University of Nevada, Reno

Collaborative Modeling to Assess Climate Adaptation and Science Information Needs in Snow-fed River Systems

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Abstract

Snow-fed river systems are acutely sensitive to climate change, providing unique case studies to advance an emergent field of socio-hydrology. Climate change alters seasonal snowpack dynamics with warmer temperatures bringing precipitation as rain versus snow, increasing winter flood events, decreasing snowpack accumulation, advancing snowmelt to earlier in the year, shifting peak streamflow, and altering surface water storage and groundwater recharge. Water management based on historical and stationary climate patterns is further challenged under a warmer climate. Participatory research approaches, such as collaborative modeling, are ideally suited in the case study setting and acknowledge the role of local stakeholder knowledge in understanding dynamics between human and water systems.

This work presents research as part of a larger collaborative modeling case study underway in the snow-fed Truckee-Carson River System in California and Nevada. Through systematic and iterative engagement with local diverse water managers across the river system, researchers harness local knowledge to assess climate adaptation, identify science information needs, and prioritize hydrologic and operations model simulations accordingly. The following research questions are addressed by this work: 1) How do water supply challenges vary as a function of hydroclimate conditions? 2) How do local adaptation and implementation barriers change coincident with interannual hydroclimate variability? 3) Under a warmer climate and earlier snowmelt regimes, to what extent do locally-identified adaptation strategies enhance water supply? 4) What science information is needed to further support local climate adaptation?

Comparison of interviews conducted with key water managers during the 2015 and 2016 consecutive warmer drought years reveals increased drought adaptation efforts that include: enhancing water supply through alternative sources, collecting data to monitor climate impacts, increasing flexibility of existing water management, and fostering improved communication and collaboration among other water managers. Despite drought relief brought by the historic 2017 wet year, these same managers described ongoing drought adaptation efforts to enhance water supply that gained momentum as a result of the improved relationships required to mitigate flood damage. While managers described climate uncertainty as the greatest impediment to their adaptation efforts during consecutive warmer drought years, managers referred to this barrier less often, exemplifying recent climate variability as the “new normal” climate for which they should plan. Instead, managers identified as a critical barrier existing water management practices based on stationary climate patterns and requested researchers simulate locally-identified water management strategies under a warmer climate.

To facilitate an evaluation of locally-identified adaptation strategies, researchers simulate Truckee River reservoir reoperation to allow for earlier storage under a warmer climate scenario. Simulation results from an integrated hydrologic and operations model tailored to the Truckee River Basin demonstrate that reservoir reoperation effectively absorbs earlier snowmelt runoff and peak streamflow timing and provides downstream benefits for urban, agricultural, and environmental water users. This work illustrates how collaborative modeling involving local stakeholders and researchers generates information essential for local climate adaptation and also advances applied climate and socio-hydrology research. The collaborative modeling research design can be replicated in other regulated snow-fed river systems characterized by diverse and competing stakeholders managing scarce water supplies under climate change and researchers willing to work closely with stakeholders to investigate strategies in support of local climate adaptation.

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This work would not have been possible without the support and guidance of so many.

I would first like to thank my advisor, Greg Pohll, for his mentorship, support, and encouragement that the study of hydrology can and should involve a human and social dimension - even if the research questions are harder to develop.

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Dedication

Pursuing a doctoral degree has forever been a goal of mine. I believe my parents Kim and George knew that it would happen - I simply had to trust the path for which it would come.

I dedicate this achievement to you both - for providing an exploratory learning environment at an early age, valuing education and self-discovery, and encouraging me to pursue my passion. Your words kept me afloat, and surprise sweaters provided just the boost of confidence I sometimes needed.

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As I write these words, I am forever grateful for my husband Michael, for believing in me, supporting me through the highs and lows, and sacrificing just a few adventure weekends these last four years. You have been the constant reminder that hard work earns great rewards.

“Without love in a dream it will never come true.” – Robert Hunter

Table of Contents

List of Tables

Chapter 1: Adapting to Variable Water Supply in the Truckee-Carson River System, Western USA 6

Chapter 2: Hydroclimate Variability in Snow-fed River Systems: Local Water Managers' Perspectives on Adapting to the New Normal 44

Chapter 3: Collaborative Modeling in Snow-fed River Basins: Implications of Reservoir Reoperation Under a Warmer Climate 68

List of Figures

Introduction

Snow-fed river system communities are acutely sensitive to climate change (IPCC, 2014; USGCRP, 2017) as the majority of their water supply is derived from snow (Barnett et al., 2005; Li et al., 2017; Mankin et al., 2015). A warmer climate shifts precipitation regimes from snow to rain (Knowles et al., 2006), reduces snowpack accumulation and persistence (Mote, 2003; Mote et al., 2005; Trujillo & Molotch, 2014), and shifts peak streamflow timing to earlier in the year (Barnhart et al., 2016; Stewart et al., 2005). As a result, the effective storage volume in a river system decreases due to reduced surface water stored in reservoirs (Georgakakos et al., 2014) and decreased groundwater recharge (Huntington & Niswonger, 2012; Jasechko et al., 2014; Taylor et al., 2013). A warmer climate can also increase the risk of winter flooding, as rain falls and melts existing snowpack (Dettinger et al., 2015; McCabe & Wolock, 2007). Water management practices engineered based on historical and stationary climate patterns can further exacerbate climate change impacts (Georgakakos et al., 2014; Van Loon et al., 2016; Milly et al., 2008).

Assessing climate adaptation in snow-fed river systems, or the adjustments made to moderate harm exploit beneficial opportunities in response to actual or expected climatic stimuli (Adger et al., 2005; IPCC, 2014), situates itself in the emerging field of socio-hydrology. The "new science of people and water" considers water management practices, stakeholders, and their adaptation actions as part of the hydrologic cycle as opposed to an external forcing (Murugesu Sivapalan et al., 2012; Wagener et al., 2010). Integrating human and social dimensions within the physical aspects of hydrology facilitates a more holistic understanding of the dynamics underlying coupled human-water systems (Blair & Buytaert, 2016; Evers et al., 2017; Murugesu Sivapalan et al., 2012; Troy et al., 2015; Wagener et al., 2010). Socio-hydrology evaluates climate-induced water supply variability by integrating multiple disciplines and methods, such as developing coupled human-water system models to simulate past and future dynamics (Blair & Buytaert, 2016) and conducting case study research to better understand the system and factors driving water management changes (Mostert, 2018).

In the case study environment, participatory research approaches are ideally suited to convene researchers with local stakeholders and facilitate an assessment of local climate adaptation (Adger et al., 2012; Reed, 2008). These approaches rely upon local knowledge and perspectives of river system function and community interdependence on water resources, and acknowledge local stakeholders are key to adaptation (Hinkel et al., 2014; Villamor et al., 2014). Collaborative modeling, as an example of a participatory research approach, becomes useful in understanding local climate adaptation and information needs among diverse and competing local stakeholders in a river system (Beall King & Thornton, 2016; Langsdale et al., 2013; Singletary & Sterle, 2017, 2018). In this environment, insights into local adaptation are gained through social learning and information exchange (Ensor & Harvey, 2015; McGreavy et al., 2015) and innovations arise as a result of iterative and ongoing interaction and communication (Nauwelaers, 2011; Simmie & Martin, 2010). Ultimately, specifying model simulations based on local knowledge and information needs generates new knowledge useful for local adaptation while also advancing applied climate and socio-hydrology research (Dessai, Lu, & Risbey, 2005; Klenk et al., 2015; Meadow et al., 2015; Parris, 2016; Prokopy et al., 2017; Voinov et al., 2016; Voinov & Bousquet, 2010).

The literature reveals that climate adaptation strategies pursued and barriers encountered, that may constrain or impede adaptation (Eisenack et al., 2014; Moser & Ekstrom, 2010), ultimately relate to a systems’ hydrologic, socioeconomic, and ecological components, and their respective capacities to adapt (Adger et al., 2007; Moser and Boykoff, 2013). Prolonged drought and flood events can motivate adaptation, particularly when conditions exacerbate water management challenges, reveal vulnerabilities, or cause damage (Berrang-Ford et al., 2011; Bierbaum et al., 2013; Engle, 2012; McNeeley, 2014; McNeeley et al., 2016; Travis, 2014). However, interannual variability and climate uncertainty can challenge adaptation planning and eventual implementation (Berrang-Ford et al., 2011; Bierbaum et al., 2013; Coleman et al., 2016; Kates et al., 2012; Keskitalo et al., 2012; Van Loon et al., 2016; López-Hoffman et al., 2013). Adaptation may be further constrained by lack of communication and coordination (Burnham et al., 2016), existing institutional arrangements (Gallaher et al., 2013; Kates et al., 2012; McNeeley, 2017; Pulwarty & Maia, 2015), and already scarce or overallocated water supply (Fuller & Harhay, 2010; Owen, 2014; Padowski & Jawitz, 2012).

Adaptation barriers can be overcome with climate change projections at local usable scales and integrated models that examine viable, site-specific adaptation strategies (Maurer et al., 2015; Maurer & Hidalgo, 2008; Morway et al., 2016; Singh, 2010; Vicuna et al., 2010). Stakeholders working with researchers helps navigate barriers and can provide science information to support evaluation and implementation (Burnham et al., 2016; Engle, 2012; McNeeley, 2014; Nava et al., 2016; Pulwarty & Maia, 2015). Snow-fed river system case studies, therefore, can provide an opportunity to use participatory research to examine relationships between interannual climate variability and local climate adaptation (McNeeley et al., 2016; Mills-Novoa et al., 2017; Mostert, 2018; Sterle & Singletary, 2017).

Research Objectives

This work presents research that is part of a larger collaborative modeling case study underway in the snow-fed Truckee-Carson River System in California and Nevada (Singletary & Sterle, 2017, 2018). This river system typifies snow-fed systems, where snowpack originating in the Sierra Nevada supplies substantial water supply for diverse and competing downstream urban, environmental, and agricultural water use communities. The recent water years 2012-2017 (WY; 1 October to 30 September) in the region brought variable snowpack accumulation and earlier melt onset, historic drought accompanied by anomalously warmer temperatures, and flooding as a result of record precipitation and historic snowpack. While precipitation in this region varies dramatically (Dettinger, 2016; Dettinger et al., 2011; Ralph & Dettinger, 2012), WY2012-2017 illustrate the range of hydroclimate conditions anticipated under projected climate change (Cayan et al., 2010; Hatchett et al., 2017).

The collaborative modeling research design developed for and implemented in this case study harnesses local knowledge by convening diverse water managers and an interdisciplinary team of researchers to assess climate adaptation, simulate strategies that address implementation barriers, identify science information to support local adaptation, and further prioritize research activities. Water managers comprise municipal and industrial, agricultural, environmental, and regulatory water use communities, and researchers hold expertise in surface and groundwater hydrology, hydrometerology, climatology, civil engineering, applied economics, and participatory research methods.

The research questions addressed in the following three chapters are as follows:

- How do water supply challenges vary as a function of hydroclimate conditions?
- How do local climate adaptation and implementation barriers change coincident with hydroclimate variability?
- Under a warmer climate and earlier snowmelt regimes, to what extent do locally-identified adaptation strategies enhance water supply?
- What science information is needed to further support local adaptation?

The first chapter, “Adapting to Variable Water Supply in the Truckee-Carson River System, Western USA” features a comparative analysis of primary data collected from key water managers in the Truckee-Carson River System during consecutive fourth and fifth warmer drought years (WY2015 and WY2016, respectively). This chapter presents baseline water supply challenges inherent to the region, challenges exacerbated under warmer drought years, and adaptation responses based on water managers’ location and/or roles and responsibilities in the river system. Comparison of these interview data reveal that in response to continued warmer drought conditions, managers increase efforts to enhance water supply to meet current and future water demand, collect data to monitor climate impacts, increase flexibility of existing water management, and foster communication and collaboration among other water users. Managers describe climate uncertainty as the greatest barrier to their adaptation efforts, meriting continued collaboration with researchers and other water managers, to quantify climate change impacts.

The second chapter, “Hydroclimate Variability in Snow-fed River Systems: Local Managers’ Perspectives on Adapting to the New Normal” reports a third-round of primary data collected from the same water managers following the historically wet WY2017. Additionally, this chapter presents an analysis of recent (WY2012-2017) hydroclimate variability in a historic and paleoclimate context, as well as projected future climate, in order to situate managers’ perspectives. Despite some drought relief, managers describe continued drought adaptation efforts indicating that recent interannual variability represents the “new normal” conditions for which they should plan. An assessment of hydroclimate variability reveals recent water years bound historical observations and are consistent with estimated paleoclimate extremes and projected climate change. Compared to previous drought years, managers refer to climate uncertainty as an implementation barrier less often and instead identify existing water management institutions based on stationary climate patterns as the greatest impediment to adapt. Subsequently, managers identify hydrologic and operations model simulations to better understand the viability of alternative management strategies during both wet and dry years.

The third chapter, “Collaborative Modeling in Snow-fed River Basins: Implications of Reservoir Reoperation Under a Warmer Climate” illustrates collaborative modeling in practice, demonstrating how researchers utilize managers’ science information needs to specify climate scenarios and simulate local adaptation strategies. This chapter features interview results that identify Truckee River reservoirs operated based on stationary climate patterns as a barrier to enhance water supply under a warmer climate and earlier snowmelt regimes. Managers and researchers co-develop research questions to evaluate the extent to which allowing reservoirs to store earlier under a warmer climate scenario enhances water supply basin-wide. Simulating reservoir reoperation reveals that earlier storage effectively absorbs shifts in streamflow runoff timing, providing downstream benefits for urban, agricultural, and environmental water use communities. Collaborative review of simulation results affirm reoperation is a viable strategy to enhance water supply and prioritizes additional simulations to examine more closely the implications.

Chapter 1: Adapting to Variable Water Supply in the Truckee-Carson River System, Western USA

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Abstract

In snow-fed inland river systems in the western United States, water supply depends upon timing, form, and amount of precipitation. In recent years, this region has experienced unprecedented drought conditions due to decreased snowpack, exacerbated by exceptionally warmer winter temperatures averaging 3–4 °C above normal. In the snow-fed Truckee-Carson River System, two sets of interviews were conducted as part of a larger collaborative modeling case study with local water managers to examine local adaptation to current drought conditions. A comparative analysis of these primary qualitative data, collected during the fourth and fifth consecutive years of continued warmer drought conditions, identifies shifts in adaptation strategies and emergent adaptation barriers. That is, under continuous exposure to climate stressors, managers shifted their adaptation focus from short-term efforts to manage water demand toward long-term efforts to enhance water supply. Managers described the need to: improve forecasts and scientific assessments of snowmelt timing, groundwater levels, and soil moisture content; increase flexibility of prior appropriation water allocation rules based on historical snowpack and streamflow timing; and foster collaboration and communication among water managers across the river system. While water scarcity and insufficient water delivery infrastructure remain significant impediments in this arid region, climate uncertainty emerged as a barrier surrounding adaptation to variable water supply. Existing prior appropriation based water institutions were also described as an adaptation barrier, meriting objective evaluation to assess how to best modify these historical institutions to support dynamic adaptation to climate-

induced water supply variability. This study contributes to a growing body of research that assesses drought adaptation in snow-fed inland river systems, and contributes a unique report concerning how adaptation strategies and barriers encountered by local water managers change over time under continuous exposure to climate stressors. These locally identified adaptation strategies forward a larger collaborative modeling case study by informing alternative water management scenarios simulated through a suite of hydrologic and operations models tailored to this river system.

1.0 Introduction

The Truckee-Carson River System (18,197 km^2 area) supplies water to the Great Basin high desert communities of northwestern Nevada through spring snowmelt originating as winter snowpack in the Sierra Nevada in eastern California. Recent multi-year drought conditions in the region remain unprecedented in the context of the last 500 years due to decreased winter snow accumulation, exacerbated by winter temperatures averaging 3–4 °C warmer than normal (Belmecheri et al., 2016; Bond et al., 2015; Cayan et al., 2016; Cook et al., 2015; Dettinger et al., 2015; Harpold, Dettinger, et al., 2017). Less snowpack (Mote et al., 2005; Trujillo & Molotch, 2014), earlier and more rapid snowmelt (Fritze et al., 2011; Regonda et al., 2005), and warmer temperatures bringing winter precipitation in the form of rain versus snow, (Knowles et al., 2006) challenge water management in this snow-fed inland river system (Mankin et al., 2015).

Historically, spring snowmelt in this region sustains streamflow through the summer irrigation season (Barnhart et al., 2016; Godsey et al., 2014) and recharges groundwater aquifers (Harpold, 2016; Jasechko et al., 2014) used as both primary and supplemental water supply. Earlier snowmelt reduces surface water supply particularly during dry, warm periods (Georgakakos et al., 2014), while warmer precipitation arriving as Atmospheric Rivers, or rain-on-snow events, can cause both major flooding and water shortages within the same season (Das et al., 2009; Dettinger, 2013; Harpold et al., 2017). Warmer spring temperatures compound the effects of precipitation deficits through increased surface water storage evaporation, diminished soil moisture, and increased crop transpiration rates, which increase agricultural irrigation demand (Hatchett et al., 2015).

Under these conditions, water managers are challenged to sustain water supply for diverse uses that include municipal, industrial, environmental, and agricultural (Dettinger et al., 2015; Howells et al., 2013), exacerbating water demand and competition for already scarce supplies (Diffenbaugh et al., 2015). Such *adaptation strategies* should increase community resilience to climate induced variable water supply, thereby mitigating harm or exploiting beneficial opportunities (IPCC, 2014).

Increased occurrence and severity of droughts and floods are known to motivate adaptation planning while observed changes in precipitation patterns and increased seasonal variability, for example, challenge water managers' ability to devise sustainable solutions (Berrang-Ford et al., 2011; Coleman et al., 2016; Keskitalo et al., 2012). For example, In California's Central Valley, perceived changes in water availability had significant effects on farmers' intentions to adopt adaptation strategies (Haden et al., 2012; Jackson et al., 2011). During a recent (2000-2012) drought in Arizona, learning, information and knowledge exchange, and research through either formal or informal collaborations, provided opportunities for adaptation that included water supply enhancement, infrastructure upgrades, conservation, rate restructures, and long-term drought planning (Engle, 2012).

In implementing adaptation strategies, adaptation barriers may emerge that constrain or impede implementation (Eisenack et al., 2014). In Utah, for example, water managers described adaptation barriers that included water reallocation and equitable water transfers, stakeholder cooperation, population growth, and securing additional water supplies (Burnham et al., 2016). Existing prior appropriation doctrine and supporting institutional arrangements can also constrain adaptation (Kates et al., 2012), as observed in Colorado (Gallaher et al., 2013).

Adaptation barriers identified in other case studies to date include existing water management practices, lack of communication, and *climate uncertainty* (Bierbaum et al., 2013). Climate uncertainty refers to the uncertainty associated with future anthropogenic climate change, climate system response to past and future change, and limitations in accurately downscaling global climate projections to local and regional scales (Global Commons Institute, 2010). In responding to 2002 drought conditions in northwest Colorado, for example, quantifying climate change uncertainty is paramount to adaptation planning (McNeeley, 2014).

While current research reports a broad range of adaptation strategies toward sustainable water management solutions to cope with climate uncertainty and drought conditions (Burnham et al., 2016; Engle, 2012; Nava et al., 2016; Pulwarty & Maia, 2015), devising effective solutions becomes difficult due to the variance in rate of change of conditions and degree of spatial heterogeneity across a given hydrologic river system. This can ultimately constrain adaptive options available to institutions and individual water managers (Van Loon et al., 2016; López-Hoffman et al., 2013) and challenge efforts to balance the hydrologic aspects of snow-fed river systems with meeting the needs of diverse water user communities located across the system. For example, system-wide regulatory management efforts are supported only if such efforts do not negatively impact environmental or agricultural water use (Stoutenborough & Vedlitz, 2014).

Capturing the local knowledge and the information needs of diverse water users is made possible through basin-scale participatory research approaches, such as collaborative modeling (Adger et al., 2009; Beall King & Thornton, 2016; Engle, 2012; Moser & Ekstrom, 2010; Parris, 2016). Embracing both knowledge and diverse values enhances our understanding of complex environmental problems (Reed, 2008). Participatory research, experiential learning, and shared best practices results in new knowledge that enhances local capacity to manage water resources sustainably (Meadow et al., 2015).

Primary data collected during interviews with local managers provide researchers the opportunity to assess adaptation strategies and adaptation barriers (Adger et al., 2005; Engle, 2012; Moser & Ekstrom, 2010) in response to the most salient changes (Barnett et al., 2014). Ultimately, this improves our understanding of how adaptation strategies and actions may change over time under continuous exposure to climate stressors and uncertainty (Bierbaum et al., 2013; Eisenack et al., 2014; Ekstrom & Moser, 2014). Further, primary data collection provides the opportunity to learn about adaptation firsthand from different water user groups.

This paper reports the results of an analysis of qualitative data collected as part of a larger collaborative modeling research project in the Truckee-Carson River System case study area (Singletary & Sterle, 2017). Face-to-face interviews conducted with local water managers illuminate how local water managers are adapting to consecutive years of warmer drought conditions. We explore the extent to which these adaptation strategies change over time with continuous exposure to climate stressors, and identify barriers that constrain or impede their efforts to adapt.

Drawing upon local knowledge and expertise, we pose the following research questions: (1) What are typical water supply challenges in a snow-fed arid inland river system independent of warmer drought conditions? (2) How does water management adapt to consecutive warmer drought years? (3) What barriers to adaptation, if any, exist? To answer these questions, we analyze primary qualitative data collected from local water managers across the river system over a two-year period (2015–2016) coincident with fourth and fifth consecutive years of warmer drought conditions.

2.0 Case Study Area: The Truckee-Carson River System

The Truckee-Carson River System encompasses an area of 18,197 km^2. Both the Truckee (195 km) and Carson Rivers (211 km) originate as snowpack in the Sierra Nevada of eastern California, flow northeastward, and terminate in the Great Basin of northwestern Nevada (Figure

1). Areas in the headwaters receive over 70 inches (1778 mm) of precipitation annually, with 90% of the precipitation above 6000 feet (1829 m) accumulating as snow between November and April. Due to a rain shadow effect, the middle reaches of the system receive less than 15 inches (381 mm) of precipitation annually on average, with lower reaches of the Carson River receiving on average less than five inches (127 mm) annually. Spring snowmelt runoff from April to July generates the majority of river flow, with historical peak runoff occurring in June, sustaining river flows through August. Thirty year (i.e., 1981–2010) annual average temperatures for the region range from 47.8 to 68.9 °F (8.8 to 20.5 °C) in the higher elevations in the headwaters to 67.0 to 94.5 °F (19.4 to 34.7 °C) in the lower elevations near the system terminus (USBOR, 2015).

