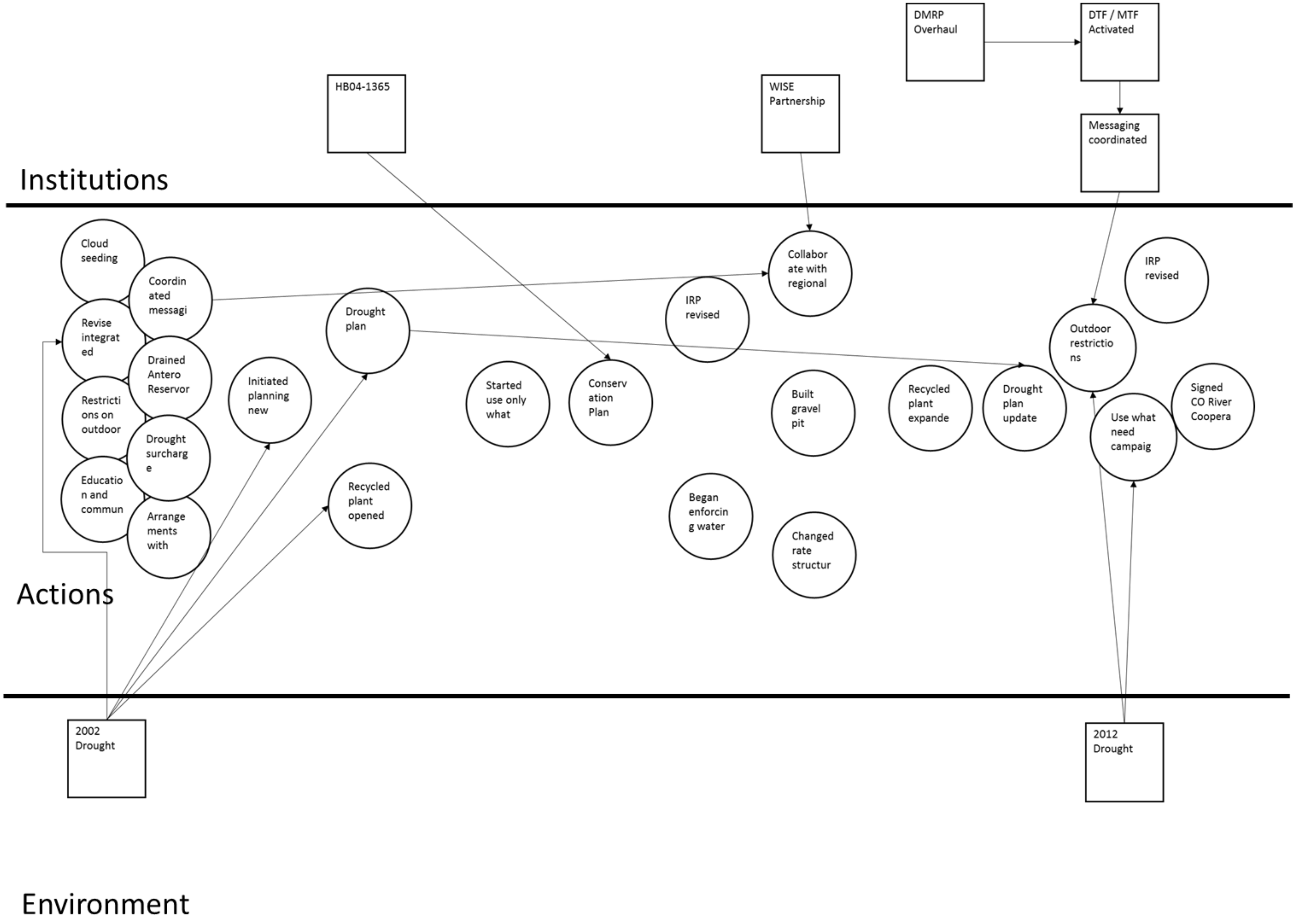

1991 Conservatio n Act
HB04-1365
HB05-1177
Population Growth
Changing customer base
Regional pressure
Institutions
Adapted Water Master
Acquired addition al
Conserv ation Plan
Conserv ation Plan
Changed rate structur
Pilot testing ASR
Began operatin g SW
Conserva tion Plan Update
Acquired addition al
Drought Plan
Develop ed surface
Rebate program
Began tracking water
Conserv ation program
Actions
Environment