2.1 Water Management

The Truckee-Carson River System provides water for municipal and industrial use, irrigated agriculture, environmental flows for the endangered (Cui-ui) and threatened (Lahontan cutthroat trout) fish species in Pyramid Lake, a rare natural desert terminus lake located on sovereign tribal lands. The system aspect derives from an inter-basin transfer of Truckee River water away from the natural terminus (Pyramid Lake) to the Truckee Canal, to supplement Carson River flows. These flows are stored in Lahontan Reservoir to be released for agricultural irrigation in the Newlands Irrigation Project area (e.g., the nation’s first Bureau of Reclamation project, 1906) and for environmental uses on the Stillwater National Wildlife Refuge (Wilds, 2014). A substantial number of users on the river system rely heavily on Truckee River upstream reservoirs that store snowmelt for fixed calendar-based releases later in the year, based on historical snowmelt.

Figure 1. The Truckee-Carson River System (Singletary & Sterle, 2017).

Water use across the river system is highly regulated through federal, tribal, state, and local water sharing agreements based on historic prior appropriation doctrine (Wilds, 2014). Carson River allocations follow the Alpine Decree, initiated by the United States Department of Interior in 1925 and signed into law in 1980, following 55 years of litigation, to adjudicate surface water rights to individual parties. The Orr Ditch decree (1944) adjudicated Nevada water rights for the Truckee River and its tributaries, and regulates flows through a series of reservoirs and irrigation canals. The decree includes the right to store snowmelt in Lake Tahoe for use in the Newlands Irrigation Project, and incorporates the 1935 Truckee River Agreement among water users on the Truckee River (NDWP, 1999). The Truckee River Operating Agreement (TROA), a negotiated settlement implemented in 2016, aims to increase the operational flexibility and efficiency of upstream reservoirs to enhance Truckee River Basin surface water supply, particularly during drought years (USBOR, 2015).

The Truckee River’s most populated urban area, Reno-Sparks (population 425,000), satisfies water demand through combined surface and groundwater supply management. That is, during an average water year, 85–95% of Reno-Sparks water supply originates as surface flows from Sierra Nevada snowmelt stored in the Truckee River upstream reservoirs, with several groundwater basins supplying the remaining 5–15% to meet summer municipal irrigation peak demand (TMWA, 2016). Smaller communities in the Truckee River headwaters (i.e., Lake Tahoe Basin, pop. 68,000 and Truckee, pop. 16,000) rely almost entirely on groundwater (Horton, 1997). Downstream, the city of Fernley (pop. 19,200) provides municipal and industrial supply through groundwater, recharged mostly by leakage from the Truckee Canal (Mihevc et al., 2002).

In contrast to the Truckee River, 95% of municipal and industrial water use in the Carson Watershed originates as groundwater, including Carson City, the capital of Nevada (population 54,000) and smaller but rapidly growing municipalities in the Carson Valley (i.e., Minden and Gardnerville, population 8600; and Dayton, population 9000) (Cobourn, 2001). Carson City, the largest urban area on the Carson River, satisfies water demand through conjunctive use where surface water primarily from the Carson River and tributaries is maximized to conserve groundwater and reduce the use of municipal wells (CCPW, n.d.).

More than 80% of the total annual Carson River surface flow is diverted for agricultural irrigation in the Carson Valley (Cobourn, 2001), serving approximately 575 land parcels with surface water. Of those parcels, roughly half have access to supplemental groundwater to support irrigation, but agricultural producers use this water source infrequently due to the costs of accessing this supplemental water source. Carson River surface flows supply approximately 30%, with the Truckee River supplying the remainder, of water to the Newlands Irrigation Project located below Lahontan Reservoir to irrigate 57,000 acres of cropland (USBOR, 2015) . Surface water for agricultural irrigation system wide is delivered through the original network of earthen ditches and canals constructed during the late 19th and early 20th centuries. The city of Fallon (pop. 8,400) located in the heart of the Newlands Irrigation Project relies largely upon domestic wells (Townley, 1998). Population growth has increased exponentially since the mid-19th century when the area was first settled and the demand for water has diversified from agricultural and mining uses which typified the river system historically (Wilds, 2014).

2.2 Recent Drought Conditions

While severe prolonged drought periods have occurred in the Truckee-Carson River System in the last millennia (Kleppe et al., 2011), decreased snowpack and warming temperatures observed during the recent drought period (i.e., water years 2012-2016) compound existing water scarcity inherent in this high desert region (Kahil et al., 2015). Table 1 illustrates water supply variability for the Truckee and Carson River Basins during the 2015 and 2016 water years, reported as percent of normal snow water equivalence (SWE).

Table 1. Water supply reported as snow water equivalence percent of normal ranges for the Truckee and Carson River Basins. The Lake Tahoe Basin is included as it is also a source of Truckee River waters.

Month	2015	2016
January	39–56%	106–121%
February	18–29%	114–130%
March	22–38%	89–96%
April	2–15%	106–115%
May	0–8%	106–116%

Source: Natural Resource Conservation Service (NRCS, n.d.-b).

March 2015 was recorded as the driest month in the case study region in nearly 35 years, and snowpack measured 1 April was the lowest in over a century. Snowpack percentages ranged from 2% of median SWE in the Carson Basin to 13% of median SWE in the Truckee Basin (NRCS, 2015a). Median SWE in Carson and Truckee Basins measure approximately 24 inches (610 mm) and 28 inches (711 mm), respectively (NRCS, n.d.-a). These record lows coincided with record high January through March temperatures where half or more of snowpack was lost before April 1 (NOAA National Centers for Environmental Information, 2015). That year resembled *dry snow drought* conditions, defined as lack of precipitation enhanced by warmer temperatures (Harpold, Dettinger, et al., 2017).

While soil moisture conditions were near average in May 2015 due to early snowmelt and April precipitation, crop growing conditions were roughly one month earlier than normal. Record low streamflow coupled with extremely low reservoir storage levels resulted in severe agricultural surface water shortages, with downstream agricultural users in the Newlands Irrigation Project receiving only 20% of their normal surface water allocation—enough for one alfalfa cutting compared to four cuttings in a normal growing season (NRCS, 2015b). To stretch drought reserves, municipal water utilities requested that customers voluntarily reduce use by 10% (Anonymous municipal and industrial water manager, August 2015, personal communication), and environmental water managers worked to minimize risks to wildlife and protect water quality (Anonymous environmental water manager, June 2015, personal communication).

One year later, snowpack measured 1 April 2016 reflected near average conditions, despite a comparatively dry February and fewer mid-season winter snowstorms. However, warmer temperatures (e.g., 2 to 4 °F) during the remainder of April accelerated snowmelt considerably (NRCS, 2016a, 2016b; Nevada State Climate Office, 2016). New snow accumulation in the higher elevations at the end of April 2016, paired with unseasonably cooler temperatures in May, stretched water supply sufficiently to satisfy early season irrigation water demand. Similar to 2015, these wet late-spring conditions also resulted in above average soil moisture levels with projected high efficient runoff (NRCS, 2016a). Many agricultural managers at the river system terminus still faced water supply shortages due to previous consecutive years of warmer drought conditions (NRCS, 2016c; NOAA National Centers for Environmental Information, 2017).

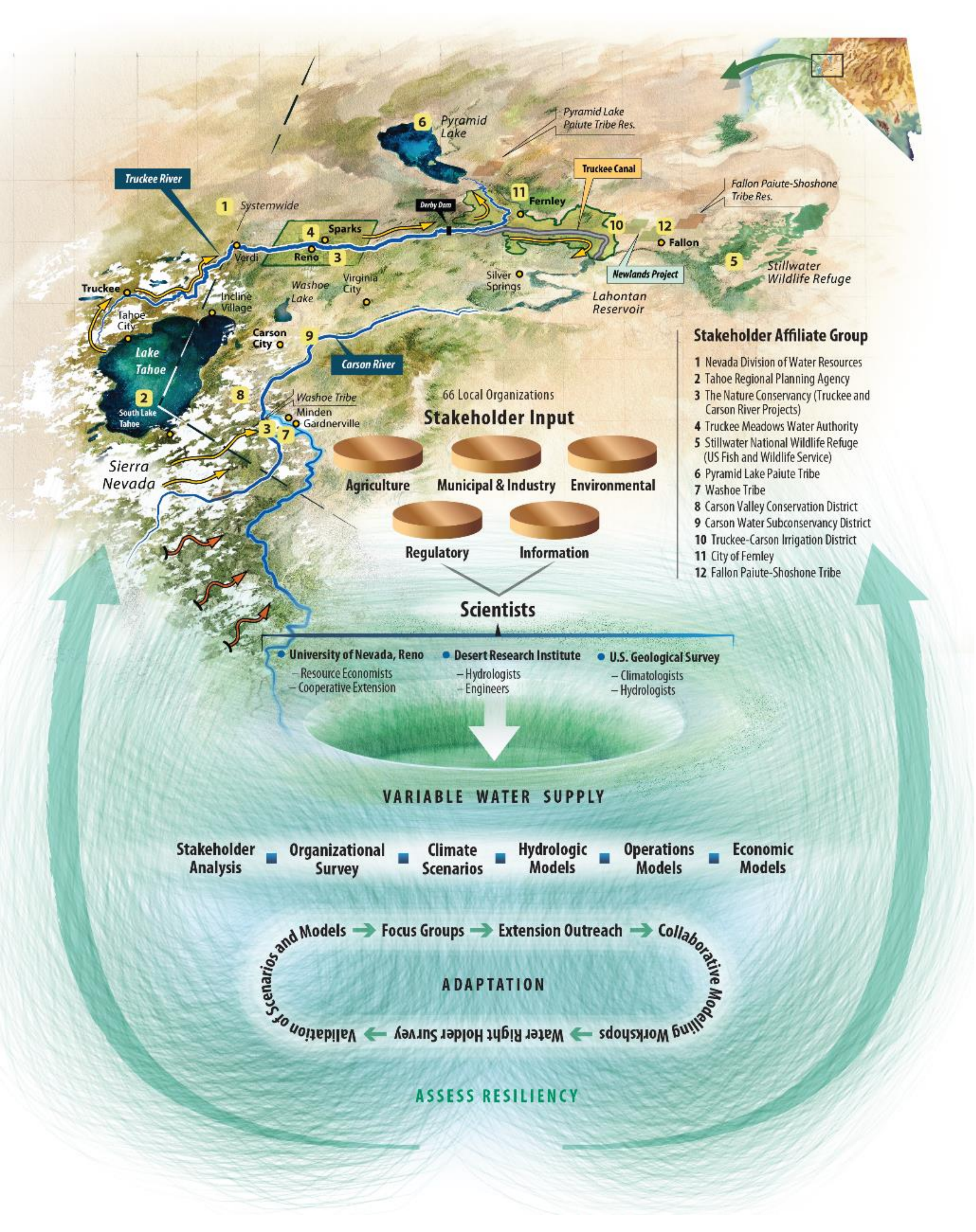
3.0 Methods

3.1 Collaborative Modeling Research Design

As mentioned, this qualitative interview study is part of a larger collaborative modeling research design implemented in the Truckee-Carson River System case study area (Singletary & Sterle, 2017). Briefly, this project relies on iterative interaction with 12 water managers, each representing large numbers of individual water users that comprise the primary and diverse water uses geographically distributed from the headwaters to the system terminus (Beall King & Thornton, 2016; Langsdale et al., 2013; Meadow et al., 2015; Singletary & Sterle, 2017). Figure 2 illustrates the research design, including the location on the river system of the 12 water management organizations.

These water managers, formally identified through a stakeholder analysis (Prell et al., 2009; Reed et al., 2009) conducted at the project's onset in 2015, comprise a *Stakeholder Affiliate Group* that partner voluntarily with the case study research team. The collection of interview data was made possible through this ongoing information exchange partnership (Singletary & Sterle, 2017). When collected at strategic points in time, primary qualitative data provide perspectives unique to each organization's water management adaptation strategies and barriers (Kaplowitz & Hoehn, 2001; Krueger & Casey, 2015; Rossman & Rallis, 2016).

Figure 2. Collaborative Modeling Research Design, highlighting the location of *Stakeholder Affiliate Group* organizations (Singletary & Sterle, 2017).



Stakeholder Affiliate Group

1 Nevada Division of Water Resources
2 Tahoe Regional Planning Agency
3 The Nature Conservancy (Truckee and Carson River Projects)
4 Truckee Meadows Water Authority
5 Stillwater National Wildlife Refuge (US Fish and Wildlife Service)
6 Pyramid Lake Paiute Tribe
7 Washoe Tribe
8 Carson Valley Conservation District
9 Carson Water Subconservancy District
10 Truckee-Carson Irrigation District
11 City of Femley
12 Fallon Paiute-Shoshone Tribe

3.2 Study Participants

The 12 water managers represent sufficiently diverse water use in this case study area distributed by location across the river system, from headwaters to terminus (i.e., Truckee River, Carson River, below Truckee Canal in Newlands Irrigation Project, or system-wide) (Singletary et al., 2016; Singletary & Sterle, 2017). To examine responses by water use and location on the river system, interview data were aggregated as belonging to one of four types of water use: municipal and industrial, agricultural, environmental, and regulatory. Table 2 defines these water uses, provides examples of water management organizations per use, and lists the corresponding *Stakeholder Affiliate Group* representative organization for each use.

Table 2. Water use, example organizations, and *Stakeholder Affiliate Group* organizations. The number in parentheses corresponds to the location of the organization as indicated in Figure 1.

Water Use	Example Organizations	Stakeholder Affiliate Group Organizations
Municipal and Industrial	Utility districts, water purveyors, wastewater treatment facilities, public works	Truckee Meadows Water Authority (#4) Carson Water Subconservancy District (#9) City of Fernley (#11)
Agricultural	Irrigation districts, water purveyors, water right holders, county government, tribal communities	Washoe Tribe (#7) Carson Valley Conservation District (#8) Truckee-Carson Irrigation District (#10)
Environmental	Conservation districts, watershed restoration, wildlife protection, land management, tribal communities	The Nature Conservancy (Truckee and Carson River Projects) (#3) Stillwater National Wildlife Refuge (#5) Pyramid Lake Paiute Tribe (#6) Fallon Paiute-Shoshone Tribe (#12)
Regulatory	Enforcement of prior appropriation based institutions, river operations, and land-use	Nevada Division of Water Resources (#1) Tahoe Regional Planning Agency (#2)

3.3 Data Collection

Primary qualitative data used in this study were collected during face-to-face, semi-structured interviews conducted with each of the 12 water managers during the 2015 and 2016 summer irrigation seasons. Data collection followed a consistent protocol pertaining to human subject research, reviewed and approved by the University of Nevada, Reno Office of Research Integrity, including participant recruitment, question items, and data collection and analysis protocol.

The authors facilitated approximately 90-min interviews at water managers' offices. The survey instrument totaled 21 questions, including the four open-ended questions reported in this study (Table 3). Question item #1 was asked in 2015 to determine how water managers define normal water years and to establish a baseline for normal water year challenges. Question item #2 was asked in 2015 to determine how water managers define moderate and severe drought conditions. Question items #3 and #4 were asked in 2015 and again in 2016 to compare and contrast responses to assess the extent, if any, to which perceived adaptation strategies and adaptation barriers change over time under continuous exposure to warmer drought conditions. Question items were not provided to water managers in advance.

Table 3. Open-ended interview question items.

	Question
Q1	Define a normal year. What water supply challenges do you face in these years?
Q2	Define a moderate and severe drought. How has the current drought challenged your daily operations?
Q3	What are you doing to adapt to current drought conditions?
Q4	As you strive to implement these strategies, do barriers exist? If so, please explain.

Open-ended questions, as opposed to closed-ended and/or Likert-type scale questions, provided water managers the opportunity to respond in detail and reduced potential for survey error associated with forcing managers to choose answers from a limited menu of choices (Sandelowski, 2000). A member of the research team, other than the facilitator, recorded the discussion as typed transcripts using a laptop computer. Data were reviewed and transcribed within 24 h following each interview.

3.4 Data Analysis

Primary qualitative data collected in 2015 were analyzed to: (1) determine baseline water supply challenges; (2) identify adaptation strategies to cope with current (i.e., 2012–2015) warmer drought conditions; and (3) assess adaptation barriers. Data collected in 2016 were analyzed to determine whether and how these adaptation strategies and adaptation barriers changed during a fifth consecutive year of warmer drought conditions (i.e., 2015 to 2016). The unit of analysis selected was *water manager*, representing the strategies and barriers of their respective organizations (Onwuegbuzie et al., 2009).

Interview transcripts were analyzed using *constant comparison analysis* (Glaser & Strauss, 1999), a qualitative data analysis technique used to identify consistent patterns and relationships (Krueger & Casey, 2015). This method is useful particularly when data are collected at two or more points in time during the life of a case study (i.e., 2015 and 2016) (Onwuegbuzie et al., 2009) and when the key task is to compare one dataset with another to identify similarities or differences over time (Krueger & Casey, 2015; Thorne, 2016). Three coding stages characterize our analysis: (1) *open coding*, where data are chunked into smaller units and assigned a descriptive code; (2) *axial coding*, where codes are grouped into categories; and (3) *selective coding*, where one or more themes are developed to express the grouped content (Miles et al., 2014; Onwuegbuzie et al., 2009; Strauss & Corbin, 2008).

For purposes of this study, open coding identified specific subcategories for each of the three key variables (i.e., baseline water supply challenges, adaptation strategies, and adaptation barriers). During axial coding, these subcategories were grouped into broader categories for each variable. Selective coding identified themes as a function of water use (i.e., municipal and industrial, agricultural, environmental, and regulatory). This grouping further reduced the data, providing a broader understanding of adaptation by water use while ensuring that data were de-identified. To assess shifts in adaptation strategies and adaptation barriers, categories from 2015 were compared to 2016.

Two researchers independently conducted three stages of coding within 72 h following each interview, followed by an intercoder reliability assessment to minimize coder bias (Kurasaki, 2000). That is, researchers compared coding categories for each variable to identify agreements and disagreements, revising the final categories as necessary. Direct quotes were selected illustrating local managers' responses. Categories for each variable and an example illustrating how raw data were coded using this three-stage coding process are provided in the Appendix (Tables A1 and A2, respectively).

4.0 Results

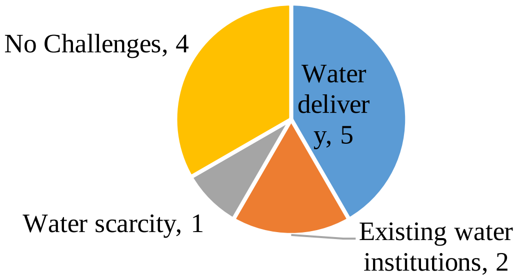
In this section, results are reported by: (1) baseline water supply challenges; (2) identified adaptation strategies and adaptation barriers; and (3) shifts in adaptation strategies and adaptation barriers over a one-year period. These shifts in adaptation strategies over this same period are examined in more detail, highlighting barriers impeding water managers' efforts to adapt. Water managers' direct quotes are presented to provide context, further illustrating variance among municipal and industrial, agricultural, environmental, and regulatory water managers.

4.1 Baseline Water Supply Challenges

Water managers regardless of water use defined the baseline, or normal water year, as a year when snowpack SWE is measured at 100% of normal, river flows are sustained through the summer irrigation season, or when all water rights and full allocations are met. More than half (67%, n = 12) of water managers experience water supply challenges during normal water years that include: (1) water scarcity, defined as conditions inherent to arid lands and drought; (2) water delivery, defined as existing infrastructure available to deliver adjudicated water rights; or (3) existing water institutions, defined as prior appropriation based water law and operations that govern water use.

Of those managers who experienced baseline challenges (n = 8), water delivery (n = 5, or 63%) was cited most frequently (Figure 3). Municipal and industrial water managers described delivery challenges associated with lack of infrastructure necessary to treat and deliver marginal quality surface and groundwater for human consumption. Both agricultural and environmental water managers identified water delivery inefficiencies related to antiquated earthen networks and insufficient environmental instream flows. These water managers also noted that existing water institutions presented challenges in normal years as a result of over adjudicated water rights and municipal population driven increases in water demand. Regulatory water managers noted similar institutional challenges relating to fulfilling water right duties and enforcing environmental and related water quality regulations.

Figure 3. Baseline water supply challenges during normal water years, defined as years when snowpack is measured at 100% of normal, river flows are sustained through the summer irrigation season, or when all water rights and full allocations are met.



Satisfying diverse water uses under scarce supplies did not present any additional challenges. Instead, new water supply challenges identified in recent years focused on warming temperatures. Managers defined warming temperatures as temperatures a few degrees warmer in winter which: prevent precipitation from falling and accumulating as snow; accelerate snowmelt in spring, affecting the timing of water supply for agriculture; and increase water demand in summer months.

Warming temperatures compound the effects of both moderate and severe drought conditions, exacerbating baseline water supply challenges. The majority of water managers defined moderate and severe drought conditions by percentage of allocation and duration. Municipal and industrial managers appeared to be less sensitive to short-term water supply reductions than agricultural and environmental managers. Regulatory water managers used drought indicators as opposed to percentage of allocation or duration. These results are presented in Table 4.

Table 4. Moderate and severe drought thresholds defined by water use.

Drought Type	Municipal and Industrial	Agricultural	Environmental	Regulatory
Moderate drought	10–50% allocation 1–3 years	40–90% allocation 2–4 years	30–75% allocation 2–3 years	As indicated by the U.S. Drought Monitor
Severe drought	5–20% allocation 2–10 years	20–50% allocation 1–4 years	10–50% allocation 3–5 years	As indicated by the U.S. Drought Monitor Lake Tahoe drops below the natural rim, preventing outflow Groundwater levels drop 12–14 feet

4.2 Identified Adaptation Strategies and Adaptation Barriers

Responding to drought conditions, water managers described up to five strategies to adapt to drought conditions that included actions to: (1) collect science-based information; (2) explore modifications to water institutions; (3) increase collaboration and communication; (4) enhance water supply; and (5) manage water demand. Table 5 provides examples of each of these adaptation strategies as a function of water use.

In discussing these strategies, five adaptation barriers that impede each of these adaptation strategies were identified and did not differ by water use. Rather, these categories were defined unanimously across all water managers. These barriers are defined in Table 6 and include: (1) climate uncertainty; (2) existing water institutions; (3) lack of coordination; (4) water scarcity; and (5) water delivery.

4.3 Shifts in Adaptation Strategies and Adaptation Barriers

A comparative analysis of 2015 with 2016 interview data demonstrates that, as a result of continued warmer drought conditions, water managers increased efforts to implement adaptation strategies, and, in doing so, identified corresponding barriers (Figure 4). Figure 4a illustrates by number of water managers shifts in adaptation strategies and Figure 4b illustrates shifts in adaptation barriers.

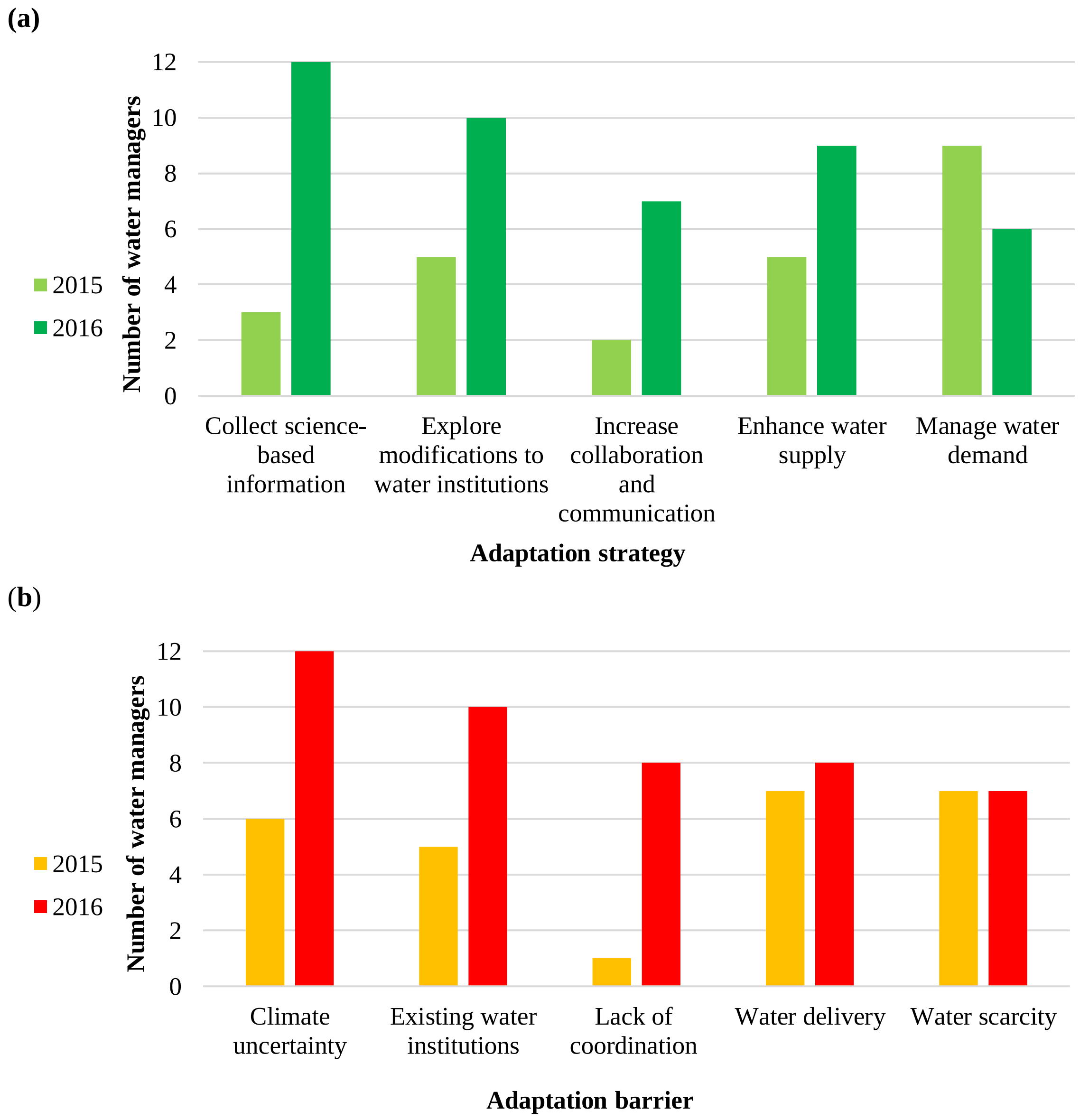
Table 5. Examples of adaptation strategies identified by water use.

Adaptation Strategy	Municipal and Industrial	Agricultural	Environmental	Regulatory
Collect science-based information	Increase groundwater monitoring; project population and economic growth	Understand relationship between groundwater pumping and surface water flows	Monitor surface water flows, water quality, and ecosystem health; assess riparian area function	Support research efforts to inform decision-making; fund new science investigations
Explore modifications to water institutions	Conjunctively manage surface and groundwater; modify rate structures to sustain revenue	Allow winter and/or earlier irrigation season; request expedited temporary changes in place of water use and point of diversion	Increase flexible water use; revisit existing environmental permitting and regulations	Facilitate temporary changes in place of water use and point of diversion; explore shifts in operational dates based on historical snowmelt and streamflow timing
Increase collaboration and communication	Coordinate local and regional meetings; devise regional-scale adaptation	Work with other irrigators to devise multi-farm improvements	Gather local managers' input on watershed health	Facilitate cooperation among local communities; participate in regional climate initiatives
Enhance water supply	Explore groundwater sources; build storage, delivery, and treatment infrastructure	Repair delivery infrastructure to optimize irrigation supply	Increase drainage through forest thinning; restore natural meadows	Support managers' strategies to enhance supply
Manage water demand	Enforce conservation mandates; develop regional conservation plans	Diversify crops; fallow marginal lands; deficit irrigate	Prioritize restoration projects least resilient to drought	Support managers' strategies to manage demand

Table 6. Definition of adaptation barriers identified.

Adaptation Barrier	Definition
Climate uncertainty	Highly uncertain and variable climate conditions impede adaptation efforts
Existing water institutions	Prior appropriation lacks flexibility to adequately support adaptation
Lack of coordination	Lack of stakeholder coordination inhibits regional-scale adaptation
Water scarcity	Overall scarce water supply prevents adaptation
Water delivery	Lack of infrastructure, and/or antiquated and earthen delivery networks create inefficiencies

Figure 4. Shifts in adaptation strategies (a) and adaptation barriers (b) between 2015 and 2016.



4.3.1 Adaptation Strategy 1: Collect Science-Based Information

In 2015, only three of 12 water managers described efforts to collect science-based information to improve water management. In comparing 2015 with 2016 responses, all 12 water managers described increased efforts to collect information for their respective water uses, and specifically to better understand the effects on surface and groundwater supply of continued warmer drought conditions. Municipal and industrial managers referred to “critical thresholds to functionality” as the point at which groundwater levels drop below domestic well pump intakes. As one municipal and industrial manager commented: “Until there are impacts on [domestic] well levels, then we aren’t going to change our operations.” A fifth consecutive warmer drought year also decreased surface flows, which led to increased groundwater pumping to supplement these surface water shortages. Paired with less groundwater recharge, this resulted in some local wells going dry. As one water manager explained: “We lost up to 20 feet in static water level in one well due to changes in pumping.”

Municipal and industrial managers were concerned particularly with the sustainability of perennial groundwater yield, set by the State Engineer based on historic recharge, under a warmer future with increased precipitation falling as rain versus snow. As one municipal and industrial manager commented: “Rain [instead of winter snowpack] causes reduced recharge. If we have a drought that changes [the type of] precipitation, then the perennial yields would change. Then, everyone has less to bank on.”

Another commented: “How much is too much [groundwater] pumping? How much impact [on the aquifer] are we having? We want scientific answers: This [amount] is too much. We don’t want it to be a political answer.” Municipal and industrial managers noted that hydrologic models that simulated drawdown levels surrounding domestic wells would improve their ability to predict where new delivery infrastructure might be needed.

In contrast, agricultural managers sought science-based information to understand how increased reliance on groundwater impacts surface water supply, noting that artesian wells are drying up earlier each year. These managers reflected: “Just about our entire world revolves around river flow. Because it all constitutes how we apply forecasting.” Many were concerned about the effects of increased groundwater pumping by the steadily growing number of non-agricultural residential domestic well users in the area that, during drought years, reduces downstream surface flows to agricultural users.

Environmental managers expressed the need to gather science-based information to understand the effects of reduced in-stream flows, warmer water temperatures, and increased evaporation on aquatic and terrestrial species. As an environmental manager noted: “We need to figure out a way to monitor evaporation in a real-time way. This will help us understand how evaporation is changing. We know it is temperature driven.” This information would also be useful to prioritize restoration projects and quantify potential hydrologic benefits from forest thinning. Another manager emphasized the need to establish a “one-stop-shop for climate information” so that managers across the system could utilize the same dataset for decision-making.

Regulatory managers described accelerated efforts to collect data to support hydrologic modeling of conjunctive surface and groundwater use to be incorporated as part of a comprehensive water management plan. This would also require increased collaboration with local scientists to gather additional data and identify knowledge gaps. Ideally, this information would also inform where best to administer drilling permits to access new groundwater sources. Local regulatory managers involved with Lake Tahoe land use planning announced in 2016 a newly formed joint-task force to monitor and inventory shoreline changes to support revisions to existing plans.

Regardless of water use, all managers agreed with the need to improve the accuracy of projections of snowmelt runoff timing, peak streamflow, and soil moisture content. This included investing in improved higher elevation snowpack telemetry (SNOTEL) stations to measure snowpack change in order to track Lake Tahoe surface elevation, which drives upper Truckee River flows. Managers also requested additional USGS stream gages to measure surface flows in the upper catchments of the Carson River and the development of hydrologic models to better understand arsenic mobility in groundwater.

Adaptation Barriers

All water managers agreed that climate uncertainty acted as a key adaptation barrier specifically in their efforts to increase the collection and use of science-based information. They posed questions such as: “What conditions are we planning for? There isn’t much planning to be done in a really bad drought. What do you do?” Another stated: “Do we need to completely change our management alternatives? Should we be planning for a new Lake [Tahoe] state [elevation] altogether?” Planning and forecasting were noted as obstructive particularly when future conditions are unknown, or as one water manager reflected: “We are at the mercy of Mother Nature.”

4.3.2 Adaptation Strategy 2: Explore Modifications to Water Institutions

In 2015, five of 12 water managers suggested the possibility of exploring modifications to prior appropriation based water institutions. In 2016, as warmer drought conditions continued, 10 of 12 water managers indicated the need to explore further this adaptation strategy. As one manager noted: “Somewhere down the line it [prior appropriation doctrine] must change and be based on real water.”

Comparatively more managers in 2016 use the word “rigid” when describing the existing water law, often referring to management practices affixed to specific calendar dates based on historical snowpack and streamflow timing. As a manager shared: “We are used to having prescriptive policies and a rigid approach to water management. Right now, our system is tended toward limits and caps in specific locations at certain times. This is exactly where you can do something, and this is when you do something. As the system gets more dynamic, we might need to change this."

Exploring modifications to water institutions as an adaptation strategy varied as a function of water use, particularly with regards to location on the river system. For example, water managers on upper and middle reaches of the Truckee River anticipated positive impacts of the recently (2016) implemented Truckee River Operating Agreement, designed to increase flexibility for select water managers on the system to store and move water to where it is needed most during drought—water that otherwise would have been released from or passed through Truckee River reservoirs to serve a downstream water right. As one manager described: "Under TROA [Truckee River Operating Agreement], the capacity upstream to release water later [in the year] is no longer a binding constraint." Thus, these managers had less to say regarding requested changes.

In contrast, agricultural managers at the system terminus described challenges in delivering water to municipal and environmental water users, in addition to individual agricultural producers under existing water institutions. That is, completed in 1905, the purpose of the Truckee Canal was to divert Truckee River waters to irrigate agricultural lands in the Newlands Irrigation Project area, while also supplementing Carson River flows. Currently, the Newlands Irrigation Project is responsible for all deliveries, which, in addition to irrigated agriculture, include federal wetlands, sovereign tribal lands, and the city of Fallon. As one agricultural manager noted: "I wish we lived in a world where we are only talking about agricultural producers. That ship has sailed. Now we're providing water to a municipality, the [federal wildlife refuge]—the largest water right holder in the project—and then the Fallon [Native American] reservation. Even the Pyramid Lake Tribe has some Newlands project water that sails to Pyramid [Lake]."

Environmental managers at the system terminus described how changes to existing institutions should support the need to time water deliveries such that they compliment the natural river system. As one environmental water manager stated, “We are tied to an agricultural [irrigation and growing season] timeframe [March to November], rather than a natural system [year-round]. This is problematic.” Because water delivery remains tied to the irrigation and growing season, the altered timing of supplies under earlier snowmelt regimes threatens environmental water supplies needed primarily during the latter part of the growing season when agricultural deliveries might be shutoff prematurely.

In contrast, agricultural managers on the upper Carson River were less amenable to modifying existing prior appropriation based water institutions, comparing the Alpine Decree that governs water allocations on the Carson River to the “Ten Commandments.” They maintained that, with regards to the river’s hydrology, the Alpine Decree is sound because the assigned duty for each of the eight river segments accounts for gaining and losing reaches of the river. Agricultural managers indicated that modifications instead should occur within the existing institutional framework, because as one manager explained: “the Alpine Decree is adaptable.”

Regulatory managers described the need for new approaches that facilitate alternative management, suggesting that current water institutions are not equipped to deal with climate change. As described by one manager: “State law is very limited on what we can do. It would require changes to Nevada water law. We don’t have the tools in place.”

Adaptation Barriers

Lack of consensus and coordination emerged as a barrier to exploring this adaptation strategy. Overall, water managers offered different ideas on “how the river should be run.” As a manager noted: “You try to change it, people up and down the watershed have their own ideas.” Water managers, regardless of water use, agreed on the idea that climate uncertainty also acts as a barrier in devising suitable modifications and alternative management strategies since policies proposed may not alleviate impacts sufficiently under a “new and unknown climate future.” Thus, to improve water use efficiency managers suggested modifying existing prior appropriation based rules to “increase flexibility,” as opposed to replacing this institution with entirely new prescriptive policies.

4.3.3 Adaptation Strategy 3: Increase Collaboration and Communication

In 2015, efforts to increase collaboration and communication were described as an adaptation strategy only by two of 12 water managers. Water managers explained how historical conflicts surrounding competing uses across the system had for decades inhibited regional coordination and adaptation. In 2016, seven of 12 water managers emphasized the importance of increased collaboration and communication with one another from headwaters to terminus to strengthen the resiliency of the river system.

All managers referred to problems stemming from a “huge educational disconnect,” indicating that science-based outreach education programs that target individuals and communities would encourage and improve adaptation on a regional scale. As one agricultural manager framed the problem: “We have an emergency response commission set up. We just don't know how to deal with water and drought situations. We need an understanding of climate and how this is different than weather.” As a municipal and industrial manager stated: “People think that because we had a fairly good [wet] year [2016], the drought is over. People just don’t get it. We live in a desert, water is scarce.”

Municipal and industrial managers indicated the need to communicate climate change science concerning the effects of persistent warming temperatures and variability on future water supply. Communication should target domestic well users outside municipal service areas, with one manager stating: “Getting the word out to domestic well users [in the unincorporated areas] is a challenge because they aren’t our customers … they are not within our service area, but they are [within our service area] hydrologically.”

Environmental managers noted that improved coordination in the upper and lower reaches of the river system would strengthen adaptation system-wide. This level of coordination would encourage collaborative solutions, working alongside local and project researchers, to inform local decision-making. As an agricultural manager noted: “We had a tour with the tribe and Truckee-Carson Irrigation District in March. It might have been the first ever. We had three to four vehicles [on the tour]. We are trying to build our relationships.”

Regulatory managers also shared this interest to increase collaboration between reaches of the river system, suggesting the importance of information exchange to inform local management plans. As one regulatory manager stated: “If lake [Lake Tahoe elevation] level drops, do downstream users care? We would like the [Truckee] downstream urban communities [Truckee Meadows] to participate in our ecosystem management year round. Does the [Pyramid Lake] tribe care about our issues?”

Adaptation Barriers

Water managers noted lack of facilitation as a key barrier to increase collaboration and coordination. For example, an appropriate forum, or regularly scheduled meetings at the basin-scale, was either not available or often conflicted with managers’ agendas. Managers confirmed the importance of continued interaction specifically with project researchers, suggesting that ongoing engagement has potential benefits: “You’re dealing in this game before we are in a crisis. If you can convey this as part of the project that could make a big difference.” As another regulatory manager described: “We have nothing to lose … we have nothing to lose to something that is already happening. Why not prepare ourselves for this?”

4.3.4 Adaptation Strategy 4: Enhance Water Supply

Efforts to enhance water supply increased notably between 2015 and 2016, with four to nine of 12 water managers indicating the need to simply find more sources of water. Ways in which to implement this strategy varied based on water use. For example, in 2015, municipal and industrial managers described “deep, infinite” groundwater reserves as part of their “long-term” plan to cope with drought conditions. These managers more often described strategies to manage demand, such as voluntary or mandatory conservation.

However, in 2016 as groundwater levels and upstream storage diminished, municipal and industrial managers shifted their focus to finding new water sources to meet the demand of existing customers, former domestic well users, and the 7.1% increase in population expected in the region by 2019 [87]. As one manager explained: “Our outputs are greater than our inputs. As drought continues, we’ve seen some of those [domestic] wells be abandoned and users needing to be connected to the [municipal] system.”

Municipal and industrial managers described efforts to explore new groundwater sources, emphasizing that locating potable water was challenging due to high levels of arsenic that occur naturally in the region. As one manager described: “Contaminants in the wells are just too much. It makes no sense, because two wells in my area are fine, but then there are high arsenic levels on the other side.”

To hone in on potential areas, managers worked with local scientists to quantify arsenic concentrations and model migration in the groundwater system, particularly under scenarios of decreased recharge and increased pumping. Others sought funding to construct new treatment plants or update existing treatment facilities. Some proposed aquifer storage and recovery to alleviate future scarcity. Additional strategies to enhance supply, such as potable reuse, were desired but not deemed feasible in this highly regulated river system where “all water is spoken for.”

Agricultural managers’ strategies to enhance supply varied by location on the system. For example, agricultural managers on the Carson River discussed the possibility of supplementing surface flows through increased groundwater reliance and infrastructure upgrades. As one manager noted: “As it stands most [agricultural] wells pump at 220 voltage. If you upgraded your pump motor [from 220 to 480 voltage], you could fill the ditch faster, and water the fields faster. So, this is less time where water is lost in the ditch through evaporation and saturation."

Agricultural managers at the system terminus in the Newlands Project, who as part of their institutional agreement are prohibited from using supplemental groundwater, discussed the possibility of pursuing additional surface water storage facilities. As a manager stated: "The capacity of the Rattlesnake Reservoir [in the Newlands Irrigation Project] is supposed to increase so we might be able to use that as a [surface] water storage space. We tried to use it last year, but it [the water] was gone. How increasing storage works, I don't know that."

Environmental managers noted that supply would be enhanced naturally through restoration efforts to protect meadows and wetlands that act as natural reservoirs for the river system. As one manager stated: "In places like Independence Lake and Clear Lake [in the Truckee headwaters], we are also doing logging for the purpose of improving water quality and water quantity. We are working with the USGS to study this."

Regulatory managers generally indicated their support of managers' efforts to enhance water supply under continued drought conditions. However, as one regulatory manager noted: "Additional surface reservoirs are not going to happen. The additional reservoirs will be in the ground." These managers expressed interest in supporting adaptation actions that local communities originate and support, as one manager explained: "The groundwater management plan must come from the local community. You need a grassroots movement to make a change. Here at the state level, we can't entertain it or initiate it."

Adaptation Barriers

Municipal and industrial managers noted that barriers to enhance supply involved water delivery, including a lack of infrastructure to deliver new water sources to municipal customers or to connect domestic well users to municipal systems. A lack of infrastructure to transport non-potable water to treatment facilities was also identified as a water delivery barrier. As one water manager explained: “We must have the infrastructure to get the water from the [Truckee] canal to the treatment plant.”

Agricultural managers noted that under continued warmer drought conditions, water delivery infrastructure for irrigation acts as a barrier. As one manager stated: “Water conveyance becomes a lot tougher. It is challenging to push the water [down the ditches] without the [hydrologic] head. Soil is dry, so we start to send water and the ditch soaks it up.”

Climate uncertainty also remained a key barrier as all 12 water managers strived to accurately forecast surface and groundwater supply. The time horizon for which existing supplies would alleviate the impacts warmer drought remains unknown, and water managers may be forced to seek additional new sources of water. Continued scarce water supply could result in population decline and economic downturns, adding additional uncertainty as water managers strive to predict future water demand and estimate needed water supply.

4.3.5 Adaptation Strategy 5: Manage Water Demand

In contrast to other identified adaptation strategies where actions increased between 2015 and 2016, actions to manage water demand actually decreased and appeared to be no longer effective when implemented alone. Forced to conserve increasingly scarce water supply in 2016, municipal and industrial managers paired actions to manage demand with actions to enhance supply. As one manager described: “Under increased temperature with long drought, we may not be able to get massive voluntary conservation efforts. So, what becomes important is accurately predicting demand, while also managing storage. Timing was the game changer.”

As municipal and industrial managers asked their customers to conserve water use in 2015, they saw their revenues fall. As one manager noted: “We asked for 10% [reduction], we got 20%. Now what is the problem? I don’t think people are going back to pre-2015 water use levels. Something shifted. What happened is that people fixed a bunch of [water use] inefficiencies [i.e., in their homes, businesses, and landscapes] that there was no motivation to fix before.” To address these economic impacts, municipal and industrial managers initiated studies in preparation for restructuring utility rates. These same managers also discussed linking local conservation plans with the development of a regional plan, facilitating more collective strategic planning among local utilities.

Agricultural managers focused on minimizing revenue losses through their efforts to explore low water use crops that can survive a new climate future. As one described: “We used to get two crops of Timothy-grass. Now, it’s too hot. Our grasses are different. We need warmer winter grasses.” Another water manager described: “We are looking at elderberry. It survives no matter what. They blossom later, and are a high value crop. They are native and they work. Other options would be to only do [annual] grass hay, and no [perennial] alfalfa.” In 2016, agricultural managers irrigated only their most productive lands in an effort to manage their water demand.

Environmental managers focused on reducing degradation to ecosystem health and maintaining species habitat diversity. Insufficient flows compromised environmental water managers’ restoration efforts, requiring them to rethink and prioritize projects during warmer drought years. As one water manager commented: “The first part of the restoration equation is being able to get water there. The timing issue has cascading implications on all the critters. If the water comes before the milkweed is ready to start, then it won’t be blooming when the monarchs arrive.”

Regulatory managers noted their interest in facilitating institutional changes in support of water managers’ efforts to manage water demand more effectively, particularly as water use shifts. As one manager described: “One change is that Carson Valley [population and economic] growth will replace agriculture. This will reduce your opportunity to use irrigation to change water law. This hardens your [water] demand. In the Truckee Meadows, they have already turned the agriculture [use] to residential [use]. But turning to residential provides different opportunities for sustainable water use, especially regarding consumptive use since we are no longer farming.”

Adaptation Barriers

Similar to barriers to enhance water supply, particularly at the lower and terminus reaches of the river system, water delivery acted as a barrier to manage water demand more effectively. An antiquated delivery system and aging infrastructure failed further under low river flows, diminished soil moisture, and warmer temperatures driving higher evaporation rates. As one water manager explained: “Our drain ditches were dry. We had application of the water all over the valley. Soil conditions were what they are, we’ve never encountered a condition so bad. It’s no conspiracy, just Mother Nature, just hadn’t fully considered the dryness of those conditions system-wide. In these tough years, we have to be very efficient for how we move water.”

Climate uncertainty also acted as a barrier, particularly as agricultural water managers relied on changing monthly water supply forecasts coincident with planning for the growing season. As one manager noted: “They missed the mark in terms of forecasting. The opening of the season was mid-March with 85% [of normal allocation]. We had thought preceding that allocation that we were going to have a healthy supply in terms of snowpack. We are now [July] at 75%.”