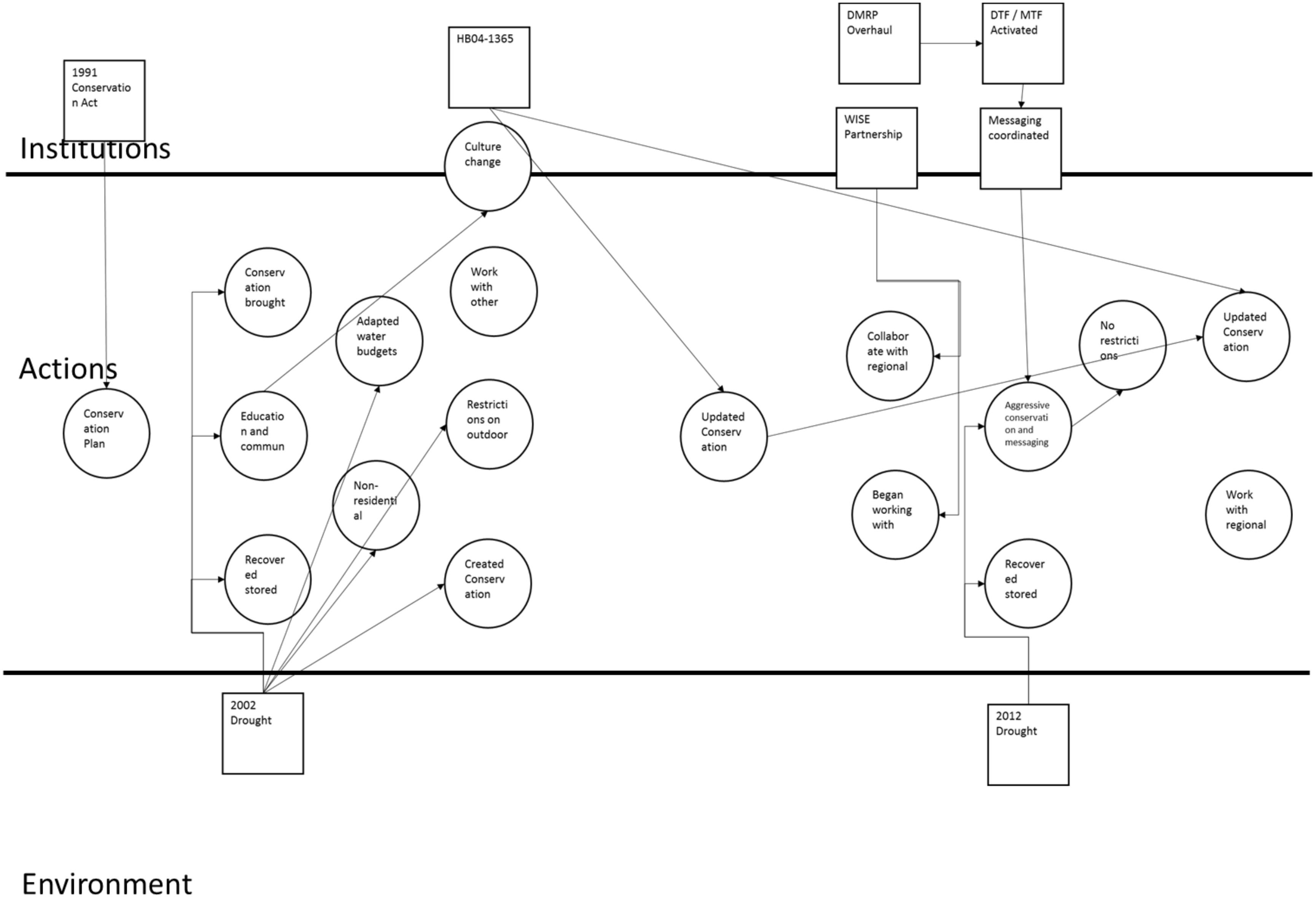

1991 Conservation Act
HB04-1365
Institutions
Education and commun
Conservation Plan
Conservation Plan
Restrictions on outdoor
Drought surcharge
Built pipeline for
Purchased gravel
Irrigation audits
Conservation Plan Update
Actions
Master Supply Plan
Changed rate structur
2002 Drought
Environment