5.0 Discussion

A number of recent case studies that highlight local water managers’ identified strategies and barriers in adapting to climate-induced water supply variability compare well with our case study findings (Beall King & Thornton, 2016; Burnham et al., 2016; Endter-Wada et al., 2009; Engle, 2012; Jenni et al., 2014; McNeeley, 2014; Sandoval-Solis et al., 2013). In the Wasatch Range of northern Utah, for example, water managers described challenges with enhancing water supply to meet growing population demand, obtaining funds to build and restore aging infrastructure, and coordinating diverse water use interests (Burnham et al., 2016). In Arizona, devising adaptation strategies became difficult due to uncertainty surrounding how and when to adapt to climate change, and the effects on water supply of continued warmer drought conditions (Engle, 2012). Monitoring the detrimental ecological impacts led to innovative water management in northwest

Colorado where "in-season" management strives to maintain ecosystem health during water shortages (McNeeley, 2014).

As adaptation barriers related to climate change emerge, increasingly adaptation strategies incorporate cooperation to mitigate the risk of uncertainty (Lach et al., 2005). Continuous and iterative engagement with local water managers in the Palouse and Spokane basins in northwest Washington, for example, clarified science communication needs and facilitated more adaptive water governance (Beall King & Thornton, 2016). Mutual recognition of their interdependent water uses motivated adaptation to 2004 drought conditions among water users in the Bear River Basin of Idaho, Utah, and Wyoming. This recognition led to cooperative and innovative strategies involving water settlement agreements, science-based information sharing, and hydrologic and river operations modeling (Endter-Wada et al., 2009).

Faced with climate-induced water supply variability, managers in other river systems were reluctant to coordinate with one another to enhance institutional adaptive capacity to achieve mutually agreeable solutions (Endter-Wada et al., 2009), mobilize regional knowledge exchange to balance adaptive capacity (Engle, 2012), and institutionalize resilience and adaptive management in advance of a potential water management crisis (Beall King & Thornton, 2016). Thus, collaborative research that facilitates increased communication and coordination should inform future climate planning so that it meets the needs of diverse water users (Sandoval-Solis et al., 2013).

In contrast to these other case study results, results from our case study illustrate variance in adaptation strategies by water use inherent to location on a river system and subsequent access to the resource. For example, during warmer drought conditions, agricultural water managers located closest to the Truckee-Carson River System headwaters, whose water right holders were more likely to receive their full duty, demonstrated less interest in exploring modifications to existing water institutions. Comparatively, agricultural and environmental water managers located closer to the system terminus expressed greater interest in modifying existing institutions to increase adaptive flexibility, and repairing and updating antiquated delivery systems to reduce the vulnerability of their water users during warmer drought years.

Municipal, industrial, and agricultural managers, who represent private business enterprises, focused on continued warmer drought conditions leading to revenue losses. In contrast, environmental managers shared concerns more in common with regulatory managers. That is, their adaptation strategies focused on implementing the mission of their respective organization, whether that be environmental protection or enforcing existing water allocation institutions and operations.

The results of this study demonstrate that continuous qualitative data collection, occurring as part of a larger collaborative modeling research case study, improves our understanding of the human dynamics surrounding adaptation concurrent with ongoing drought conditions and climate stressors. Involvement in ongoing research of local water managers also builds local adaptation capacity, including increased interaction, communication, and coordination among managers from headwaters to river system terminus. The methodology may identify similarities existing other snow-fed inland river systems that are highly regulated and where operations are based on historical climate records (Burnham et al., 2016; Creswell & Poth, 2017; Wehlage, 1981).

6.0 Conclusions

Findings reported here from a collaborative modeling case study in the Truckee-Carson River System revealed that variable water supply in the fourth and fifth consecutive years of warmer drought conditions surpass baseline water supply challenges. As identified by 12 local water managers who represent large numbers of diverse and competing water uses across the river system, these challenges include arid lands water scarcity, insufficient and inefficient water delivery infrastructure, and rigid constraints to adaptation posed by existing water allocation institutions.

A comparison of these 12 local water managers' identified adaptation strategies and barriers in these fourth and fifth years revealed that, as drought conditions continue, managers increased their efforts to collect science-based information to improve water supply forecasts based on timing of snowmelt, in addition to groundwater levels and soil moisture. To sustainably manage variable water supply, managers increased their efforts to explore revisions to existing prior appropriation based water institutions established on historical snowpack and streamflow timing. Managers also increased collaboration and communication with one another. Efforts to enhance water supply were noted more frequently in the fifth consecutive year of warmer drought, while strategies to manage water demand were mentioned less often.

As a result of adaptation strategies implemented in 2016 during the fifth consecutive drought year, adaptation barriers became more explicit to local managers. Climate uncertainty emerged as a barrier to every adaptation strategy that managers identified to increase system resilience in this river system. Additional barriers included a lack of coordination between organizations across the river system, antiquated and insufficient water delivery networks that resulted in water losses, and water scarcity inherent to a high desert environment exacerbated by climate change.

Respondents suggested that managing variable water supply under continued climate uncertainty would require an objective and science-based evaluation of existing institutional arrangements, supported by hydrologic and operations models that simulate the river system under projected scenarios of warmer drought conditions. However, any modifications to existing water institutions may pose new barriers unless such changes ensure that water resources are managed sustainably to balance the natural river system while also satisfying human needs.

The results of the qualitative data analysis reported here suggest that many local water managers view existing water institutions as an adaptation barrier. Additional research in this case study area is underway to examine the efficiency of prior appropriation in allocating water [94]. Additional objective analysis is warranted to examine the extent, to which the historical legacy of prior appropriative doctrine may be modified, and the specific changes needed to support dynamic adaptation to climate-induced water supply variability. These findings would be especially useful to other snow-fed inland river system communities faced with similar adaptation barriers.

The locally identified adaptation strategies in the Truckee-Carson River System case study reported here are informing the selection of adaptation measures to be simulated using a suite of hydrologic and operational models tailored to this river system (Singletary & Sterle, 2017; Sterle, Singletary, & Pohll, 2017). To date, these adaptation measures focus on alternative water management strategies to enhance supply and include: reoperating federally managed Truckee River reservoirs to enhance surface water storage under earlier snowmelt regimes (Sterle, Singletary, Rajagopal, et al., 2017), constructing a reservoir in the Carson River headwaters to store snowmelt for downstream agricultural irrigation (Morway et al., 2016), and exploring managed aquifer recharge in the Carson Valley through off-season/winter irrigation in agricultural areas (Niswonger et al., 2017).

As warmer drought conditions are projected to increase in duration, frequency and intensity (Cook et al., 2015; Dai, 2011), this research is likely to play a critical role in supporting local adaptation efforts that reflect local stakeholder knowledge and scientific evidence. These data will be extended to include a third round of interviews with the same 12 water managers. These interviews will be conducted at the end of the 2017 summer irrigation season, where 1 April snowpack along the eastern Sierra Nevada measured 192–217% of median (approximately 50–56 inches, or 1270–1422 mm SWE) (Natural Resource Conservation Service (NRCS), 2017). Collection of these data will facilitate further assessment of shifts in adaptation strategies and barriers following one of the wettest October to February periods in Sierra Nevada history (Harpold, Dettinger, et al., 2017).

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Appendix

Table A1. Coding categories of identified baseline water supply challenges, adaptation strategies, and adaptation barriers. These categories depict locally identified water supply challenges, adaptation strategies, and adaptation barriers specific to the Truckee-Carson River System case study area.

Variable	Baseline Water Supply Challenges	Adaptation Strategies	Adaptation Barriers
Categories	Water scarcity Water delivery Existing water institutions	Collect science-based information Explore modifications to water institutions Increase collaboration and communication Enhance water supply Manage water demand	Climate uncertainty Existing water institutions Lack of coordination Water delivery Water scarcity

Table A2. Example coding for a municipal and industrial water manager illustrating the three stage coding process.

Coding Stage		Baseline Water Supply Challenges	Adaptation Strategies	Adaptation Barriers
Raw Data	Transcript	“We need better conjunctive use programs to manage water.”	“We’re firming up sources of supply to meet late summer demand”	“What conditions are we planning for?”
Open Coding	Sub-Category	Increase programs for managing water	Seeking new sources of water	Climate is too variable to plan
Axial Coding	Category	Existing water institutions	Enhance water supply	Climate uncertainty
Selective Coding	Theme	Continued warmer drought conditions challenge municipal and industrial water managers “infinite” supply of water.		

Chapter 2: Hydroclimate Variability in Snow-fed River Systems: Local Water Managers' Perspectives on Adapting to the New Normal

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Abstract

Between 2012 and 2016, drought characterized by low Sierra Nevada snowpack and anomalously warm temperatures exacerbated water scarcity in the snow-fed Truckee-Carson River System of California and Nevada. However, in winter of 2016/2017, numerous atmospheric rivers made landfall resulting in record precipitation, historic snowpack, and winter and spring flooding. Through interviews conducted annually with key local water managers, a collaborative modeling case study underway in this river system examines local climate adaptation coincident with hydroclimate variability. The following research questions are addressed: 1) How does recently observed hydroclimate variability compare to historic and projected climate? 2) How did 2016/2017 challenge water management compared to previous consecutive drought years? 3) To what extent have local climate adaptation and implementation barriers changed over time? and 4) What science information is needed to support long-term climate adaptation? An analysis of interview data collected during the 2015, 2016 and 2017 water years demonstrates that managers continue drought adaptation efforts to enhance water supply and revise management practices based on stationary climate patterns, exemplifying recent conditions as the "new normal" climate for which they should plan. An assessment of recently observed hydroclimate variability reveals recent water years bound historical observations and are consistent with estimated paleoclimate extremes in terms of magnitude, but not persistence, of both dry and wet conditions. To support

local adaptation, managers requested researchers simulate alternative water management strategies. This study illustrates how the integration of local knowledge with applied climate research can support adaptive water management in snow-fed river systems.

1.0 Introduction

Snow-fed river system communities are acutely sensitive to climate change (IPCC, 2014; USGCRP, 2017) because the majority of their water supply is derived from annual snowpack (Barnett et al., 2005; Li et al., 2017; Mankin et al., 2015). A warmer climate shifts precipitation phase from snow to rain (Knowles et al., 2006), altering snowpack dynamics, shifting peak streamflow timing, reducing groundwater recharge, and increasing winter flood hazards (Barnhart et al., 2016; Dettinger et al., 2015; Harpold, Kaplan, et al., 2017; Jasechko et al., 2014; McCabe et al., 2007; Mote et al., 2005; Stewart et al., 2005; Trujillo & Molotch, 2014). Warmer spring and summer temperatures further compound these snow droughts conditions (Harpold, Dettinger, et al., 2017), increasing evaporation rates and irrigation water demand (Hatchett et al., 2015). This presents critical challenges in managing seasonal water supply and demand engineered for stationary climate patterns (Georgakakos et al., 2014; Milly et al., 2008).

Snow-fed river systems offer unique case studies to examine the relationship between hydroclimate variability, or the influence of climate on water supply, and local climate adaptation efforts across diverse and competing water use communities (McNeeley et al., 2016; Mills-Novoa et al., 2017; Mostert, 2018; Sterle & Singletary, 2017). Climate adaptation strategies seek to moderate harm or exploit beneficial opportunities (Adger et al., 2005) in response to climatic stimuli that may include extreme droughts and floods, seasonal and interannual variability, and changes in long-term average conditions (Smit et al., 2000). The strategies undertaken ultimately relate to the systems’ hydrologic, socioeconomic, and ecological components, and their respective capacities to adapt (Adger et al., 2007; Moser & Boykoff, 2013). While adaptation strategies are not exclusive to any one system (Bierbaum et al., 2013), implementation barriers that constrain or impede progress can be site-specific (Eisenack et al., 2014; Moser & Ekstrom, 2010).

In the arid western U.S., for example, revising existing water management practices to adapt to snow droughts and atmospheric river (AR; Ralph et al., 2004) flooding is constrained by existing prior appropriation based water law and related institutionalized arrangements (Gallaher et al., 2013; Kates et al., 2012; McNeeley, 2017; Pulwarty & Maia, 2015). Enhancing water supply to meet population and economic growth is further limited by inherent water scarcity and over-allocated water rights (Fuller & Harhay, 2010; Owen, 2014; Padowski & Jawitz, 2012). Adaptive water management may be further constrained by lack of communication and coordination (Burnham et al., 2016), stemming from the diverse and competing water use communities (Barnett et al., 2014; Coleman et al., 2016), or climate uncertainty (Bierbaum et al., 2013; Kates et al., 2012) associated with both natural and anthropogenic climate change, system response, and limitations in downscaling global climate projections to scales usable for adaptation studies (Maurer et al., 2015; Maurer & Hidalgo, 2008; Vicuna et al., 2010).

A participatory research design, such as collaborative modeling, supports an understanding of local climate adaptation by harnessing local stakeholders’ knowledge and science-information needs (Beall King & Thornton, 2016; Langsdale et al., 2013; Singletary & Sterle, 2017, 2018). Iteratively interacting with local stakeholders coincident with hydroclimate variability provides an opportunity to assess how adaptation strategies and implementation barriers shift over time (Bierbaum et al., 2013; Eisenack et al., 2014; Moser & Ekstrom, 2010; Smit et al., 2000). Linking local hydroclimate assessments to stakeholders’ perspectives and information needs can further help managers’ navigate climate uncertainty to support adaptive water management (Burnham et al., 2016; Engle, 2012; McNeeley, 2014; Nava et al., 2016; Pulwarty & Maia, 2015). This generates new knowledge about river system function under climate change (Cloutier et al., 2015; Meadow et al., 2015; Moser & Ekstrom, 2010; Prato, 2015), and advances applied climate and socio-hydrology research (Fazey et al., 2018; Klenk et al., 2015; Mostert, 2018; M Sivapalan et al., 2014).

Inspired by this growing body of climate adaptation research, we present new findings from a collaborative modeling case study underway in the snow-fed Truckee-Carson River System in the northern Sierra Nevada that spans California and Nevada (Singletary & Sterle, 2017, 2018). Building on primary data collected from key local water managers during the 2015 and 2016 consecutive drought years (Sterle & Singletary, 2017), a third-round of interviews are conducted following the 2017 historic wet year. We pose the following questions: 1) How does recently observed hydroclimate variability compare to historical (last 100 years) and paleoclimate (greater than 100 years) records, and projected future climate? 2) How did 2016/2017 conditions challenge water management compared to previous consecutive drought years? 3) To what extent have local climate adaptation and implementation barriers changed over time? and 4) What science information is needed to support local long-term adaptation?

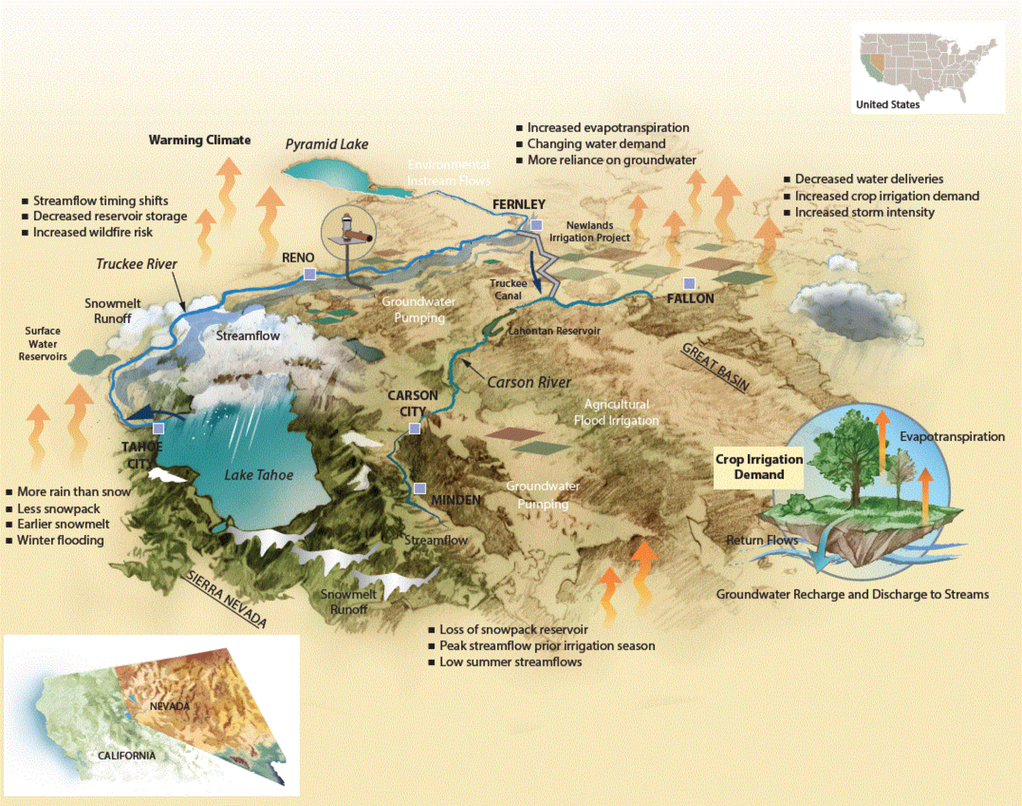
2.0 Methods

2.1 The Truckee-Carson River System

The Truckee-Carson River System encompasses an area of 18,197 km^2. The Truckee (195 km) and Carson (211 km) rivers originate in snow-dominated headwaters in the Sierra Nevada of eastern California and flow to terminal playa lakes in northwestern Nevada (Figure 1). The 3,000 m high Sierra Nevada creates a rain shadow effect resulting in a substantial climatic gradient in the river system, with an alpine forested environment in the upper basin (>1,700 m) around Lake Tahoe (498 km^2) transitioning to arid-desert in the terminal Great Basin (1,200 m). Annual headwater precipitation exceeds 1,700 millimeters (mm), with nearly 90 percent above 1,800 m observed falling as snow between November and April. The middle reaches receive less than 400 mm of precipitation annually on average, with lower reaches of the Carson River receiving less than 125 mm. The majority of streamflow is generated by spring snowmelt runoff from April to

July, with peak flows historically occurring in June, before declining to baseflow in September (USBOR, 2015). Thirty-year (1981-2010) annual average temperatures for the region range from 8.8 to 20.5 C in the higher elevations in the headwaters, to 19.4 to 34.7 C in the lower elevations near the system terminus (WRCC, 2016).

Figure 1. The Truckee-Carson River System in California and Nevada, noting the spatial impacts of a warmer climate. Graphic design by: Kelley Sterle & Ron Oden.



Water supply to meet diverse urban, agricultural, and environmental demands is highly regulated through federal, tribal, state and local prior appropriation based water law and related institutionalized agreements, which applies to most western water law grounded in the stationary climate assumption (Milly et al., 2008). Local water utilities serving Reno-Sparks (pop. 425,000) satisfy municipal and industrial water demand through conjunctive management of upstream Truckee River surface water reservoirs and regional groundwater aquifers. In contrast, Lake

Tahoe communities (pop. 68,000), Carson City (pop. 55,000), and smaller communities in the river system rely almost entirely on groundwater.

The majority of irrigated agriculture exists in the Upper Carson Valley (40,000 acres, 162 km^2), where irrigators are without upstream storage and rely almost exclusively on the natural snowpack reservoir for water supply, and below Lahontan Reservoir in the Newlands Irrigation Project (57,000 acres, 230 km^2), the first Federal reclamation project implemented in 1906. The Truckee Canal facilitates an interbasin transfer of Truckee River surface flows away from the Truckee River's natural terminus at Pyramid Lake (487 km^2), which is located on sovereign reservation lands and provides habitat for the endangered (Cui-ui) and threatened (Lahontan cutthroat trout) fish species, to supplement Carson River flows. Diverted surface flows, stored in Lahontan Reservoir, are delivered through an earthen ditch network constructed in the mid-19th and early 20th centuries to the Newlands Irrigation Project and to riparian wetlands on the Stillwater National Wildlife Refuge (Wilds, 2014).

2.2 Recent Hydroclimate Variability in Historical and Paleoclimate Contexts

To place into a historical context the hydroclimate variability observed during water years 2012-2017 (WY; 1 October to 30 September), the following station data were retrieved and synthesized: 1) daily, quality-controlled precipitation, average temperature, and snow water equivalent (SWE) from the Carson Pass (2546 m) and Tahoe City (2072 m) Snowpack Telemetery (SNOTEL) stations acquired from the National Resources Conservation Service (NRCS, 2018) and the gridMet product (Abatzoglou, 2013); 2) GPS-measured coastal precipitable water from Petaluma, California as a proxy for AR conditions acquired from SuomiNet (UCAR, 2018; Ware et al., 2000); 3) brightband-derived snow levels (White et al., 2010) from the NOAA Hydrometeorological Test bed/California Department of Water Resources (DWR)-supported snow level radar located at Colfax, California acquired from the Earth Systems Research Laboratory (ESRL, 2018); 4) daily streamflow for the Truckee River at Vista (site

#10350000) and the Carson River, where flows were summed between the East Fork near Gardnerville (site #10309000) and West Fork at Woodfords (site #10310000) to provide an estimate of natural unimpaired flows above the Upper Carson Valley, acquired from the U.S. Geological Survey (USGS 2018); and 5) soil moisture percent acquired for Lovelock, Nevada from the Natural Resource Conservation Service's Soil Climate Analysis Network (SCAN) (NRCS, 2018b). Millennial-centennial scale paleoclimate context is provided through comparison of observed precipitation and temperature anomalies with those estimated by paleohydroclimate studies for past megadrought (Hatchett et al., 2015, 2016) and pluvial periods (Barth et al., 2016; Hatchett et al., 2018).

2.3 Interviews with Local Water Managers

To build on and compare with primary qualitative data collected from 12 key water managers during WY2015 and WY2016 (Sterle & Singletary, 2017), approximately 1-hour phone interviews were conducted with the same 12 managers immediately following WY2017 (October 2017). These managers comprise a *Stakeholder Affiliate Group,* identified and selected through a stakeholder analysis conducted at the case study's outset (2014-2015) (Prell et al., 2009; Reed et al., 2009), to meet regularly and voluntarily with an interdisciplinary research team. These managers represent the diverse and competing urban, agricultural, environmental and regulatory water use communities geographically distributed from the rivers' headwaters to the system terminus (Singletary & Sterle, 2018). Primary data collection and analysis followed consistent human subject research protocols reviewed and approved by the University of Nevada, Reno Office of Research Integrity.

Open-ended interview questions aimed to: 1) understand local water management challenges faced during the historic wet WY2017, 2) assess whether adaptation strategies and implementation barriers shifted compared to previous drought years, 3) gather input on locally-identified alternative water management strategies, and 4) identify science-based information needed to support long-term adaptation (Table 1). Interviews were recorded and transcribed verbatim within 24 hours and analyzed within 72 hours using constant comparison analysis (Glaser & Strauss, 1999). This grounded theory approach (Krueger & Casey, 2015) is useful when data are collected more than once to examine shifts in perspectives within the case study area overtime (Creswell & Poth, 2017; Rossman & Rallis, 2016; Thorne, 2016). Data were descriptively coded, as described in Sterle and Singletary (2017), and categorized to identify emergent themes and to assess shifts in adaptation and implementation barriers (Miles et al., 2014; Onwuegbuzie et al., 2009; Strauss & Corbin, 2008). The authors conducted an intercoder reliability assessment (Kurasaki, 2000) to finalize themes, identify heterogeneities based on managers' locations and/or water management roles and responsibilities in the river system, and identify quotes that best illustrate managers' perspectives.

Table 1. WY2017 Phone Interview Questions

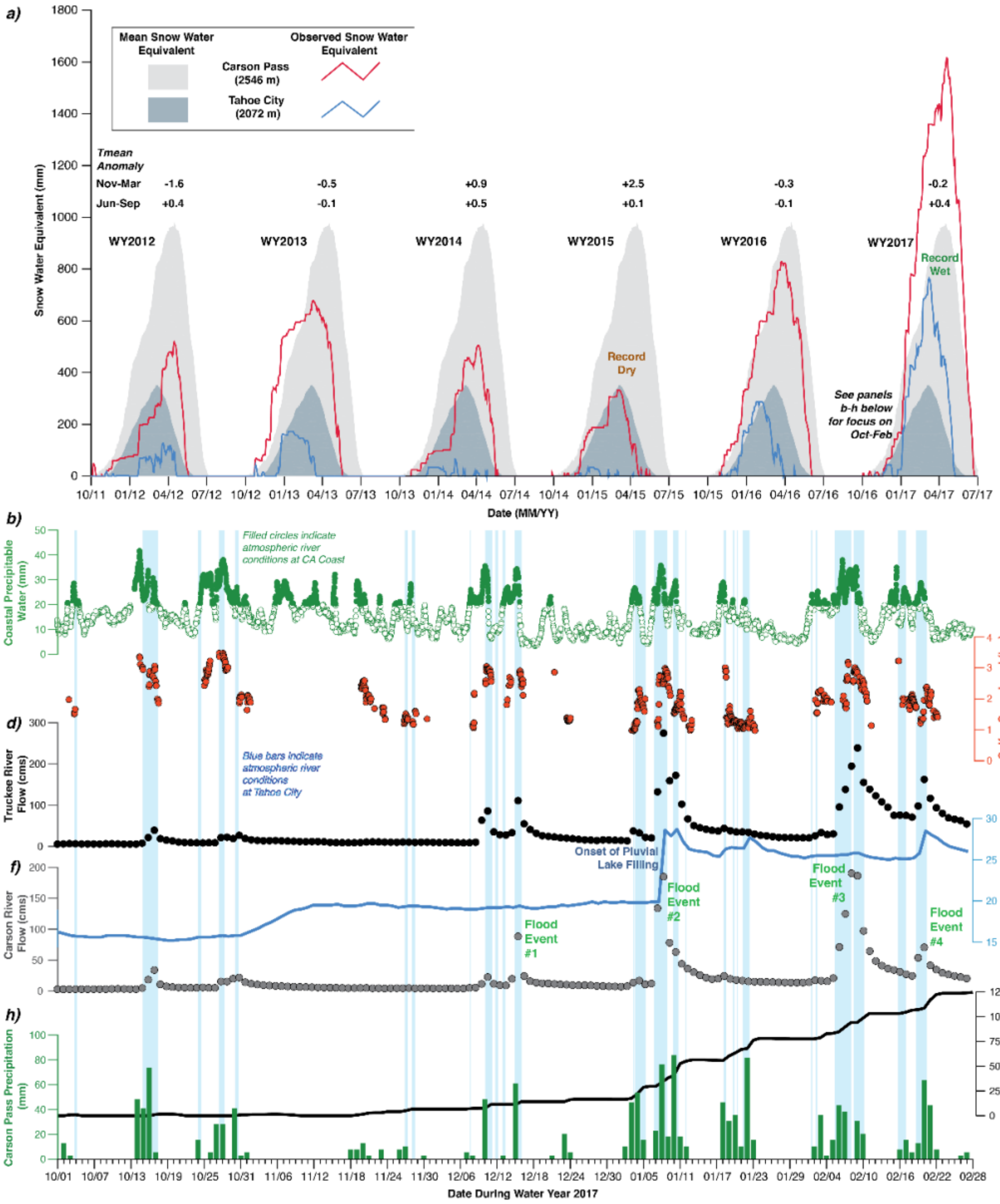
	Open-ended question
Q1	Can you briefly describe how this historic wet year impacted your organization's water management?
Q2	What adaptation strategies is your organization currently focused?
Q3	Are you still facing the same implementation barriers described in years past? Please explain.
Q4	Discuss the viability of the following locally-identified changes to existing water management: Reoperate existing reservoirs to allow for earlier storage. Construct new surface water reservoirs. Implement managed aquifer recharge on agricultural lands.
Q5	What scientific information could help support long-term adaptation?

3.0 Results

3.1 Recent Hydroclimate Variability

Figure 2a presents annual SWE over WY2012-2017 and temperature anomalies, calculated for each the wet/cool season (November to March) and dry/warm season (June to September). The multiyear drought from WY2012-2015 was notable for its record low Sierra Nevada snowpack, measuring the lowest on record during WY2015 and paired with anomalously warm winter temperatures (+2.5 C during the wet period) (Figure 2a; Belmecheri et al. 2016; Mote et al. 2016; Williams et al. 2015). Precipitation anomalies were estimated to be similar to average conditions during Medieval megadroughts (Hatchett et al., 2015), a time when many western Great Basin lakes reached low levels due to centennial-scale drought (Kleppe et al., 2011; Stine, 1994).

Figure 2. Recent hydroclimate variability in the Truckee-Carson River System. a) WY2012-2017 snow water equivalent and mean temperature anomalies (relative to 1979-2017 long-term averages) measured at Carson Pass (red line) and Tahoe City (blue line). b-h) WY2017 illustrating October through February precipitable water at the California coast and Carson Pass; snow levels at Colfax, California; streamflow for the Truckee and Carson rivers; and soil moisture percent (4 cm depth) at Lovelock, Nevada. Light blue shaded bars correspond to atmospheric river conditions measured at Tahoe City.



While WY2016 featured near normal snowpack, warmer late winter and spring temperatures created late-onset warm snow drought conditions and an early peak in snowmelt runoff (as indicated by the SWE lines declining earlier than average) (Figure 2a; Hatchett & McEvoy, 2017). Average precipitation conditions spanning the 20th century are estimated to be nearly as wet as any time during the past 4,000 years in the western Great Basin (Hatchett et al., 2018; Hatchett et al., 2015).

Figure 2b-h illustrates hydroclimate conditions during WY2017, the wettest year in the past century across much of the western Great Basin. An unprecedented number (53, 34% higher than average 1949-2017) of AR events made landfall along the California coast during WY2017, with numerous landfalls during the October to February period (light blue bars in Figure 2b-h). An estimated 33 ARs traversed the Sierra Nevada, bringing abundant precipitation to the rain shadow in northwestern Nevada (CNAP, 2017). Many of these ARs had high elevation snow levels (Figure 2c), which produced notable streamflow responses in both the Truckee (Figure 2d) and Carson (Figure 2h) rivers.

While the WY2017 AR events helped break the WY2012-2016 drought (e.g., Dettinger, 2013), they also caused flooding during the winter and spring months, particularly on the Carson River (see flood event markers on Figure 2f). From December to February, intense precipitation events (Figure 2h) paired with high elevation snow levels (Figure 2c) melted existing snowpack. Associated flooding was observed on many smaller creeks and tributaries, inundating the lower elevation valleys and increasing soil moisture (Figure 2e). Notably, the second Carson River flood event (Figure 2f) corresponds with the abrupt rise in soil moisture and the onset of pluvial lake filling in January. Although record precipitation was observed throughout the region, only the highest elevations (> 2800 m) observed record snowpack due to many storms having relatively high elevation snow levels (Figure 2c).

The precipitation anomalies observed during WY2017, approximately 200% of normal, are comparable to precipitation estimated during the deglacial period approximately 16,000 years ago when large pluvial lakes, such as Lake Lahontan, existed across the Great Basin (Barth et al., 2016; Munroe & Laabs, 2013). Larger lakes, and thus wetter conditions, are interpreted to not have occurred until the penultimate deglaciation at approximately 150,000 years ago. Thus, precipitation anomalies during WY2012-2017 spanned not only the range of historical variability, but also demonstrate magnitudes in precipitation consistent with the wettest and driest conditions captured in the paleoclimate record spanning the past 150,000 years.

3.2 Problematic Flood Challenges Manageable with Concerted Coordination

During interviews following WY2017, several managers described climate in the region as "boom or bust" with water management a "real balancing act to stay ahead of the game." As another manager said, "An average in Nevada is really an average between two extremes – flood and drought." Comparing flood to drought years, managers explained that "flooding is more instantaneous, whereas drought is a very slow moving process", leading to different but "equally problematic" challenges. Communicating flood risk factors and coordinating mitigation measures were described as key strategies to manage operational challenges and minimize flood impacts. Managers across the river system elaborated on the January and February AR events, describing how high flows washed out diversions and roads, and breached dams. Localized flooding also clogged storm-drains and inundated culverts "wreaking havoc for our public works department[s]."

For Truckee River managers, upstream reservoirs provided for flood control, but mandatory reservoir releases coincident with AR events resulted in "dangerously high" Truckee River flows and standing water throughout the floodplain east of Reno-Sparks. Thus, these managers described their close monitoring of National Water Service flood forecasts administered by River Forecast Center, upstream reservoir levels and releases coordinated by the U.S. Army Corps of

Engineers and the U.S. Bureau of Reclamation, and their physical assets, including privately-managed access roads and water conveyance and diversion infrastructure.

Carson River managers implemented more concerted communication and coordination efforts where predicted snowmelt runoff caused the Governor of Nevada to declare a state of emergency to mitigate "irreversible flood damage" below Lahontan Reservoir. Nearly four times Lahontan Reservoir's storage capacity was predicted to runoff, leading to the "Big Dig", a costly effort to divert water away from the city of Fallon (pop. 8,500) to Carson Lake and the Carson Sink (see Appendix A). Carson Valley managers above Lahontan participated in channel clearing and other flood mitigation efforts; but, flooding was less of a concern since conservation easements and agricultural lands protect the Carson River floodplain.

3.3 Drought Relief, but Not Everywhere

Whether WY2017 brought drought relief varied depending on managers' location and management role and responsibility in the river system. For example, all urban and regulatory managers described WY2017 as a year of "just enough water" to recharge aquifers and fill surface water reservoirs. Aside from "manageable damage" caused by high flows, these managers emphasized that increases in reservoir levels facilitated "starting with a clean slate." All environmental managers explained how flooding revitalized riparian areas and wetlands, and enhanced rangeland forage conditions. As one stated, "a few years of dry followed by one year of very wet… the transition was beautiful."

For others, 2017 was a year of "too much water", affecting normal operations. Upper Carson Valley agricultural managers, for example, noted how flood-inundated fields affected harvest timing: "On the alluvial fan above the floodplain, we didn't need to irrigate. We were just waiting for it to dry out… we probably harvested 30 to 45 days later [late July to early August]." Because fields and diversion ditches were so inundated, "you couldn't really fix things or assess the damage until much later… until water [flows] finally dropped [in July]. It seemed like we were dealing with flood stage for quite a while." For lower Truckee River environmental managers, flows were "too great" to manage downstream fisheries, damaging diversion infrastructure and weirs along the way.

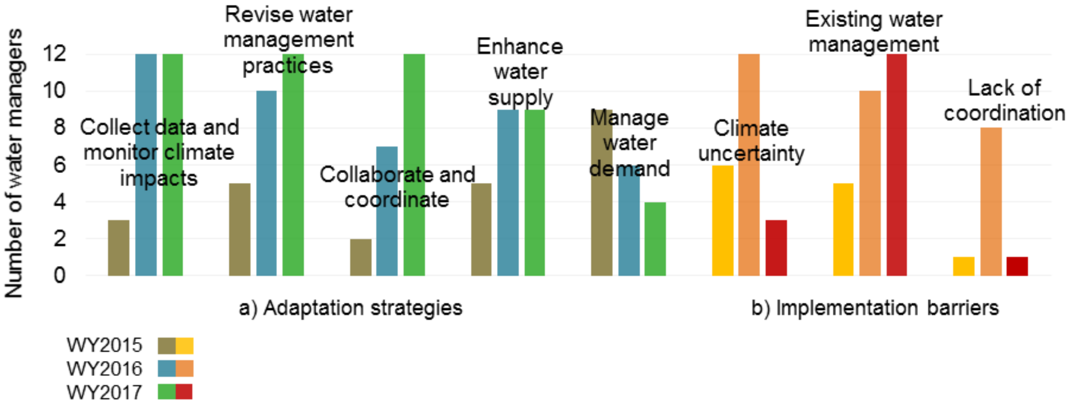
Agricultural managers at the system terminus did not declare drought relief, emphasizing how the combination of diverted floodwater and "hot [summer] temperatures" resulted in "still not enough water." As one manager explained, "those 100-degree summer days just kept coming and the evaporation was pretty incredible. Many wetland units quickly became dry, especially from years of not seeing water."

Regardless of drought relief, all managers continued the same adaptation strategies described in WY2015 and WY2016 (e.g., Sterle and Singletary 2017) that included: collecting data and monitoring climate change impacts, revising water management practices to account for nonstationary climate patterns, collaborating and coordinating to facilitate adaptation, and enhancing and diversifying water supply (Figure 3a). That is, one wet year did not deter adaptation to drought. As one manager put it, "Just because you have a wet year doesn't mean you are free. We'll go back into drought eventually." Most notable were Carson and Truckee River urban water managers' strategic efforts to enhance and diversify water supply to "create a more diverse, robust system prepared for [economic and municipal] growth and changing climate conditions." These managers described initiatives to meet emergent industrial water demand through reclaimed surface water, and to meet growing municipal demand through groundwater exploration and expanded water delivery networks. Agricultural and environmental managers across the system described collaborative efforts to "prioritize [water delivery] infrastructure [improvements] to be able to move water better during drought years."

3.4 Recent Variability Exemplifies the New Normal Climate

Compared to previous drought years, all managers referred less often to climate uncertainty as an adaptation barrier (see Figure 3b), exemplifying recent variability as the "new normal" climate for which they should be planning – “we are headed towards more drought and more flood.” Managers defined the new normal as “wetter weather patterns”, “really dry years followed by really wet years”, “winter floods with snowpack only in the highest elevations”, “incredible evaporation amounts”, and “warmer winters and hotter springs.”

Figure 3. Shifts in adaptation strategies (a) and implementation barriers (b) over the three-year period (2015, 2016 and 2017). Coded data from WY2017 were appended to WY2015 and WY2016 data presented in Sterle and Singletary (2017).



Instead, all managers emphasized existing water management as the greatest adaptation barrier. To handle this “flashier climate”, environmental and agricultural managers emphasized natural solutions, explaining how their Upper Carson and Lower Truckee river floodplain restoration projects were a “proof of concept” during WY2017. These managers noted that if upstream and downstream water users invest in continued restoration to reconnect the river to the floodplain, it will “give [the river system] a higher chance of sustainability success during extended periods of baseflow and more frequent flood events like we had this year.”

Urban and regulatory managers emphasized necessary revisions to water management practices established under historical and stationary climate patterns. For example, Truckee River urban managers cited upstream reservoirs fixed calendar date operations based on historical snowmelt and streamflow timing as “no longer applicable.” Even agricultural managers at the system terminus noted how this shift in timing affects their date-based annual irrigation season determination: “We perform that in early spring, but if the forecasts are off, like they’ve been these past years, it causes us to revise that determination. We didn’t ever have to do that.” As another manager reflected, “It’s the mismatch in timing that has us concerned.”

On the Carson River, urban and regulatory managers proposed new management strategies needed to address “the lack of long-term upstream storage options” under a warmer climate. As one urban manager explained, “Mother Nature’s snowpack reservoir used to provide storage in the upper [Carson] watershed. We’re having to bring someone in to look at future storage because we will need it when we lose snowpack.” To enhance water storage, all Carson River managers described storage options “in the ground” as comparatively more viable than building surface water reservoirs - “This is no longer the age of dam construction. I’m pulling my teeth… it’s just not going to happen.”

Instead, managed aquifer recharge (MAR) was identified as viable to enhance water supply and lower-cost compared to above ground reservoirs. MAR would be potentially feasible on Upper Carson Valley agricultural lands, where flood waters could be diverted off the river using existing diversion infrastructure. Additionally, many managers highlighted WY2017 as a year that MAR as a management option would have been a useful to “move water off the river and protect the Fallon [Newlands Irrigation Project] area.” All managers, however, cautiously discussed potential third-party impacts of this strategy since “under the existing institutional arrangements floodwaters are already appropriated to downstream users.” Across the river system, managers emphasized how improved coordination as a result of recent winter and spring flooding facilitates a collaborative evaluation of alternative management strategies.

3.5 Science and Modeling Needs to Support Adaptive Water Management

All managers requested researchers simulate alternative management strategies, using hydrologic and operations models tailored to the river system, to illustrate how these strategies “would really work” under variable hydroclimate conditions, quantify water supply benefits, and evaluate third-party effects. As one manager stated, “Modeling is the only real tool we have to project whether it’s [adaptation] going to work or not.”

To evaluate MAR, managers posed research questions directly to our research team: “Where is this [MAR] actually feasible in the Upper Carson Valley?”; “Can we develop a trigger in the model that initiates use of strategy?”; “What if fields are already saturated, like in 2017?”; “Is the coupled surface-groundwater model [GSFLOW] powerful enough to quantify long-term aquifer storage versus return flows?” If provided with simulation results, managers anticipated other research questions could be evaluated, such as “What are the implications for downstream users?” and “How are flood water rights impacted?”

Truckee River managers described interest in understanding how changes to reservoir operations enhance water supply during snow droughts, and whether operations could incorporate forecasted AR events to ensure flood risk is mitigated. Acknowledging the new normal climate as highly variable with both drought and flood extremes, managers requested researchers specify climate scenarios that incorporate high and low frequency precipitation in addition to warmer temperatures.

Managers also requested researchers help translate climate change projections for use in their long-term adaptation planning. Regulatory managers, for example, asked how the “broad predictions of climate change in the region could be translated to target the [management practices] they have regulatory control over… What does 20 degrees warmer climate mean for the 1-hr 20-year storm criteria, or other similar [engineering] project design standards?” Environmental managers requested similar climate information useful to revise water quality targets, including total maximum daily load (TMDL) and Lake Tahoe clarity (see Appendix B).

4.0 Discussion

Atmospheric river landfalls, or lack thereof, and the associated heavy precipitation, drives hydroclimate variability in the Truckee-Carson River System (Dettinger et al., 2011; Rutz et al., 2014). The extreme variability observed between WY2012-2017 is consistent with abundant AR landfalls and record wet precipitation (WY2017) and conversely, the rarity of AR landfalls (WY2012-2015). Within a three-year period (WY2015-2017), the range of historical variability was defined as a very dry period and a very wet period (Figure 2a), with both wet and dry extremes characteristic of the range of hydroclimate magnitudes on millennial-centennial timescales (Barth et al., 2016; Hatchett et al., 2015). However, as evidenced by geomorphic indicators such as terminal lake levels and the presence of terrestrial plants in present-day water bodies (Hatchett, 2018), past climate extremes were also characterized by decadal-centennial persistence of drought conditions.

While substantial interannual precipitation variability exists in the region (Dettinger, 2016; Dettinger et al., 2011; Ralph & Dettinger, 2012), the recent WY2012-2017 period illustrates the range of hydroclimate extremes anticipated to intensify under climate change (Cayan et al., 2010; Hatchett et al., 2017). Climate model projections suggest an increase in AR strength (Lavers et al., 2015) and heavy precipitation days (Pierce et al., 2013) as well as an increase in dry days (Polade et al., 2014). Should this scenario be realized, it would result in increased hydroclimate variability, particularly when combined with background increases in temperature enhancing drought impacts (Cook et al., 2015) and decreasing water supply. Water supply will be further impacted by shifts in precipitation phase from snow to rain (Hatchett et al., 2017) altering streamflow (Berghuijs et al., 2014), as well as temperature and humidity changes influencing snowmelt processes (Barnhart et al., 2016; Harpold & Brooks, 2018). The likely scenario of persistent drought punctuated by occasional extreme wet years superimposed upon warming background temperatures will necessitate adaptive strategies to optimize water availability and mitigate flood hazards.

We address gaps in understanding whether interannual variability over WY2012-2017, inclusive of persistence warmer drought and historic flooding, stagnates or fuels local climate adaptation, and whether implementation barriers diminish or intensify as a result of shifting adaptation efforts. Analysis of three rounds of interview data collected from the same key local water managers reveals that regardless of location or role in the river system, managers increased collaboration and coordination to continue collecting data and monitoring climate impacts. Recent variability fueled managers' efforts to revisit existing water management practices to account for nonstationary climate patterns. Consistent with findings elsewhere, managers were propelled to adapt as these conditions exacerbated existing management challenges, revealed vulnerabilities, and caused damage to water delivery infrastructure (Berrang-Ford et al., 2011; Bierbaum et al., 2013; Travis, 2014). Consistent with our findings, multiyear droughts in the southwest and southeastern United States motivated urban water managers to enhance and diversify water supply, upgrade existing water delivery infrastructure, and ignite collaborative regional drought planning (Engle, 2012). Environmental water managers in northwest Colorado responded to consecutive years of reduced winter snowpack and warmer temperatures by establishing a regional management plan to protect riparian ecosystems critical (McNeeley, 2014; McNeeley et al., 2016). Studies of irrigated agricultural water uses also report that changing water supply and seasonality shifts underpinned managers' adaptation (Alauddin & Sarker, 2014; Doll et al., 2017; Feola et al., 2015; Roco et al., 2014; Yung et al., 2015).

Our comparison of WY2017 to WY2015 and WY2016 interview data reveal that over this time period, managers referred to climate uncertainty as an adaptation barrier less often, exemplifying recent hydroclimate variability as the "new normal" climate for which they should be planning. Situating this perspective within the local hydroclimate assessment presented here affirms that managers are pursuing viable adaptation strategies given that recent years exemplify conditions significant within the paleoclimate and historical context, and projected under continued warming. Managers identified specific science information needs, including model simulation results, in order to support revisions to local water management practices based on stationary climate – identified as the greatest implementation barrier. Additionally, managers leveraged otherwise competing water use interests to mitigate flood risk, resulting in less mention as coordination as a barrier to implement climate adaptation strategies.

Pairing consecutive years of qualitative interview data with a quantitative hydroclimate assessment is advantageous for three reasons. First, it provides context to situate managers' perspectives and understand when climate adaptation increases. For example, a closer look at temperatures during the spring of 2016 affirms a late-onset snow drought and earlier spring snowmelt (see Figure 2a). This context helped explain why local water managers were still facing drought conditions despite near normal snowpack, and why climate uncertainty may have emerged as a barrier (Sterle & Singletary, 2017). Second, the hydroclimate assessment increased an understanding of whether recent variability indeed reflects the "new normal" conditions for which managers are planning. Affirming hydroclimate conditions of recent years are significant in a historical and paleoclimate context, and indicative of projected climate validates managers' perspectives. It also affirms the importance of researchers collaborating with local managers to identify simulate adaptation strategies that address non-stationary climate patterns, producing information useful to local management practices (Dessai et al., 2005; Meadow et al., 2015; Parris, 2016; Prokopy et al., 2017). Lastly, integrating these methods ignites an understanding of water managers' adaptation *tipping points*, defined as the point at which managing climate change requires new water management strategies (Kwadijk et al., 2010). For example, winter and spring flooding and snowmelt runoff forecasts motivated coordination and identified new management practices to potentially manage water more efficiently during high and low water years. Quantifying these tipping points can ultimately be used to specify decision-making criteria in coupled human-water systems models (Blair & Buytaert, 2016; Mostert, 2018; Voinov et al., 2016; Voinov & Bousquet, 2010).