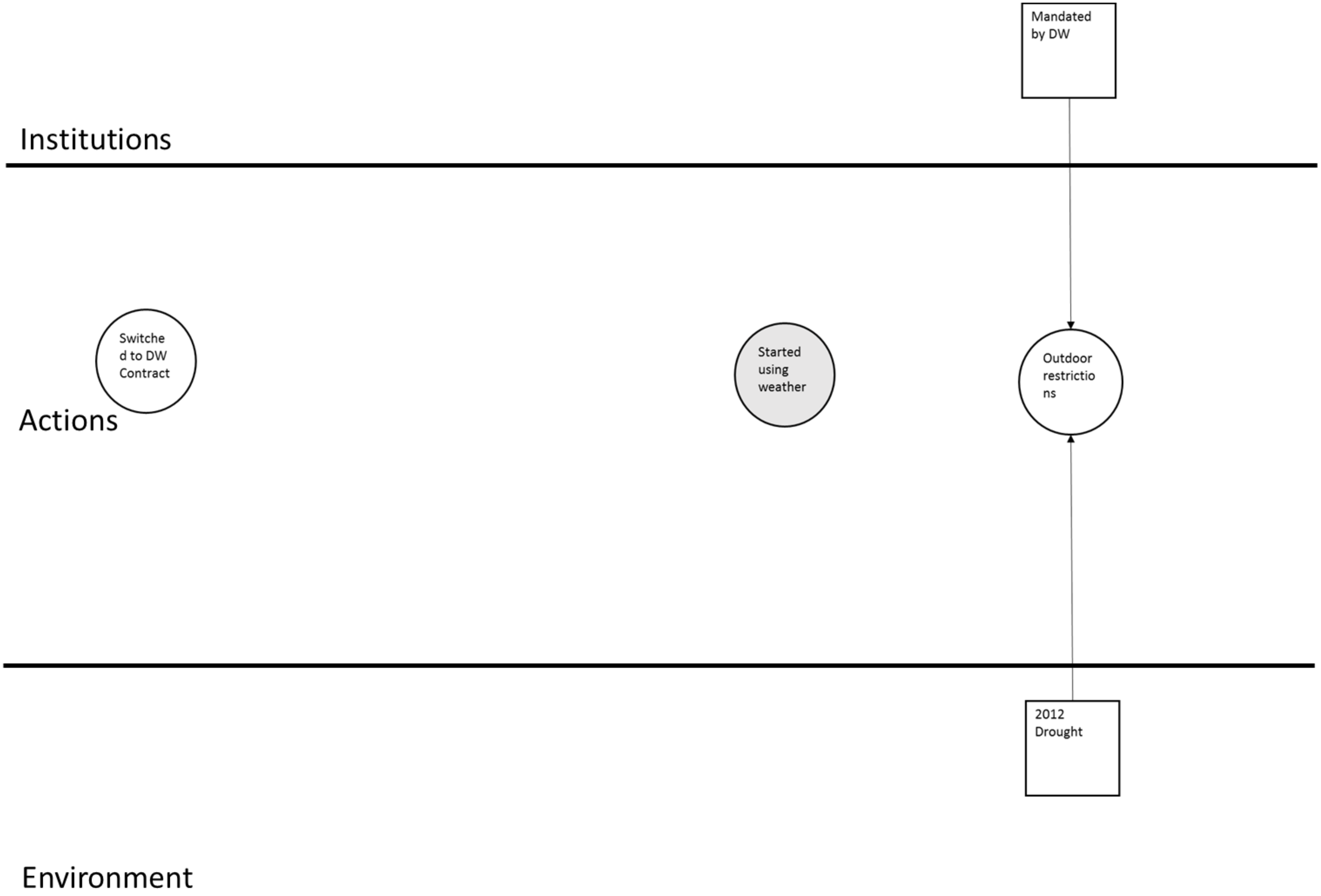

1991 Conservation Act
HB04-1365
Customer perception of lack of authority
Institutions
Revised rules and
Conservation Plan
Conservation Plan
Restrictions on outdoor
Built pipeline for
Meter replacements
Actions
Purchased gravel
Irrigation audits
2002 Drought
Environment

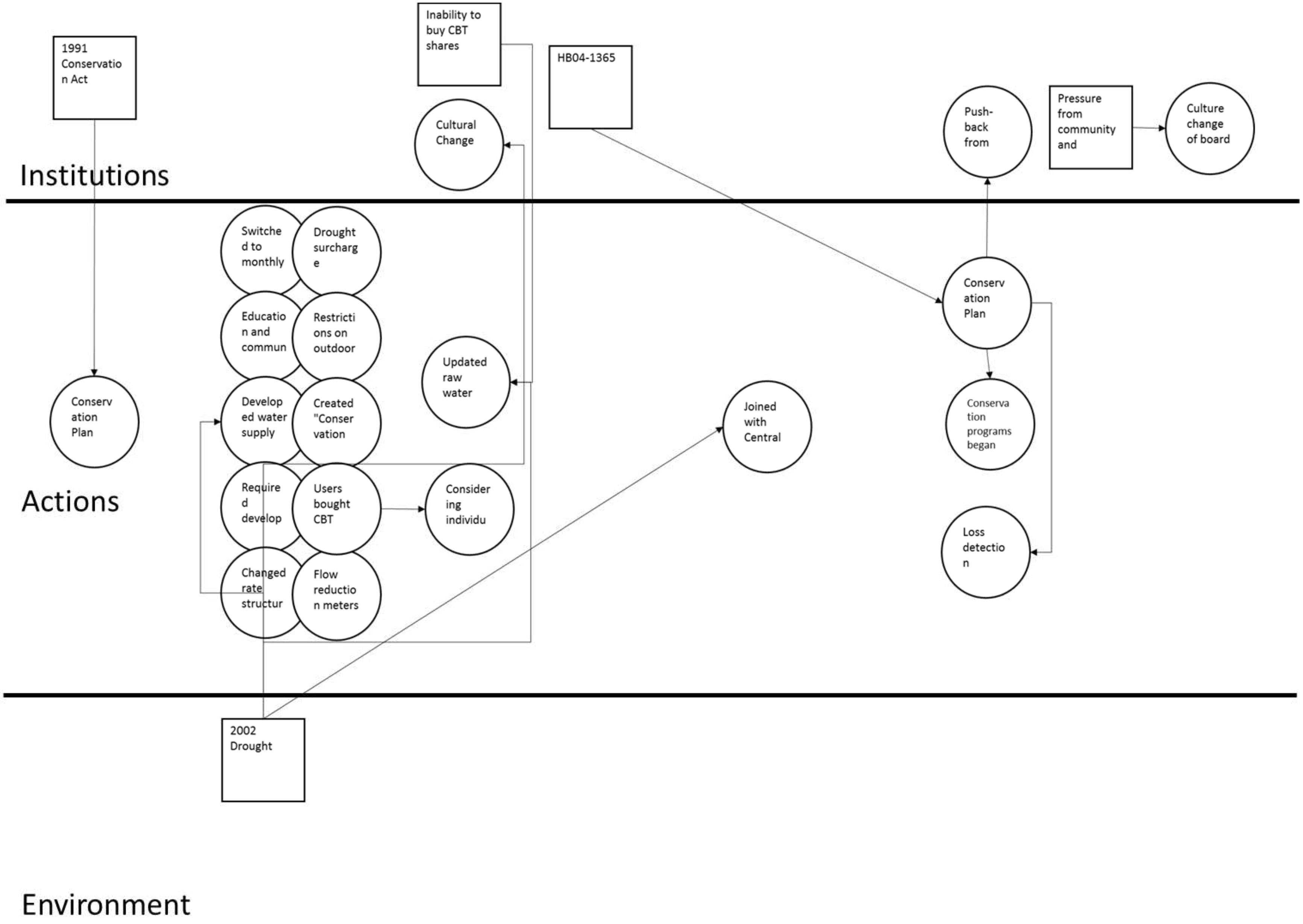

HB04-1365
Institutions
Water loss detectio
Actions
Built pipeline for
Purchas ed gravel
Conserv ation Plan
Changed tap categori
2002 Drought
Environment