The combined methods deployed by an interdisciplinary team of researchers in this collaborative modeling case study facilitates action-oriented research necessary to assess ongoing water supply challenges and the sustainability of adaptive water management under climate change (Fazey et al., 2018; Klenk et al., 2015). The collaborative modeling research design is useful in other snow-dependent river systems facing ongoing hydroclimate variability that feature diverse and competing water use communities seeking climate adaptation under similar institutional constraints and researchers willing to work together to generate results useful for local adaptation. Methods such as these should be tested and evaluated elsewhere, where synthesis of climate adaptation and information needs can advance applied climate science research.

5.0 Concluding Remarks

Historical hydroclimate variability has been observed in the Truckee-Carson River System region during the past six water years, as demonstrated by an extended severe drought followed by an average and a record wet year. Measureable shifts in local water managers' climate adaptation strategies and implementation barriers over variable water years are observed, whereby managers exemplify too little water followed by too much water as the “new normal” conditions for which they should be planning. Managers' collaboration with researchers facilitates an understanding of the viability of locally-identified strategies that increase the flexibility of water management necessary under non-stationary climate patterns.

Using a local hydroclimate assessment to situate perspectives, we conclude that managers are pursuing strategies necessary to adapt to projected future climate. Increased hydroclimate variability in snow-fed river systems is expected to become more commonplace under continued warming (Polade et al., 2017; Swain et al., in press). Managers in such delicately balanced river systems will need to continue exploring adaptation and related management strategies that enhance water availability during times of drought and manage flooding risk during heavy precipitation years.

Acknowledgements

The authors acknowledge local water managers across the Truckee-Carson River System who contributed substantively to this study. Research was funded by the National Science Foundation (NSF) Division of Earth Sciences Water Sustainability and Climate program (award #1360506), the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture (NIFA) (award #2014-67003-22105), and Grant G14AP00076 from the U.S. Geological Survey. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the USGS. This manuscript is submitted for publication with the understanding that the U.S. government is authorized to reproduce and distribute reprints for governmental purposes.

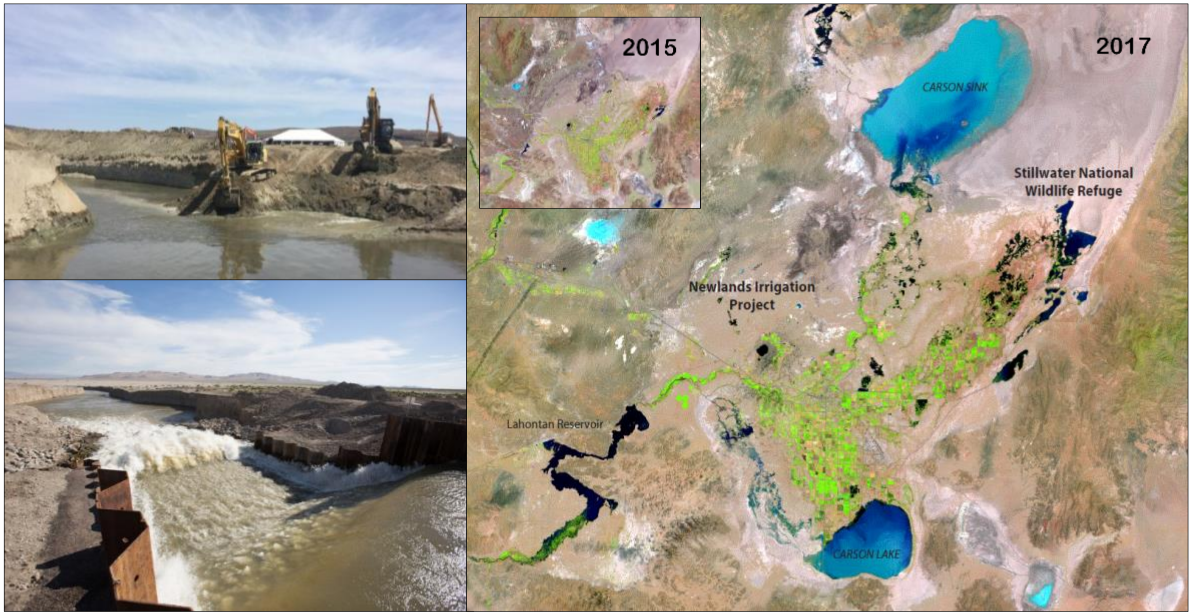
Appendix

Appendix A: The Big Dig: Channeling Floodwaters to the Great Basin

The February snowmelt runoff forecast for the Upper Carson River Basin indicated that Lahontan Reservoir (295,500 acre-feet, or 365 million cubic meters, Mm^3) and the Newlands Irrigation Project would receive nearly three times its capacity – “a volume of water far greater than ever before.” This realization came fast for Carson River water managers - “In a very short time, a matter of days, the reservoir was 1/3 full by January, after starting the water year [October] at the bottom, and we became very alarmed… we needed to take exceptional measures… as we knew we had a lot of water coming our way.” February 10, 2017 the Governor of Nevada declared a state of emergency. Local water managers and related personnel met weekly to review forecasts and coordinate efforts to clear upstream channels of sandbars and debris and prepare downstream irrigation diversions and canals for precautionary reservoir drawdowns. However, it was not enough. Managers realized that to mitigate “irreversible flood damage,” a new diversion channel was needed.

A 17-mile and roughly 60-foot wide channel, referred to as “the Big Dig,” was built to divert approximately 3,000 cfs (85 cms) around the city of Fallon to Carson Lake, the Stillwater National Wildlife Refuge, and eventually to its natural terminus at the Carson Sink (Figure A1). It was “very very concerted, a symphony of forecasting tools and personnel.” As one manager reflected, “as a result of the Big Dig…we achieved roughly a four-fold increase in Carson River [flow capacity] from 325 cfs (9 cms) to 1200 cfs (34 cms). We moved as much as a million acre-feet of water through this system this year. And recall our [annual] demand for agricultural irrigation below Lahontan is only 200,000 acre-feet (247 M cubic meters). We did this without hurting anybody in line.”

Figure A1. Lower Carson River and Lahontan Valley flood mitigation efforts. Top left: Big Dig excavation (Carlton, 2017). Bottom left: Channel diverting flows from Lahontan Reservoir (Spillman, 2017). Right: Newlands Irrigation Project, Sentinel 2 overpass from June 6, 2017. Right inset: Newlands Irrigation Project, Landsat 8 overpass from July 29, 2015. Overpass images courtesy of the Truckee-Carson Irrigation District.



Appendix B: Lake Tahoe: An Indicator of Change

The headwaters of the Truckee River, Lake Tahoe (191 sq. mi, 490km2), is a deep (1,000 feet, 300 m) freshwater lake sitting at 1900 m in the Sierra Nevada. The lake is known for its iconic clarity and world-class tourism, visited by roughly three million people per year. Variable hydroclimate presents different challenges to Lake Tahoe water managers. Compared to downstream managers who are concerned with water supply, Lake Tahoe managers face increasing wildfire risk and deteriorating water quality. Water managers are committed to "making sure our planning framework accounts for extreme weather events… to be really flexible and adaptive, and then making that a part of the new regulatory structure." One example of a new regulatory structure is summer and winter clarity targets. As one manager reflected, "What's interesting is in the dry 2015 year, we had warmer lake [Tahoe] temperatures and little runoff, which was warm runoff when it entered the lake. So, we ended up with diminished clarity due to increased algal blooms because of this warmer water. Then, in 2016, the "normal" snowpack year, we had more warm temperatures and really bad summer clarity due to algal blooms. But we realized, the species of algae has changed. So, what is our new summer clarity target number?"

Also unique for Lake Tahoe water managers is maintaining an economically viable community based on seasonal tourism, and upholding a public perception that "Tahoe is a good vacation destination even if high water years means less beach and drought means less skiing." Recent snow droughts have inserted water availability into discussions, not for environmental habitat or municipal uses (which is groundwater sourced), but for the ski industry: "They use a ton of water to make snow… will it always be available?"

Chapter 3: Collaborative Modeling in Snow-fed River Basins: Implications of Reservoir Reoperation Under a Warmer Climate

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Abstract

Mountain snowpack remains one of the fastest changing hydrologic features under a warming climate, threatening the sustainability of water management practices designed for a stationary climate. In the Truckee River Basin, recently observed changes to Sierra Nevada snowpack raises concerns that under projected continued warming, upstream reservoirs operated according to fixed calendar date-based rules cannot sufficiently meet downstream demands. In this study, we illustrate how a collaborative modeling research design, involving researchers and local water managers, identifies reservoir reoperation as a viable strategy to adapt to warmer temperatures and earlier snowmelt runoff. Using Prosser Creek Reservoir as a test reservoir, and an integrated hydrologic and operations model tailored to the Truckee River Basin, we simulate earlier reservoir storage under the 4.3°C warming predicted for the end of the 21st century. Simulation results suggest that under a warmer climate, peak streamflow timing shifts approximately 45 days earlier from mid-March to early February. Under current operations, storable inflows decrease 47% resulting in Prosser Creek Reservoir filling to 46% of capacity as compared to 76% historically. Reoperation that allows for earlier storage effectively absorbs shifts in streamflow and increases storage to 64-76% of capacity, enhancing water supply for downstream municipal and agricultural water users and environmental instream flows. An evaluation of this case study research design demonstrates that model utility is enhanced when researchers collaborate with local managers to identify plausible simulations and review results. These efforts generate new knowledge useful to local adaptation planning while advancing applied climate science research.

Plain Language Summary

Across many river basins in the western United States, substantial water supply is derived from snow that accumulates in mountains, melts into upstream storage reservoirs, and is eventually released to meet downstream demands. Efforts to understand how a changing climate affects water supply and water management requires input from local stakeholders who manage these challenges in real-time. In a collaborative case study in the Truckee River Basin, researchers and local water managers identified current reservoir operations based on historical climate records as a barrier to adapt to changing Sierra Nevada snowpack and earlier runoff. Using a hydrologic and operations model tailored to the river basin, researchers demonstrate that under a warmer climate, peak streamflow timing occurs before Prosser Creek Reservoir is permitted to fill (April), resulting in less water stored (46% versus 76% historically). Allowing the reservoir to fill earlier (February/March) captures earlier streamflow, increases reservoir storage, and benefits downstream municipal, agricultural, and environmental water users. Results from this case study suggest that when local water managers and researchers collaboratively identify adaptation strategies and review model simulation results, they generate information essential for local adaptation planning while advancing applied climate science research.

1.0 Introduction

In arid regions across the western United States, seasonal snowpack bridges the gap between winter precipitation and summer water demand (Harpold et al., 2017; Li et al., 2017; Mankin et al., 2015), yet it remains one of the fastest changing hydrologic features under a warming climate (IPCC, 2014; USGCRP, 2017). Warmer temperatures shift precipitation regimes from snow to rain (Knowles et al., 2006), and melt snowpack earlier (Barnett et al., 2005; Fritze et al., 2011;

Regonda et al., 2005), reducing snowpack accumulation and persistence (Mote et al., 2005; Trujillo & Molotch, 2014). Earlier snowmelt directly impacts streamflow timing, shifting peak streamflow to earlier in the year and reducing summer streamflow (Barnhart et al., 2016; Coats, 2010; Godsey et al., 2014; Stewart et al., 2004, 2005). This further alters groundwater recharge (Jasechko et al., 2014), groundwater discharge to streams (Huntington & Niswonger, 2012), and soil moisture content (Harpold, 2016).

Earlier snowmelt runoff and shifts in streamflow timing also have direct implications for river basin operations based on a stationary climate (Ahmadi et al., 2014; Milly et al., 2008; Steinschneider & Brown, 2012; Watts et al., 2011; Willis et al., 2011). For example, federally-managed surface water reservoirs that store spring snowmelt are generally operated according to fixed calendar dates based on historical snowpack accumulation, streamflow records, and assessments of natural climate variability conducted during the mid-20th century when most reservoirs in the West were constructed (Mateus & Tullos, 2017; Nava et al., 2016; Vogel et al., 2007). Recent studies that assess reservoir operations under changing snowpack regimes and a future warmer climate indicate that current fixed date-based operations decrease the volume of storable water (Ehsani et al., 2017; Gohari et al., 2014; Soundharajan et al., 2016), increasing water scarcity and competition among diverse municipal, agricultural and environmental water use communities (Medellín-Azuara et al., 2007; Payne et al., 2004). Dynamic reservoir operations, as opposed to fixed date-based operations, that account for earlier snowmelt runoff and streamflow timing generally met existing water demand, offsetting the vulnerability of water management to interannual variability (Ehsani et al., 2017; Gohari et al., 2014; Mateus & Tullos, 2017).

Challenges in the Truckee River Basin in Nevada and California typify regulated, snow-fed river systems, where surface water reservoirs are operated according to flood-control criteria set by the U.S. Army Corps of Engineers (USACE). These fixed date-based criteria were designed to ensure sufficient space is maintained during the winter and spring to mitigate flood risk, while also assuming significant snowmelt does not begin before 10 April (Berris et al., 1998; USACE, 1985). While management of these reservoirs has two objectives (i.e., mitigate flood risk and store runoff to meet demand), operations affixed to historical climate patterns prevent the storability of earlier snowmelt runoff and peak streamflow from the Sierra Nevada (Harpold et al., 2017), exacerbating drought impacts for local water users (Van Loon et al., 2016). Drought conditions in water year 2015 (WY; 1 October to 30 September) (Hatchett et al., 2017; Hatchett & McEvoy, 2017) exemplify these challenges, where historically low snowpack (Belmecheri et al., 2016; Mote et al., 2016) and anomalously warmer winter and spring temperatures (AghaKouchak et al., 2014; Bond et al., 2015; Nevada State Climate Office, 2016) resulted in peak streamflow runoff before the April to June reservoir fill period. Thus, even the 2015 low flows were not storable. As a result, Truckee River reservoirs started at only 28% of capacity 1 April due to previous drought years (WY 2012 to 2014), and dropped to less than 25% of capacity 1 May (NRCS, 2015a, 2015b). This resulted in limited water supply upstream and severe water shortages downstream (Sterle & Singletary, 2017).

A participatory research design, such as collaborative modeling, is useful to understanding how changes to water supply resonate across diverse water use communities (Langsdale et al., 2013; Singletary & Sterle, 2017, 2018) and whether existing management practices compound climate-induced water scarcity (Van Loon et al., 2016). It can foster dialogue among researchers and local stakeholders to evaluate climate change impacts, identify viable strategies to adapt, and develop shared research questions to prioritize research activities (Phillipson et al., 2012). When researchers engage with stakeholders often (Klenk et al., 2015; Villamor et al., 2014), they enhance the utility of research results (Voinov et al., 2016; Voinov & Bousquet, 2010). This information exchange results in social learning (Ensor & Harvey, 2015; McGreavy et al., 2015), where researchers and local stakeholders work together to evaluate local implications of water management alternatives (Sandoval-Solis et al., 2013), and revise research questions accordingly (Beall King & Thornton, 2016; Parris, 2016). These collaborative efforts benefit local water managers and researchers (Singletary & Sterle, 2017, 2018) by improving their mutual understanding of river system function and addressing science information needs to inform local climate adaptation planning (Mills-Novoa et al., 2017), while also advancing applied climate change research (Clark et al., 2016; Fazey et al., 2018; Lemos & Morehouse, 2005; Meadow et al., 2015; Wall et al., 2017).

Using the Truckee River Basin as a case study, our objectives are as follows:

- Demonstrate how collaborative modeling harnesses local stakeholder knowledge to identify viable adaptation strategies and prioritize research activities.
- Present primary qualitative data collected from local water managers that identify reservoir reoperation as one viable strategy to adapt to recently observed climate conditions.
- Simulate reservoir reoperation under a warmer climate scenario using an integrated hydrologic (PRMS) and operations (RiverWare) model tailored to the river basin.
- Evaluate changes to upstream storage under reservoir reoperations and implications for downstream water management.
- Summarize local water managers' responses to model simulation results and discuss opportunities for future research identified with local water managers and supported by research literature.

2.0 Methods

2.1 Truckee River Basin Case Study Area

2.1.1 Hydrogeography and Climate

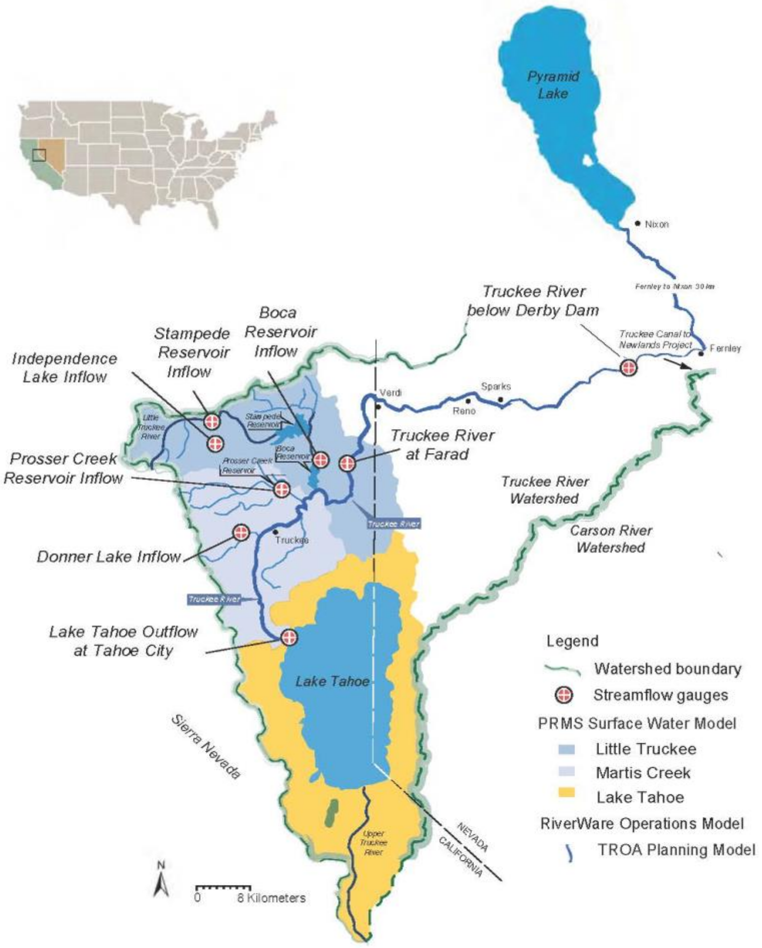
The Truckee River originates as snowpack in the Sierra Nevada of eastern California and flows 195 kilometers (km) northeastward from Lake Tahoe, terminating in Pyramid Lake in northwestern Nevada's Great Basin (Figure 1). The Sierra Nevada range creates a rain shadow effect resulting in two vastly different climates in the basin characteristic of an alpine forested environment in the upper basin over 2,700 meters (m) altitude and, on the leeward side of the range, arid-desert in the lower basin at 1,200 m. The upper basin receives 762 to 1,778 millimeters (mm) of precipitation annually on average, with 90% of the precipitation above 1,800 m typically accumulating as snow between November and April (Berris et al., 1998; Hatchett et al., 2017; USBOR, 2015). The middle basin, encompassing the cities of Reno-Sparks (pop. 425,000), receives an average of 381 mm of precipitation annually, with less than 127 mm annually on average in the lower basin from the city of Fernley (pop. 19,200) to the river terminus at Pyramid Lake. Thirty-year (WY 1981 to 2010) annual average temperatures for the region range from 8.8 to 20.5°C in the upper elevations to 19.4 to 34.7°C in the lower elevations (USBOR, 2015).

The Truckee River Basin experiences wide fluctuations in annual precipitation and runoff volumes, characteristic of the Sierra Nevada's variable climate (Dettinger & Cayan, 2014; Dettinger et al., 2011). In an average year, total runoff is 715 million cubic meters (Mm^3), ranging from high averages of 2,467 Mm^3 to low averages of 142 Mm^3. The vast majority of Truckee River streamflow is generated in the upper 35% of the basin (7925 km^2), with losing and gaining reaches of minor importance downstream (Huntington et al., 2013). Historically, peak runoff occurred in June, with more than half the volume flowing from April to July sustaining streamflow through August (USBOR, 2015, 2016a).

2.1.2 Truckee River Water Use Communities

The majority of water demand in the basin exists downstream in Nevada where water use is highly regulated through federal, tribal, state, and local water-sharing agreements based on historic prior appropriation doctrine (Wilds, 2014). The Truckee River supplies water for municipal and industrial use in the Reno-Sparks urban area (i.e., the Truckee Meadows), irrigated agriculture in the Truckee Meadows and in the lower reach below Derby Dam in the Newlands Irrigation Project, and environmental instream flows for the endangered (Cui-ui) and threatened (Lahontan cutthroat trout) fish species in the lower Truckee River from Derby Dam to Pyramid Lake. Agriculture in the basin is primarily irrigated alfalfa and grass hay in addition to beef and dairy cattle production (USDA, 2016).

Figure 1. The Truckee River Basin case study area.



An interbasin transfer of Truckee River water away from its natural terminus at Pyramid Lake through the Truckee Canal supplements flow to the Carson River to meet Newlands Irrigation Project water rights, the nation's first desert reclamation project (1906). The timing and amount of flow diverted are regulated according to operating criteria (OCAP) established in 1967 and revised substantially in 1988 and 1997, that limit Truckee River diversions to increase Pyramid Lake levels (USBOR, 2017). Diverted flows are also used for wetlands management on the Stillwater National Wildlife Refuge and the Fallon Shoshone-Paiute Reservation (Wilds, 2014).

2.1.3 Reservoir Operations and Water Management

Managing the diverse and competing water demands in the basin is made possible due to a network of upstream lakes and reservoirs with a combined total capacity of approximately 1233 Mm^3. Three lakes in the basin have dams constructed to increase storage capacity. Lake Tahoe Dam (completed in 1913) controls the top two meters of Lake Tahoe, increasing its natural storage capacity to 918 Mm^3, and is managed and operated by the Federal District Court Watermaster to meet the Floriston rate (discussed below). Donner (13 Mm^3) and Independence (22 Mm^3) lakes, two smaller lakes, provide Reno-Sparks municipal and industrial water supply and are privately owned by the Truckee Meadows Water Authority, the largest local water utility in the basin.