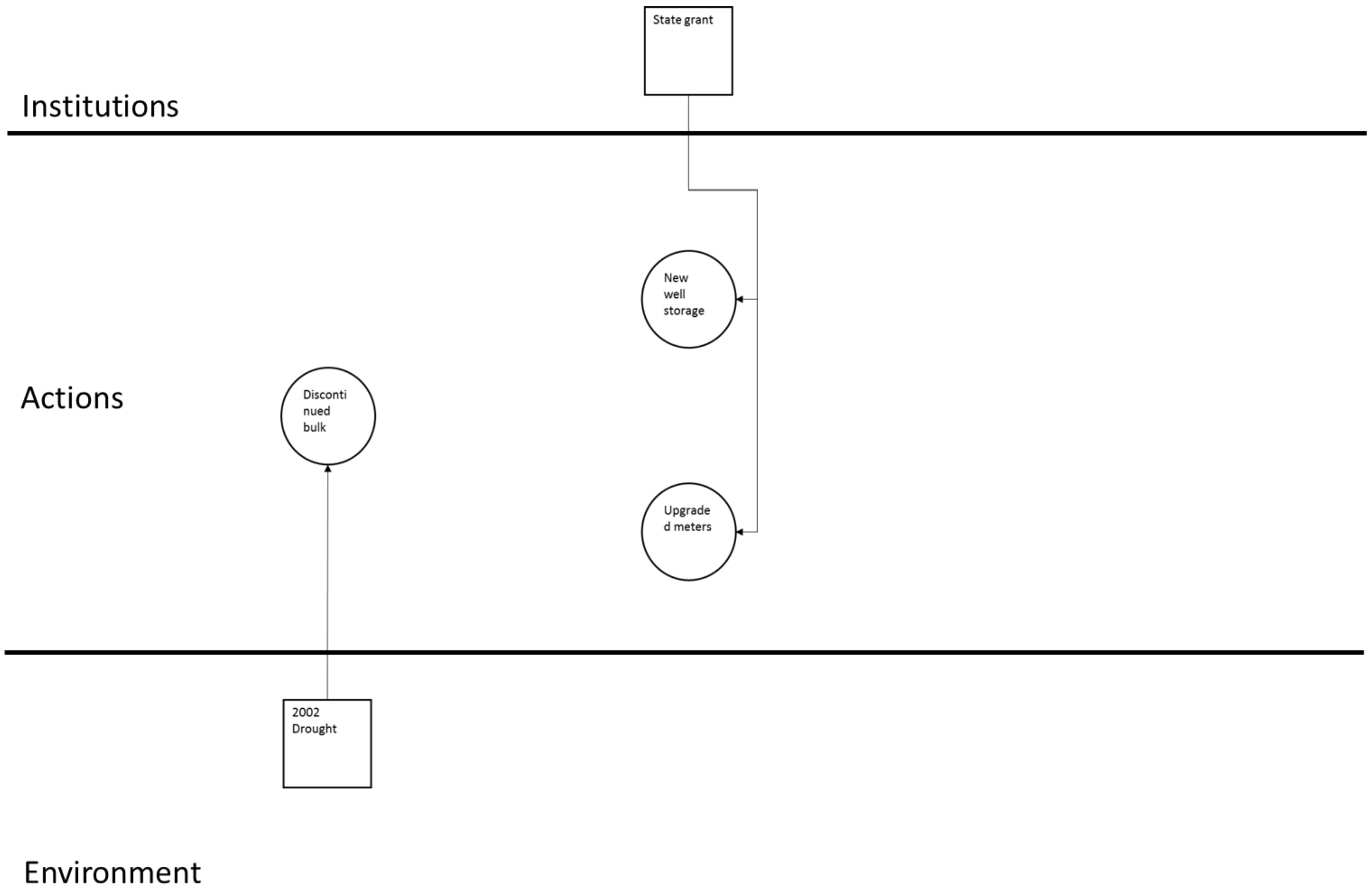

EPA standard changes
Institutions
Capped water use
Restrictions on outdoor
Hauled in water
Dramatically raised rates
Built dam to create reservoir
Shut down wells
Actions
2002 Drought
Environment

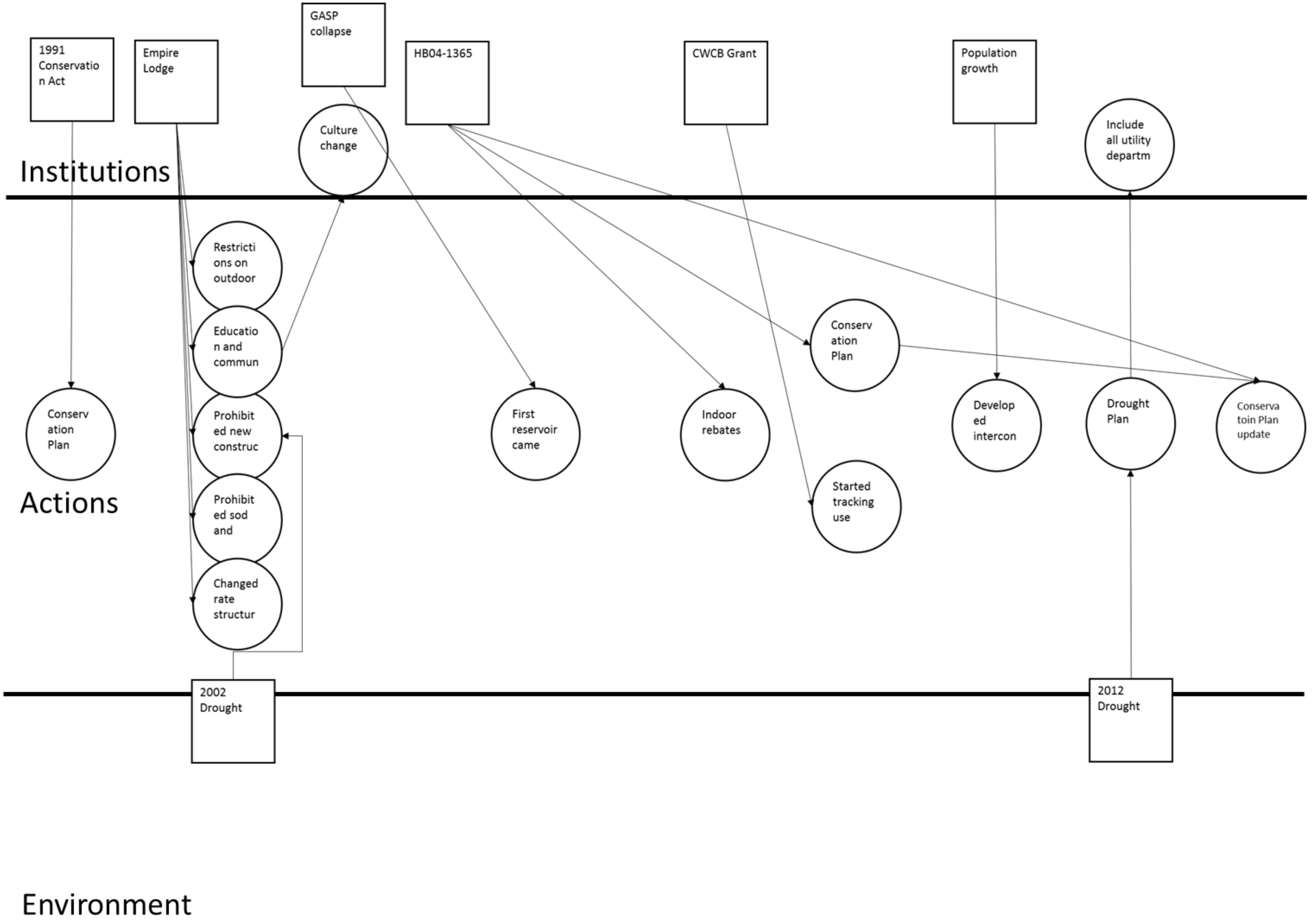

DMRP Overhaul
DTF / MTF Activated
HB04-1365
WISE Partnership
Messaging coordinated
Institutions
Cloud seeding
Coordin ated messagi
Collabor ate with regional
IRP revised
Revise integrat ed
Drought plan
IRP revised
Outdoor restrictio ns
Drained Antero Reservor
Initiated planning new
Started use only what
Conserv ation Plan
Built gravel pit
Recycled plant expande
Drought plan update
Signed CO River Coopera
Restricti ons on outdoor
Drought surcharg e
Use what need campaig
Educatio n and commun
Recycled plant opened
Began enforcin g water
Arrange ments with
Changed rate structur
Actions
2002 Drought
2012 Drought
Environment


Institutions
Actions
Environment
1991 Conservation Act
HB04-1365
DMRP Overhaul
DTF / MTF Activated
WISE Partnership
Messaging coordinated
Culture change
Conservation brought
Work with other
Adapted water budgets
Conservation Plan
Education and commun
Restrictions on outdoor
Non-residential
Recovered stored
Created Conservation
Updated Conservation
Collaborate with regional
Began working with
No restrictions
Aggressive conservation and messaging
Updated Conservation
Work with regional
Recovered stored
2002 Drought
2012 Drought