Stampede (279 Mm^3), Boca (50 Mm^3), Prosser Creek (37 Mm^3) and Martis Creek (25 Mm^3) reservoirs were constructed in the mid-20th century. They are managed by the U.S. Bureau of Reclamation (USBOR) and operated in accordance with U.S. Army Corps of Engineers (USACE) flood-control criteria to ensure sufficient space is maintained during the winter and spring to mitigate downstream flood risk. The start of the fill season can be as early as 10 April, a fixed operational date that assumes significant snowmelt does not begin earlier, and as late as 25 May, depending on the remaining snowpack at that time. Until roughly June, reservoirs fill at a designated rate to their maximum storage capacity. From June through September, reservoirs are managed to augment water supply during low flow periods and to meet summer downstream demands until the October fall precautionary period returns, requiring that reservoir levels be lowered to a winter time cap from 1 November until 10 April (Berris et al., 1998; USACE, 1985).

Releases from Lake Tahoe and upstream reservoirs are managed to maintain the Floriston rate (established in 1908), the most fundamental operational policy in the basin that defines the target rate of flow at the Farad gage, located at the California and Nevada state line west of Verdi (see Figure 1). Established under the 1935 Truckee River Agreement, the rate specifies 14 cubic meter per second (cms) (500 cubic feet per second, cfs) of flow between 1 March and 30 September, and at least 11 cms (400 cfs) of flow between 1 October to 2 February (USBOR, 2016a). Historically, the Floriston rate was met through 30 September 84% of years. The earliest date the Floriston rate was missed was 6 June 1992, until 2015 when the rate was missed 17 April setting a new record.

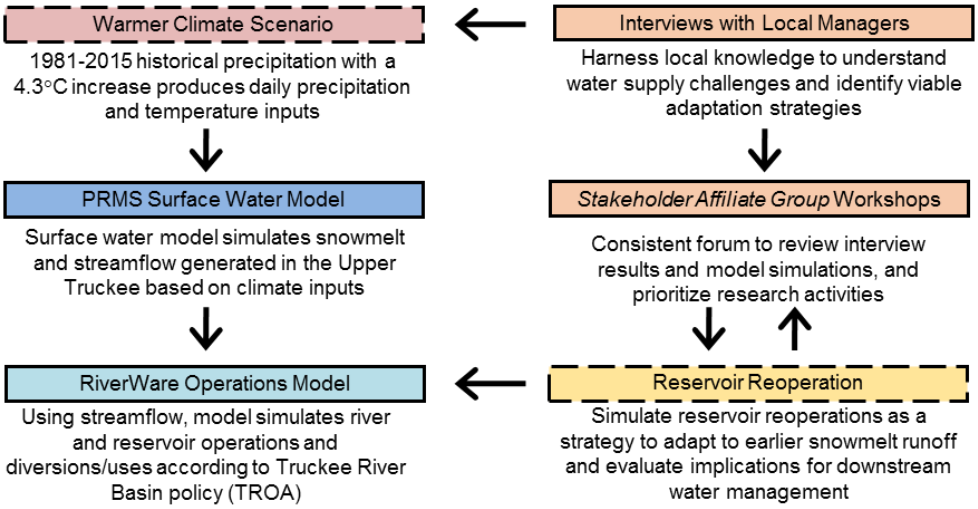
Releases are also managed to maintain instream environmental flows, established in the early 1970s, to stimulate spawning and recovery of the of native fish species in the lower reach below Derby Dam to Pyramid Lake. Developed jointly by the Pyramid Lake Paiute Tribe and the U.S. Fish and Wildlife Service (USFWS), monthly instream flow targets are defined for six fish flow regimes selected 1 March and dependent on Stampede Reservoir storage volume and forecasted inflows. The resulting selection indicates the yearly fish flow regime (i.e., above average, average, below average, dry, very dry, extremely dry), with regime targets greatest during the April through July spawning period (USFWS, 2003). Stampede and Prosser Creek reservoir releases historically attained annual flow targets until 2015, when the Pyramid Lake Paiute Tribe was forced to operate fisheries below the extremely dry regime to keep water in Stampede Reservoir.

The Truckee River Operating Agreement (TROA), implemented 1 December 2015, was intended to increase the operational flexibility and efficiency of upstream reservoirs while honoring water rights under existing decrees (i.e., Orr Ditch Decree, 1944). The agreement, the result of a 26-year negotiated settlement process, replaces the former management system and acknowledges decreasing agricultural water use and increasing municipal and industrial water demand in the region (USBOR, 2016b). Intended to address long-standing water conflict in the region among diverse users, TROA does not explicitly address climate change or reduced storage under earlier snowmelt runoff and shifts in peak streamflow.

2.0 Collaborative Modeling Research Design

The collaborative modeling research design for this case study draws upon local knowledge and information needs to inform simulations using an integrated hydrologic and operations model tailored to the basin (Singletary & Sterle, 2017, 2018). This design is collaborative in that managers and researchers iteratively work together to: (1) develop plausible climate scenarios; (2) review the results of hydrologic and operations model simulations under these climate scenarios; (3) identify viable strategies to adapt water management to hydrologic conditions; and (4) evaluate implications of those strategies basin-wide. Figure 2 presents the conceptual framework illustrating components of the collaborative modeling research design, and the identified warmer climate scenario and reservoir reoperation adaptation strategy featured in this study.

Figure 2. Conceptual framework illustrates components of the collaborative modeling research design. Solid-line components represent primary data collection and hydrologic and operations models. Dashed-line components represent the collaboratively identified warmer climate scenario and reservoir reoperation strategy featured in this study.



2.2.1 Primary Data Collection

Table 1 summarizes primary data collection methods. Data collection followed a consistent protocol pertaining to human subject research reviewed and approved by the University of Nevada, Reno Office of Research Integrity.

Table 1. Primary data collection methods.

Method	Participants and Procedure	Purpose
Baseline interviews	Conduct face-to-face semi-structured interviews with water managers representing diverse water management organizations geographically distributed from headwaters to terminus	Assess local water supply challenges, assess warmer temperature impacts on water management, and gather input on strategies to adapt
Follow-up interviews	Conduct follow-up interviews with selected Stakeholder Affiliate Group water managers representing key water use communities across the basin	Refine local water managers' information needs, prioritize model simulations, and co-develop research questions
Stakeholder Affiliate Group workshops	Conduct biannual workshops convening Stakeholder Affiliate Group water managers and interdisciplinary researchers	Share interview results, introduce hydrologic and operations modeling capabilities, review model simulation results, and further prioritize research activities

Interviews were conducted at the study's outset (2015) to establish baseline understanding of water supply challenges, assess warmer temperature impacts on water management, and gather input on specific strategies to adapt. Water managers were selected for interviews if their organizations: (1) consume, deliver, protect or supply water; (2) participate in water resource planning and conservation efforts; (3) regulate surface water or groundwater use; or (4) possess scientific expertise on river basin function. The sample of managers was intended also to achieve uniform geographical representation, resulting in the following number of water managers: upper reach, 10; middle reach, 10; lower reach, 6; and below the Truckee Canal, 9. Eighteen additional managers with basin-wide perspectives were selected, resulting in 53 total interviews.

Two researchers conducted approximately 90-minute face-to-face semi-structured interviews at water managers' offices over the 2015 summer irrigation season. The researcher, other than the facilitator, recorded the discussion as typed transcripts using a laptop computer. Within 24-hours, interview transcripts were analyzed and descriptively coded using constant comparison analysis, a qualitative data analysis method used to identify recurring themes (Glaser & Strauss, 1999) and understand shifts in perspectives over time (Krueger & Casey, 2015; Thorne, 2016). Researchers conducted an intercoder reliability assessment to minimize coder bias (Kurasaki, 2000).

Follow-up interviews were conducted one year later during the 2016 summer irrigation season with 12 key water managers to refine understanding of information needs, prioritize modeling simulations, and co-develop research questions. Identified through a stakeholder analysis (Prell et al., 2009; Reed et al., 2009), these 12 water managers comprise the *Stakeholder Affiliate Group* and were selected to represent the diverse municipal, industrial, agricultural, environmental and regulatory water use communities in the basin. Interviews featured the same questions and procedures, except that hydrologists and engineers responsible for model simulations were present during the interviews to answer technical questions pertaining to the models. Following each set of interviews, *Stakeholder Affiliate Group* workshops convened these same key water managers with researchers to provide a consistent forum for information exchange and to review simulation results.

2.2.2 Integrated Hydrologic and Operations Model

An integrated hydrologic (PRMS) and river operations (RiverWare) model tailored to the Truckee River Basin was used to simulate climate-induced changes to water supply and subsequent implications for water management. The models' extents are included in Figure 1. PRMS, a high-resolution (300 m), modular, distributed-parameter, physical-process model that simulates streamflow response to temperature, precipitation, land type and land use, as well as snowpack processes (Markstrom et al., 2015), was used to simulate hydrologic processes in the three Upper Truckee River sub-basins (Little Truckee, Martis Creek, and Lake Tahoe) (Huntington et al., 2013). PRMS was calibrated using historical daily precipitation and temperature data (WY 1980 to 2010) from 11 climate stations. Climate inputs drive the Upper Truckee PRMS model, producing daily streamflow outputs.

Truckee River Basin operations were simulated using the TROA Planning Model developed using the RiverWare modeling framework. RiverWare is a river operations and accounting model that simulates river and reservoir operations and diversions/uses according to TROA river basin policy (Rieker et al., 2005; Zagona et al., 2001). Using daily inputs of streamflow, reservoir physical contents, and reservoir account storages, the model distributes water based on scheduled water demands to meet reservoir storage and release targets according to USACE flood-control criteria space, Floriston rate maintenance, and environmental instream flows targets. The two models are integrated, meaning that simulated streamflow from the Upper Truckee PRMS model are used as inputs to the TROA Planning Model (see Figure 1). The integrated model facilitates a basin-wide assessment of climate change impacts on water supply and river and reservoir operations, and allows researchers to examine and quantify upstream and downstream implications of alternative operations.

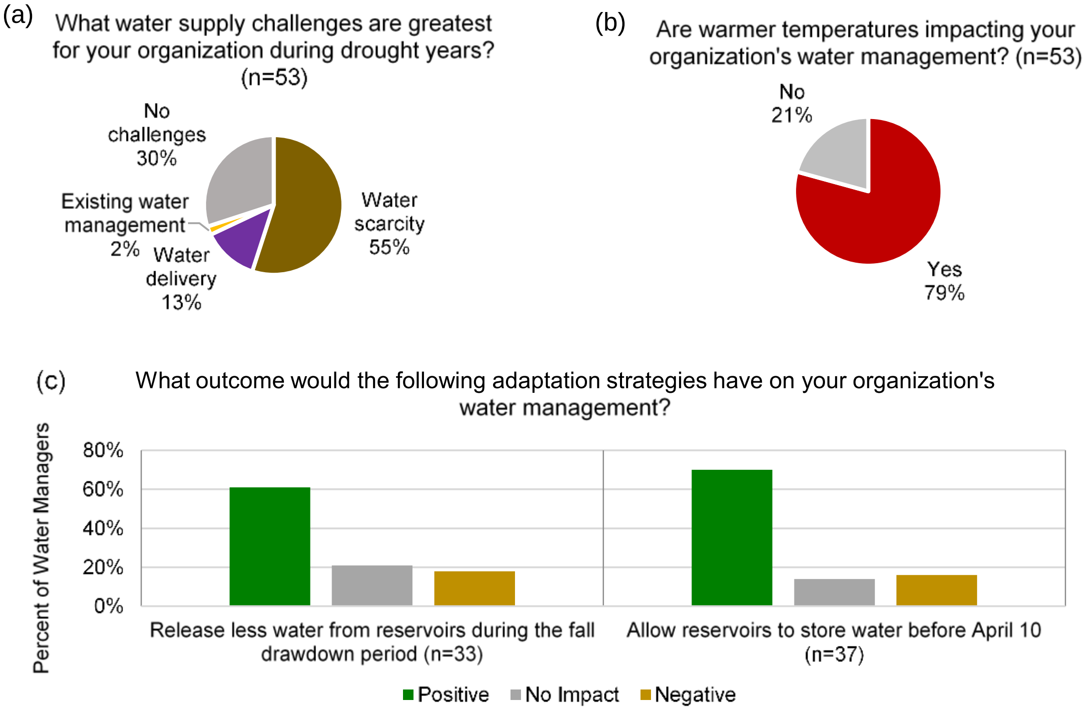
3.0 Results

3.1 Identifying Local Water Supply Challenges and Adaptation Strategies

Results from baseline interviews conducted with 53 Truckee River Basin water managers in 2015 provided insight needed to ignite the case study research (Figure 3). Of those who experience water supply challenges (55%, n=33), water scarcity was cited most frequently, defined as conditions inherent to arid lands and exacerbated by climate change (Figure 3a). The majority of managers (79%, n=53) described how warmer temperatures impact their organization’s water management (Figure 3b). Managers defined warming temperatures as temperatures a few degrees warmer in: (1) winter that prevents precipitation from falling and accumulating as snow; (2) spring that accelerates snowmelt and shifts the timing of water supply used for agriculture; and (3) summer that increases irrigation water demand and evaporation.

upstream storage for municipal, agricultural, and environmental water users downstream?

Figure 3. Results of interviews with 53 Truckee River water managers illustrating the percentage of managers who responded their organization: (a) experiences water supply challenges during drought years; (b) faces water management challenges as a result of warmer temperatures; and (c) anticipates positive impacts under reservoir reoperations.



When presented with strategies to adapt existing water management, the majority of managers anticipated positive impacts if reservoir operations could be modified to account for observed earlier spring snowmelt and shifts in peak streamflow timing (Figure 3c). Reservoir reoperation is expected to enhance water supply by either releasing less water during the fall drawdown period (61%, n=33) or allowing reservoirs to store water before April 10 (70%, n=37).

Follow-up interviews conducted in 2016 revealed that despite a normal snowpack year (NRCS, 2016), lack of carry-over storage in reservoirs is an issue salient to managers. During *Stakeholder Affiliate Group* workshops that followed these interviews, water managers emphasized the usefulness of model simulations that evaluate whether revisions to existing water management mitigate increased water scarcity under projected warmer temperatures. Researchers and managers identified reservoir reoperation to allow for earlier storage as one viable strategy to adapt to earlier snowmelt runoff and peak streamflow timing recently observed in the region.

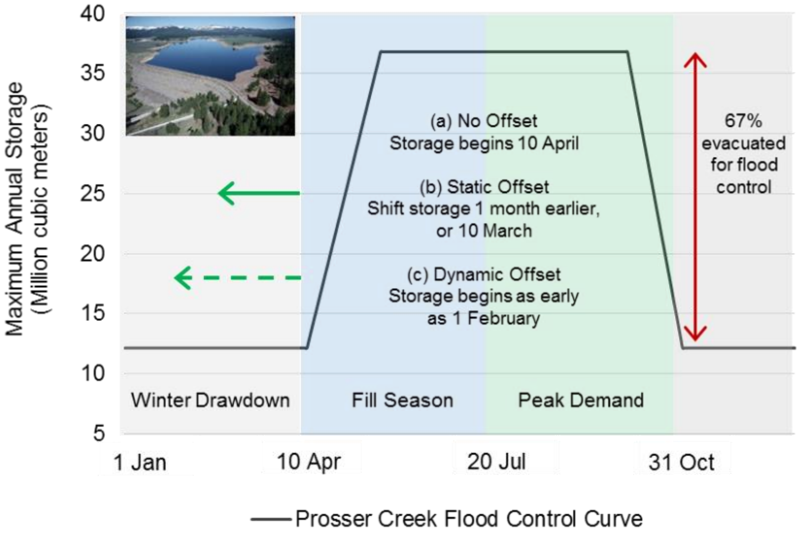
The following three research questions were co-developed to evaluate this strategy: (1) What are the impacts of operating Truckee River reservoirs historically based on fixed calendar dates if the actual snowmelt season is changing? (2) Under a plausible warmer climate scenario, to what extent does reoperation increase reservoir storage? (3) What are the implications of earlier upstream storage for municipal, agricultural, and environmental water users downstream?

3.2 Developing a Warmer Climate Scenario and Reservoir Reoperation Simulations

Answering the co-developed research questions required researchers to: (1) develop a plausible warmer climate scenario to produce projected streamflow; (2) define reservoir reoperation simulations that allow for storage earlier, or before 10 April; and (3) identify a test reservoir and metrics to evaluate implications. The warmer climate scenario was developed by applying a 4.3°C temperature increase to the regions historical precipitation record (WY 1981 to 2015 + 4.3°C), creating a hypothetical 34-year scenario. The degree of warming was selected from the 4th California Climate Change Assessment's 10-GCM average end of the 21st century warming (i.e., 2080 to 2089) (Dettinger et al., 2016).

Two reoperation simulations were defined to quantify the extent to which changes to current operations enhance water supply under the warmer climate scenario: (1) static offset that shifts storage one month earlier to 10 March, and (2) dynamic offset that determines the fill date based on inflows to Boca, Stampede and Prosser Creek reservoirs, but occurs no earlier than 1 February (Figure 4). Dynamic offset was optimized to store peak inflow in order to maximize water supply for downstream users. When peak runoff is early, the storage start date shifts as early as 1 February. This simplification does not consider additional operational conditions that determine whether inflows are actually storable or required to be passed through to meet higher priority water rights (i.e., flows to meet the Floriston rate). Note that reoperation does not alter the fall precautionary drawdown season, but explores only changes to the spring fill season.

Figure 4. Prosser Creek Reservoir operation simulations. (a) No offset defines the current operations that do not allow for storage before 10 April. (b) Static offset reoperation shifts the flood control curve (black line) to allow for storage one month earlier, or 10 March. (c) Dynamic offset reoperation calculates a fill date annually based on peak inflows, but occurs no earlier than 1 February. Note, 67% of reservoir capacity is evacuated making it susceptible to reduced storage under earlier snowmelt.



To evaluate reoperation, a test reservoir and downstream metrics were selected. Prosser Creek Reservoir (elev. 1750 m) was identified as the most susceptible to earlier snowmelt because approximately 67% of the total capacity is evacuated for flood control to meet its wintertime cap (approximately 12 Mm^3, or 10,000 acre-feet), compared to only 10% and 20% of Stampede and Boca Reservoirs capacity, respectively. Additionally, Prosser Creek Reservoir drains mid-elevation (2000 m) terrain, where changes in precipitation phase are most pronounced (Hatchett et al., 2017).

Prosser Creek Reservoir’s ability to store earlier inflows directly affects the ability of the reservoir to meet downstream demands that are met by that stored water, including the Floriston rate at the California-Nevada state line and USFWS fish flow targets in the lower river from Derby Dam to Pyramid Lake. That is, if Prosser Creek Reservoir is precluded from storing earlier runoff and inflows, then it cannot deliver stored water during summer months when demand is greatest and inflows are at lowest levels. Therefore, maintenance of the Floriston rate and USFWS fish flow regimes were selected as metrics to further evaluate implications of reoperations downstream.

3.3 Simulating Reservoir Reoperation under a Warmer Climate

Comparison of historical Prosser Creek Reservoir inflows (WY 1981 to 2015) to simulated inflows under the 34-year warmer climate scenario (WY 1981 to 2015 + 4.3°C) reveals an approximately 45-day shift from mid-March to early February, consistent with other studies in the region (Barnhart et al., 2016; Coats, 2010; Lundquist & Flint, 2006; Stewart et al., 2004, 2005). During the April to June spring fill season, inflows decrease 47% (44 to 21 Mm^3) on average, resulting in decreased storage.

Table 2 compares historical Prosser Creek Reservoir average storage utilization to reoperation under a warmer climate. Historically, Prosser Creek Reservoir fills an average of 76% of capacity (28 Mm^3). Under a warmer climate, current reservoir operations fail to capture shifts in peak streamflow timing and result in less storable water, or an average of 46% of capacity (17 Mm^3). Reoperation under a warmer climate increases average storage to 64% of capacity (24 Mm^3) under static offset and 76% of capacity (28 Mm^3) under dynamic offset retaining its historical average.

Table 2. Prosser Creek Reservoir average storage utilization of current operations and reoperations under a warmer climate compared to the historical average.

Climate scenario	Reservoir operation	Average percent of reservoir total capacity	Average reservoir storage (Mm3)
Historical (WY 1981 to 2015)	No offset	76%	28
Warmer Climate (WY 1981 to 2015 + 4.3°C)		46%	17
	Static offset	64%	24
	Dynamic offset	76%	28

Figure 5 presents the annual volume of storable inflows over a hypothetical 10-year period, illustrating that decreases in storable water under a warmer climate compared to historical (Figure 5a). Reoperation under a warmer climate increases the annual volume, with typically greater storage under dynamic offset (Figure 5b). Figure 6 further presents these results, illustrating the increase in runoff volume storable under static and dynamic offset reoperation.

Figure 5. Prosser Creek Reservoir annual volume of storable inflows for a hypothetical 10-year period. (a) Current operations under a historical versus warmer climate, illustrating decreased storage. (b) Static and dynamic offset reoperation under a warmer climate, illustrating enhanced storage. Axis scales for each plot are equivalent.