Mandated by DW
Institutions
Switched to DW Contract
Started using weather
Outdoor restrictions
Actions
2012 Drought
Environment


1991 Conservation Act
Inability to buy CBT shares
HB04-1365
Cultural Change
Push-back from
Pressure from community and
Culture change of board
Institutions
Switched to monthly
Drought surcharge
Education and commun
Restrictions on outdoor
Updated raw water
Conservation Plan
Developed water supply
Created "Conservation
Joined with Central
Conservation Plan
Conservation programs began
Required develop
Users bought CBT
Considering individu
Actions
Loss detection
Changed rate structur
Flow reduction meters
2002 Drought
Environment


State grant
Institutions
New well storage
Actions
Disconti nued bulk
Upgrade d meters
2002 Drought
Environment


1991 Conservatio n Act
Empire Lodge
GASP collapse
HB04-1365
CWCB Grant
Population growth
Culture change
Include all utility departm
Institutions
Restricti ons on outdoor
Educatio n and commun
Prohibit ed new construc
Prohibit ed sod and
Changed rate structur
Conserv ation Plan
First reservoir came
Indoor rebates
Conserv ation Plan
Started tracking use
Develop ed intercon
Drought Plan
Conserva toin Plan update
Actions
2002 Drought
2012 Drought
Environment

APPENDIX 3.6. WATER PROVIDER MANAGEMENT CHANGE INDEX VALUES

Provider ID	Index value	Management change
P01	0.69	0
P02	1.97	1
P03	0.12	0
P04	1.84	1
P05	1.54	1
P06	-0.01	0
P07	1.37	1
P08	0.87	0
P09	0.55	0
P11	0.34	0
P12	1.39	1
P13	0.62	0
P14	1.33	1
P15	1.31	1
P16	0.86	0
P17	0.90	0
P18	0.91	0
P19	0.16	0
P20	1.84	1
P21	1.36	1
P22	1.25	1
P23	1.29	1
P24	0.19	0
P25	1.12	1

APPENDIX 3.7. TRUTH TABLE

M	**D**	**I**	**Outcome**	**n**	**incl**	**cases**
1	1	1	1	3	1	2,15,21
1	0	1	1	1	1	7
1	1	0	1	1	1	25
0	1	1	1	4	0.750	1,5,14,20
0	0	1	1	7	0.429	4,9,12,16,17,18,23
0	0	0	0	8	0.125	3,6,8,11,13,19,22,24

Response variable

Outcome: Changed to adaptive management after 2002 drought

Contributing conditions

M: Interacted with formal policy processes to increase management options

D: Interacted with formal processes to mitigate drought impacts

I: Interacted with informal provider networks

APPENDIX 4.8. UNIVARIATE DISTRIBUTIONS AND PARAMETERIZATION

Drought Characteristic	Scenario	Distribution	Transformation	Shape 1	Shape 2
Duration	Historical	geometric	x	prob=0.24	--
	RCP 4.5 NF	geometric*		prob=0.23	--
	RCP 4.5 FF	geometric*		prob=0.21	--
	RCP 8.5 NF	geometric*		prob=0.27	--
	RCP 8.5 FF	geometric*		prob=0.16	--
Severity	Historical	lognormal*	-x	mealog=1.10	sdlog=0.90
	RCP 4.5 NF	weibull*		shape=1.28	scale=3.58
	RCP 4.5 FF	exponential**		rate=0.17	--
	RCP 8.5 NF	lognormal**		meanlog=0.90	sdlog=0.81
	RCP 8.5 FF	lognormal*		meanlog=1.44	sdlog=1.09
Peak	Historical	weibull**	log(-x)	shape=1.20	scale=0.17
	RCP 4.5 NF	weibull**		shape=1.18	scale=0.14
	RCP 4.5 FF	weibull**		shape=1.24	scale=0.17
	RCP 8.5 NF	weibull**		shape=0.94	scale=0.13
	RCP 8.5 FF	weibull**		shape=1.11	scale=0.14

* k-m significance level p>0.01

** k-m significance level p>0.05

Otherwise, best fitting distribution