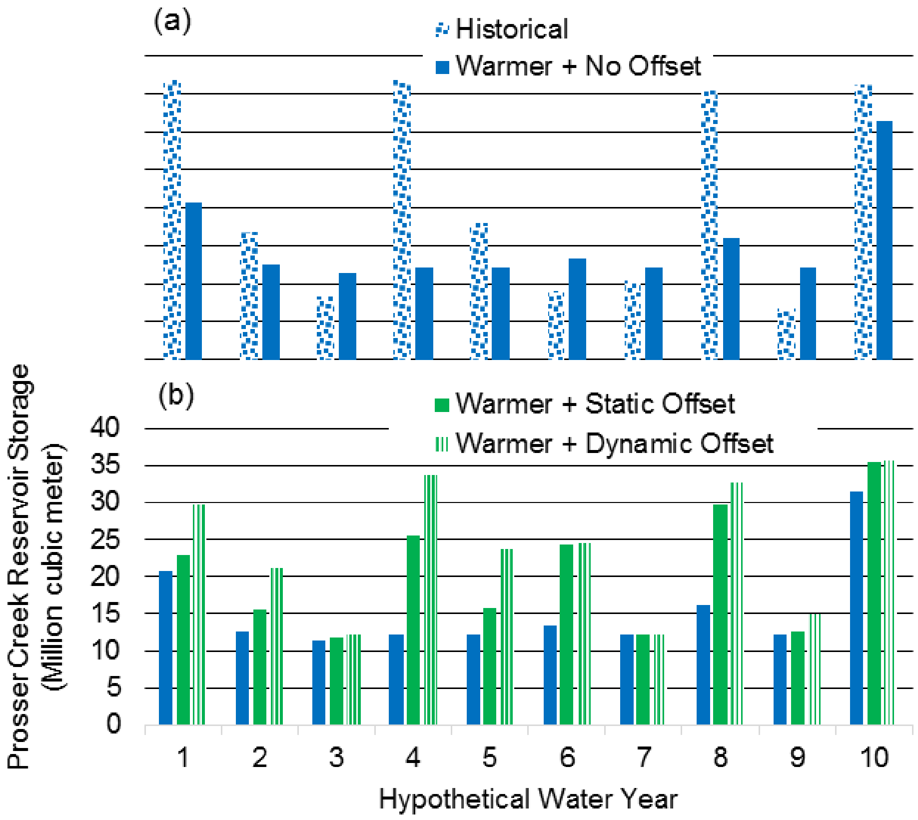
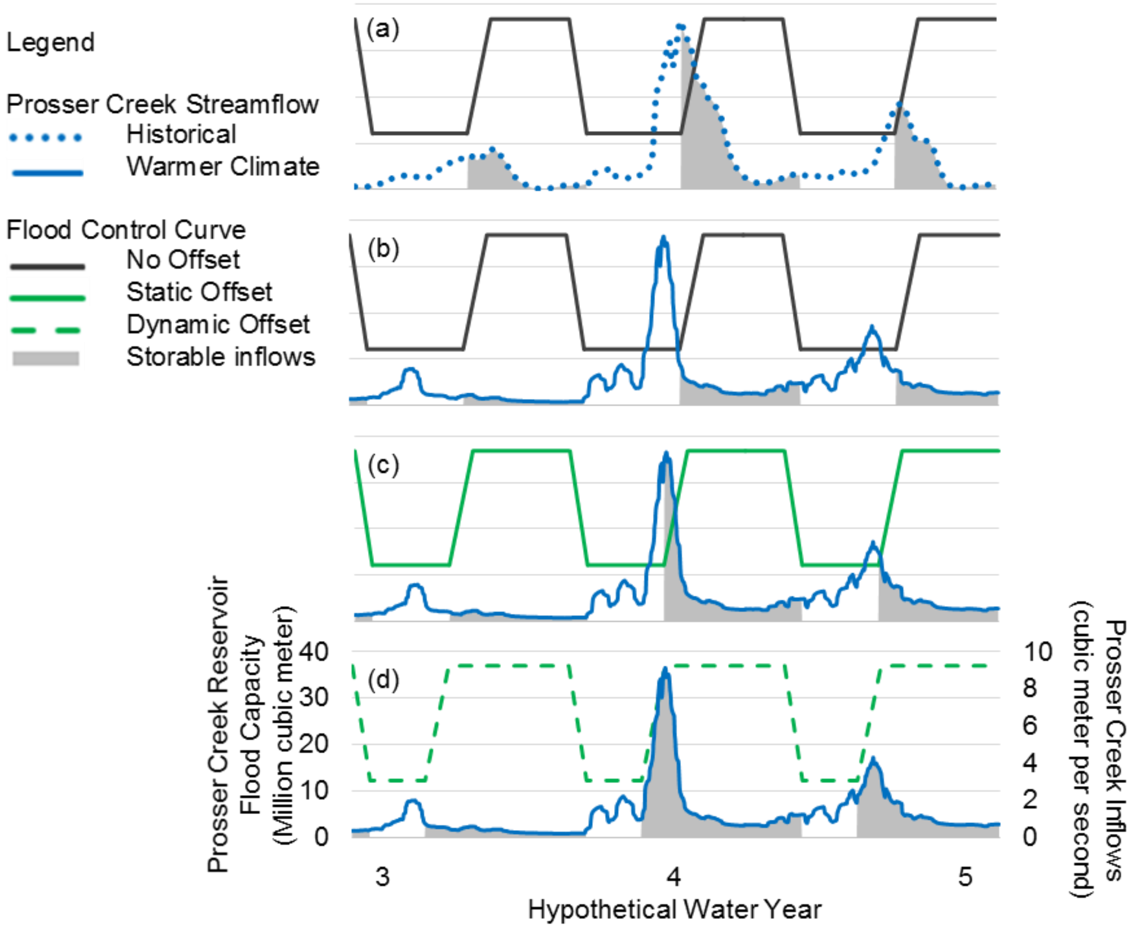


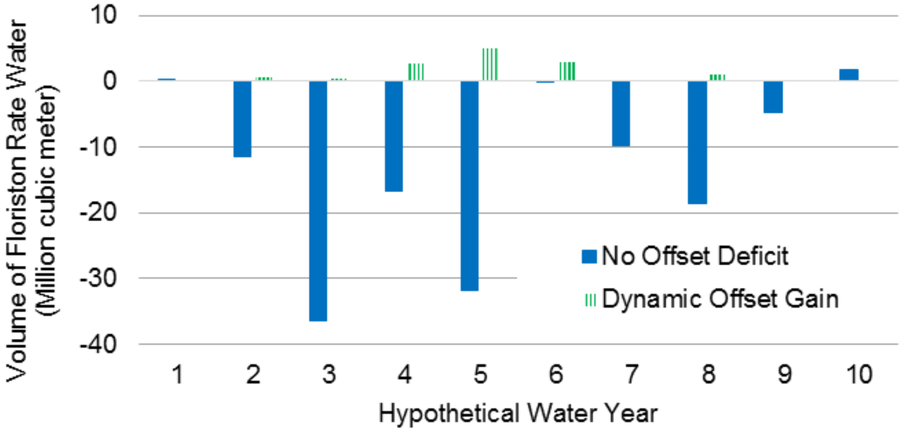
Figure 6. Prosser Creek Reservoir operation simulations for three selected water years corresponding to the hypothetical 10-year period presented in Figure 5. (a) Current operations (dark gray) under the historical climate and streamflow (blue dotted). (b) Current operations under a warmer climate (blue solid). (c) Static offset reoperations (green solid) under a warmer climate. (d) Dynamic offset reoperations (green dashed) under a warmer climate. Grey shading illustrates Prosser Creek inflows storable depending on the flood control curve. Axis scales for each plot are equivalent.



3.4 Evaluating Reservoir Reoperation Implications Downstream

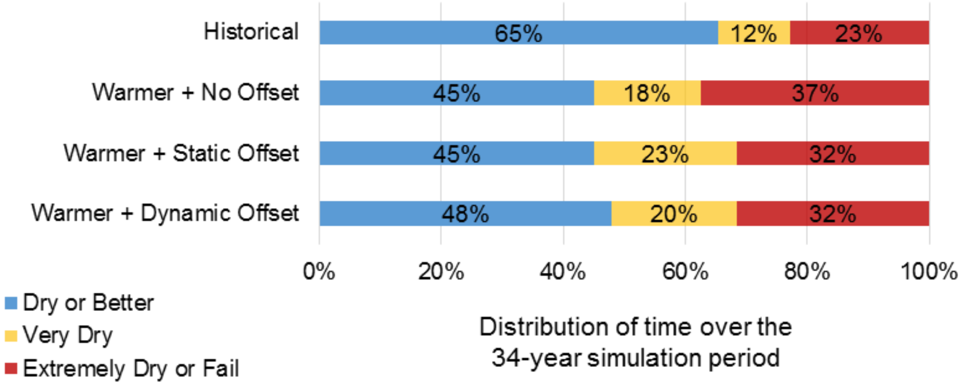
A Floriston rate maintenance analysis quantifies benefits of reoperation to downstream water users. Under a warmer climate and current operations, the Floriston rate is met through the end of September less often, or 49% as compared to 84% of years historically. When Prosser Creek Reservoir is operated dynamically, as many as 14 additional days of Floriston rate water is met, with an average of 5 additional days per year over the 34-year simulation period, thereby reducing shortages downstream. Figure 7 further compares the deficit under current operations and gains under dynamic offset.

Figure 7. Floriston rate maintenance analysis under a warmer climate for a hypothetical 10-year period. No offset deficit (blue bars) illustrates the volume of water missed under current operations. Dynamic offset gain (green striped bars) illustrates volume of water gained under dynamic offset reoperations.



Benefits of reoperation to fish flow targets is evaluated based on whether dry or better (above average, average, below average, dry) flow regimes are selected more often than the driest regimes (very dry, extremely dry, or fail). Figure 8 illustrates the distribution of time spent over the 34-year simulation period. Under the warmer climate scenario and current operations, dry or better regimes (blue bar) are selected only 45% of the time (Figure 8b), compared to 65% historically (Figure 8a). Dynamic offset (Figure 8d) improves the distribution greater than static offset (Figure 8c), increasing the percent of time spent in dry or better to 48%. Under dynamic offset, above average happens 6% more often, extremely dry happens 4% less often, and fail happens 3% less often compared to current operations under a warmer climate. Thus, because the reservoir is able to more effectively store inflows, fish habitat conditions are improved.

Figure 8. Fish flow regime target attainment under Prosser Creek Reservoir reoperation. Distribution of time spent in fish flow regimes historically as compared to a warmer climate. Greatest recovery of the historical distribution occurs when dynamic offset reoperation is applied.



3.5 Collaboratively Reviewing Simulation Results

Researchers and local water managers reviewed the model simulation results during a *Stakeholder Affiliate Workshop*. Managers affirmed that under a warmer climate, reservoir reoperation is advantageous for water supply, increasing the storage of both earlier and reduced inflows, providing measureable benefits basin-wide. Managers acknowledged the usefulness of simulations that examine adaptation strategies spatially and evaluate implications for diverse water users. When compared to other identified adaptation strategies to enhance supply that require structural changes, including groundwater treatment facilities and construction of additional surface water reservoirs, managers favored reservoir reoperation as a low-cost alternative that utilizes existing infrastructure.

Because modifying current reservoir operations is inherently more complex than presented in this study (e.g., Ho et al., 2017), researchers and managers identified a need for additional simulations to evaluate the viability of this strategy. For example, managers unanimously requested that future model simulations incorporate potential trade-offs of earlier storage with increased flood risk indicative of climate change (e.g., Hatchett et al., 2017; Willis et al., 2011), as well as atmospheric river storm events inherent to the region (Dettinger, 2013). As one manager asked, “How might dynamic reservoir reoperations [that allows for storage as early as 1 February] be updated to prepare for a rain-on-snow event during the fill period?” In discussing this idea, both researchers and managers acknowledged the importance of reliable forecasting tools and coordinated personnel to ensure flood risk is mitigated.

Additionally, managers asked whether researchers considered reoperation of other basin reservoirs. As one manager questioned, “Can we see if reoperation would also increase storable inflows to the larger reservoirs [Boca and Stampede] with less relative drawdown [for flood control evacuation]? Researchers agreed that an important next step is demonstrating how the cumulative storage might further enhance water supply. Ultimately, simulating reoperation on multiple reservoirs and Lake Tahoe to optimize storage and timing of releases would provide information necessary to inform decision-making since such operations are coordinated.

4.0 Discussion

Assessing water management practices designed for stationary climate patterns, such as reservoir operations, remains a key strategy to mitigate water scarcity in regions dependent on snow for water supply (Ho et al., 2017; Mateus & Tullos, 2017; Steinschneider & Brown, 2012; Willis et al., 2011). Case studies in the western United States (e.g., Brekke et al., 2009; García et al., 2014; Medellín-Azuara et al., 2007; Payne et al., 2004; Sapin et al., 2017; Watts et al., 2011), elsewhere in the United States (e.g., Ehsani et al., 2017; Mens et al., 2015; Steinschneider & Brown, 2012), and around the globe (e.g., Ahmadi et al., 2014; Diogo et al., 2016; Gohari et al., 2014; Minville et al., 2009; Soundharajan et al., 2016; Sun & Fu, 2016; Vonk et al., 2014) illustrate the importance of place-based case studies that evaluate limitations of reservoir operations that historically have met diverse and competing water demands.

The Truckee River Basin case study contributes to this growing body of literature, where local water managers described current water management practices as an adaptation barrier in light of the recent warming temperatures and drought conditions observed in the region (Sterle &

Singletary, 2017). Comparing Prosser Creek Reservoir historical storage levels (76%) to simulated storage under a 4.3°C warmer climate scenario (46%) affirms this perspective, revealing significant limitations in the reservoir's ability to capture earlier snowmelt runoff and shifts in streamflow. This limitation diminishes water available for downstream municipal, agricultural, and environmental water users. Shifting the flood control curve to allow for earlier storage effectively absorbs shifts in snowmelt runoff and streamflow timing, increasing the storage utilization to the historical average (76%). These results are consistent with other similar studies evaluating the effectiveness of reservoir operations prescribed to historic climate and snowmelt regimes (e.g., Gohari et al., 2014; Payne et al., 2004; Soundharajan et al., 2016).

Unlike these other studies, however, we equate increased storage upstream to water supply downstream, presented through local metrics that water managers can use to evaluate water supply shortages and initiate water management decisions. The Floriston rate, measured 22 km downstream from Prosser Creek Reservoir to determine water right allocations, is met for a longer time period, which equates to increased water available for municipal, industrial, and agricultural water users, and decreased reliance on supplemental groundwater sources to meet demand. Measurable benefits are also experienced 195 km downstream in the lower reach below Derby Dam to Pyramid Lake, where fish flow regimes reflecting moderate to average conditions are selected more often. Thus, because Prosser Creek Reservoir is able to more effectively store water, the conditions for fish species are improved. These results provide empirical evidence that operational changes decrease basin-wide vulnerabilities (Ehsani et al., 2017), increasing resilience to climate change.

While others have simulated climate change impacts using integrated hydrologic and operations models (e.g., Mateus & Tullos, 2017; Vano et al., 2010) and utilized RiverWare specifically to examine alternative management strategies (e.g., Wheeler et al., 2002, 2016), this study is unique in its collaborative research design that involves local water managers in setting the research objectives and reviewing simulation results and implications. Researchers and local water managers worked together to develop a warmer climate scenario salient to managers and to identify how to adapt current water management practices to account for changing snowpack regimes and earlier snowmelt runoff recently observed in the region. As a result of this iterative interaction, research questions were co-developed that reflect the information needs of local water managers and the capabilities of hydrologic and operations models utilized. Collaboratively reviewing simulation results identified simulations for future research that could provide additional key information to support local adaptation.

For example, managers requested researchers evaluate the trade-offs between reservoir reoperations specifically to adapt to earlier snowmelt and its purpose for flood control (Ehsani et al., 2017; García et al., 2014; Willis et al., 2011). Drawing from a case study example in Oregon, reoperations effectively absorbed impacts of warming temperatures, improving summer streamflow targets without compromising existing flood regulation (Mateus & Tullos, 2017). Results that evaluate trade-offs of reservoir reoperations would provide additional insight to assess the feasibility of this strategy in the case study area.

Simulating multi-reservoir reoperation (Vonk et al., 2014), also suggested by local managers, would benefit from observations of current, or real-time conditions, to capture slow processes, such as the rate of snowmelt, in addition to fast processes, such as streamflow runoff (Denaro et al., 2017). Other hydrologic refinements include simulation under rising snow-levels (Hatchett et al., 2017), improved understanding of fraction precipitation rain versus snow (Harpold et al., 2017; Rajagopal & Harpold, 2016), and the relative contribution of precipitation phase change to decreased streamflow (Berghuijs et al., 2014).

An evaluation of the research design that guided these simulations provides additional insight into the utility of collaboratively modeling water management solutions. First, structured and iterative engagement between researchers and local water managers produced a climate scenario salient to managers and identified reservoir reoperation as a plausible adaptation option. Interviews with managers served as a key forum to harness local information needs early, while workshop discussions, involving researchers and managers, were critical to introduce the integrated model, identify simulations, refine research questions, and review results. An overview of the hydrologic and operations model was also necessary to facilitate effective dialogue and to build trust in the model representation of the river basin.

Translating simulation results into downstream metrics of importance to managers (i.e., Floriston rate maintenance and fish flow regime target attainment) in addition to reservoir storage, facilitated managers' assessment of reservoir reoperation as a viable adaptation strategy. In this environment of social learning, local water managers asked researchers questions about modeling capabilities and uncertainties while researchers asked managers questions about current water management challenges under recently observed conditions.

As a result, researchers generated new ideas about how to apply their integrated model to meet local information needs. Reviewing results with managers led to a shared vision for how to improve model simulations to support implementation. These outcomes continue to influence ongoing collaborative modeling efforts that acknowledge local knowledge and information needs (Paolisso & Trombley, 2017) and enhance the utility of research results in support of local climate adaptation planning (Beall King & Thornton, 2016; Jurgilevich et al., 2017; Meadow et al., 2015).

5.0 Conclusion

This paper presents a collaborative modeling case study (Singletary & Sterle, 2017) in the Truckee River Basin, western United States that identified reservoir reoperation as one viable strategy to enhance water supply in upstream federally-managed flood control reservoirs. Water managers and researchers, acknowledging that current reservoir operations assume a stationary climate and exacerbate water scarcity (Sterle & Singletary, 2017), collaborated to evaluate implications of earlier storage on water management basin-wide. In response to local adaptation information needs, researchers developed a warmer climate scenario salient to managers, defined simulations for earlier reservoir storage, and identified Prosser Creek Reservoir as a test reservoir to quantify benefits to water supply. An integrated hydrologic (PRMS) and operations (RiverWare) model tailored to the Truckee River Basin was used to simulate reoperation and results were presented as a function of local metrics to which managers could relate.

Under a warmer climate predicted for the end of the 21st century, operating Prosser Creek Reservoir under fixed calendar dates decreases storable water in the reservoir. Under a warmer climate, peak streamflow timing shifts to 45 days earlier, resulting in the reservoir filling only 46% of capacity versus the historical average of 76% of capacity. Dynamic offset reservoir reoperation most effectively absorbs this shift, increasing reservoir storage utilization to 76% of capacity on average over the 34-year simulation period. Reoperation that allows for earlier storage enhances water supply while also mitigating water supply shortages downstream for municipal and agricultural water users, and fish flow regimes at the river's terminus. To continue to prioritize research activities, managers and researchers collaboratively identified additional simulations to further evaluate the viability of this strategy. Future simulations will incorporate multi-reservoir reoperation to examine more closely the implications, and changes in precipitation phase under a warmer climate to examine flood-control risk.

Collaborative modeling continues to evolve as a form of applied climate science research (Singletary & Sterle, 2018; Voinov et al., 2016). As warming temperatures continue to bring pervasive hydrologic and operational impacts in snow-fed regions around the globe (Georgakakos et al., 2014; Musselman et al., 2017; Sturm et al., 2017), such collaborative research approaches facilitate and foster an understanding of local stakeholder knowledge and information needs necessary to adapt water management (Cosgrove & Loucks, 2015; Van Loon et al., 2016). The collaborative modeling research design presented here illustrates the potential of these methods to other regulated snow-fed river basins with water management and operations based on a stationary climate.

Acknowledgements

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Summary and Conclusions

The collaborative modeling research design developed and implemented in the Truckee-Carson River System case study (Singletary & Sterle, 2017, 2018) involved diverse water managers and an interdisciplinary team of researchers to assess climate adaptation, navigate implementation barriers, and identify science information to support long-term adaptation. This case study exemplified action-oriented research capable of facilitating the transformative changes necessary to address climate-induced water supply variability (Fazey et al., 2018). The work presented harnessed local stakeholder knowledge to define water supply challenges, adaptation strategies, and implementation barriers typified in snow-fed river systems in the arid west. Analysis of primary qualitative data collected from key water managers over variable water years (WY2015, WY2016, and WY2017) revealed increased adaptation efforts and emergent implementation barriers that both intensified and diminished over time. Water managers exemplified recent hydroclimate variability as the “new normal” climate for which they should be planning. Managers requested researchers simulate locally-identified adaptation strategies to support their planning efforts that include alternative water management practices revised to accommodate non-stationary climate patterns.

Notable conclusions from the Truckee-Carson River System case study include:

- Warmer temperatures and changes to snowpack exacerbate existing water scarcity inherent to the arid landscape.
- Drought thresholds are defined differently based on water use community. For example, municipal and industrial water managers defined a higher threshold for drought compared to agricultural water managers who defined a lower threshold.
- The implications of warmer temperatures vary both by water use community as well as spatially across the river system. For example, regulatory managers in the Lake Tahoe region emphasized economic impacts of reduced snowpack influencing tourism in the

basin. Similarly, downstream agricultural managers noted economic impacts relating to increased evapotranspiration influencing crop production.

- Interannual hydroclimate variability experienced coincident with annual interviews ignited increased adaptation efforts, resulting in more focused, collaboration with researchers and among other water managers.
- Over time, managers demonstrated increased willingness to work more collaboratively with one another in the future regardless of longstanding conflict and competition over scarce resources.
- While managers may not be directly affected by every climate change risk identified, they are aware of what other water use communities are faced with, speaking often to system-wide issues.
- Simulations identified through iterative primary data collection, that explore plausible climate scenarios and resulting impacts on hydrology were described by managers as critical information inputs to local managers' adaptation planning.
- Managers described the integrated hydrologic and operations model tailored to the river system a useful tool to examine implications of changing water supply on existing water management to then identify viable strategies for the river system.
- The collaborative modeling research design and resulting simulations may be transferable to other river systems with similar water management practices tied to stationary climate patterns, diverse and competing stakeholders striving towards climate adaptation, and researchers willing to work together to support long-term adaptation.

In this case study area, incorporating human and social dimensions into hydrologic research advanced an understanding of water resource issues. For example, gathering local input on the viability to alternative water management strategies produced new knowledge about river system function and helped to eliminate solutions potentially beneficial in theory, but unrealistic in practice under existing water management and prior appropriation based water law. Collaborative modeling in this case study generated new knowledge attributable to the ongoing and iterative interactions between key water managers and researchers. In this environment, managers and researchers not only became familiar with project objectives and modeling capabilities, but also formed relationships and built trust. As a result, local managers observed how their knowledge and perspectives were being used, researchers increased the utility of their modeling results, and collaborative working relationships were formed. Local managers and researchers continue to work together to define hypothetical yet plausible climate scenarios (e.g., Dettinger et al., 2017), identify and simulate viable adaptation strategies to enhance water supply (e.g., Sterle et al., 2017), and quantify benefits and potential third-party impacts across the river system.

Recommendations

The following recommendations support extension of this work:

- To build on data collected during WY2015, WY2016 and WY2017, conduct a fourth round of interviews following WY2018 with key water managers to further assess shifts in adaptation strategies and implementation barriers, and identify ongoing science information needs. Review of the complete dataset will facilitate an understanding of specific metrics and indicators based on managers' role/responsibility and location in the river system.
- To demonstrate how collaborative modeling navigates an understanding of river system function and future water sustainability, illustrate how researchers and managers worked together to examine the viability of managed aquifer recharge. This strategy was identified as another strategy to enhance water supply in the river system and presented as feasible on agricultural lands in the Upper Carson Valley. Because this strategy is inherently more complex, it involved additional iterations between researchers and managers that identified specific research questions. Reporting results of these iterative

engagements and model simulations would provide an additional example of how collaborative modeling facilitates more holistic understanding of the coupled human-water system.

- To contribute to the emerging field of socio-hydrology, report these findings through a coupled human-water system lens. Recall socio-hydrology is grounded in the coupled human and natural systems literature and aims to understand the dynamics and co-evolution of coupled human-water systems. Case study research is endorsed as a useful method to better understand of these feedbacks between the human and water system, and identify thresholds, or tipping points, that drive alternative water management. Using this coupled systems lens, qualitative data collected could be revisited to identify the hydroclimate conditions that ignited an interest and recommended evaluation of new water management practices. These qualitative data, thus will be translated to quantitative inputs useful to specify human decision-making, enhancing the representation and utility of coupled human-water system models.

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