water

MDPI

Article

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

Kelley Sterle [1,*] and Loretta Singletary [2]

[1] Graduate Program of Hydrologic Sciences, University of Nevada, Reno, NV 89557, USA
[2] Department of Economics and Cooperative Extension, University of Nevada, Reno, NV 89557, USA; singletaryl@unr.edu
* Correspondence: ksterle@unr.edu; Tel.: +1-775-229-5993

Received: 31 July 2017; Accepted: 27 September 2017; Published: 9 October 2017

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.

Keywords: drought; adaptation strategies; adaptation barriers; collaborative modeling; qualitative data; climate uncertainty

---

1. 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 [1–6]. Less snowpack [7,8], earlier and more rapid snowmelt [9,10], and warmer temperatures bringing winter precipitation in the form of rain versus snow [11] challenge water management in this snow-fed inland river system [12].

Historically, spring snowmelt in this region sustains streamflow through the summer irrigation season [13,14] and recharges groundwater aquifers [15,16] used as both primary and supplemental water supply. Earlier snowmelt reduces surface water supply particularly during dry, warm periods [17], while warmer precipitation arriving as Atmospheric Rivers, or rain-on-snow events, can cause both major flooding and water shortages within the same season [5,18,19]. Warmer spring temperatures compound the effects of precipitation deficits through: increased evaporation from open surface water bodies, including lakes, reservoirs, irrigation canals, and irrigated lands; diminished soil moisture; and increased crop transpiration rates, increasing agricultural irrigation demand [20].

Under these conditions, water managers are challenged to sustain water supply for diverse uses that include municipal, industrial, environmental, and agricultural [6,21], exacerbating water demand and competition for already scarce supplies [22]. Such adaptation strategies should increase community resilience to climate induced variable water supply, thereby mitigating harm or exploiting beneficial opportunities [23].

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 [24–26]. For example, in California's Central Valley, perceived changes in water availability had significant effects on farmers' intentions to adopt adaptation strategies [27,28]. During the recent 2000–2012 drought period in Arizona, learning, information and knowledge exchange, and research through either formal or informal collaborations, provided opportunities for adaptation. Strategies included water supply enhancement, infrastructure upgrades, conservation, rate restructures, and long-term drought planning [29].

In implementing adaptation strategies, adaptation barriers may emerge that constrain or impede implementation [30]. In Utah's Wasatch Mountains, for example, water managers described adaptation barriers that included water reallocation and equitable water transfers, stakeholder cooperation, population growth, and securing additional water supplies [31]. Existing prior appropriation doctrine and supporting institutional arrangements can also constrain adaptation [32], as observed in watersheds across the state of Colorado [33].

Adaptation barriers identified in other case studies to date include existing water management practices, lack of communication, and climate uncertainty [34]. 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 [35]. In responding to 2002 drought conditions in northwest Colorado, for example, quantifying climate change uncertainty was paramount to adaptation planning [36].

While current research reports a broad range of adaptation strategies toward sustainable water management solutions to cope with climate uncertainty and drought conditions [29,31,37,38], 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 [39,40] 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 [41].

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 [29,42–45]. Embracing both knowledge and diverse values enhances our understanding of complex environmental problems [46]. Participatory research, experiential learning, and shared best practices results in new knowledge that enhances local capacity to manage water resources sustainably [47].

Primary data collected during interviews with local managers provide researchers the opportunity to assess adaptation strategies and adaptation barriers [29,43,48] in response to the most salient changes [49]. Ultimately, this improves our understanding of how adaptation strategies and actions may change over time under continuous exposure to climate stressors and uncertainty [30,34,50]. 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 [51]. 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. 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 [52].

Figure 1. The Truckee-Carson River System [51].

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 [53]. 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.

Water use across the river system is highly regulated through federal, tribal, state, and local water sharing agreements based on historic prior appropriation doctrine [53]. 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 [54]. 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 [52].

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 [55]. Smaller communities in the Truckee River headwaters (i.e., Lake Tahoe Basin, population 68,000; and Truckee, population 16,000) rely almost entirely on groundwater [56]. Downstream, the city of Fernley (population 19,200) provides municipal and industrial supply through groundwater, recharged mostly by leakage from the Truckee Canal [57].

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) [58]. 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 [59].

More than 80% of the total annual Carson River surface flow is diverted for agricultural irrigation in the Carson Valley [58], serving approximately 575 land parcels with surface water. Of those parcels, approximately 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 [52]. 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 (population 8400) located in the heart of the Newlands Irrigation Project relies largely upon domestic wells [60]. 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 [53].

2.2. Recent Drought Conditions

While severe prolonged drought periods have occurred in the Truckee-Carson River System in the last millennia [61], 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 [62]. 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 [63].

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%

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 [64]. Median SWE in Carson and Truckee Basins is approximately 24 inches (610 mm) and 28 inches (711 mm), respectively [65]. These record lows coincided with record high January to March temperatures where half or more of snowpack melted before 1 April [66]. This 2015 water year resembled dry snow drought conditions, defined as lack of precipitation enhanced by warmer temperatures [5].

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 [67]. 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 [68–70]. 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. These wet late-spring conditions resulted in above average soil moisture levels with projected high efficient runoff [68]. Many agricultural managers at the river system terminus, however, still faced water supply shortages due to previous consecutive years of warmer drought conditions [71,72].

3. 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 [51]. 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 [45,47,51,73]. 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 [74,75] 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. When collected at strategic points in time, primary qualitative data provide perspectives unique to each organization's water management adaptation strategies and barriers [76–78].

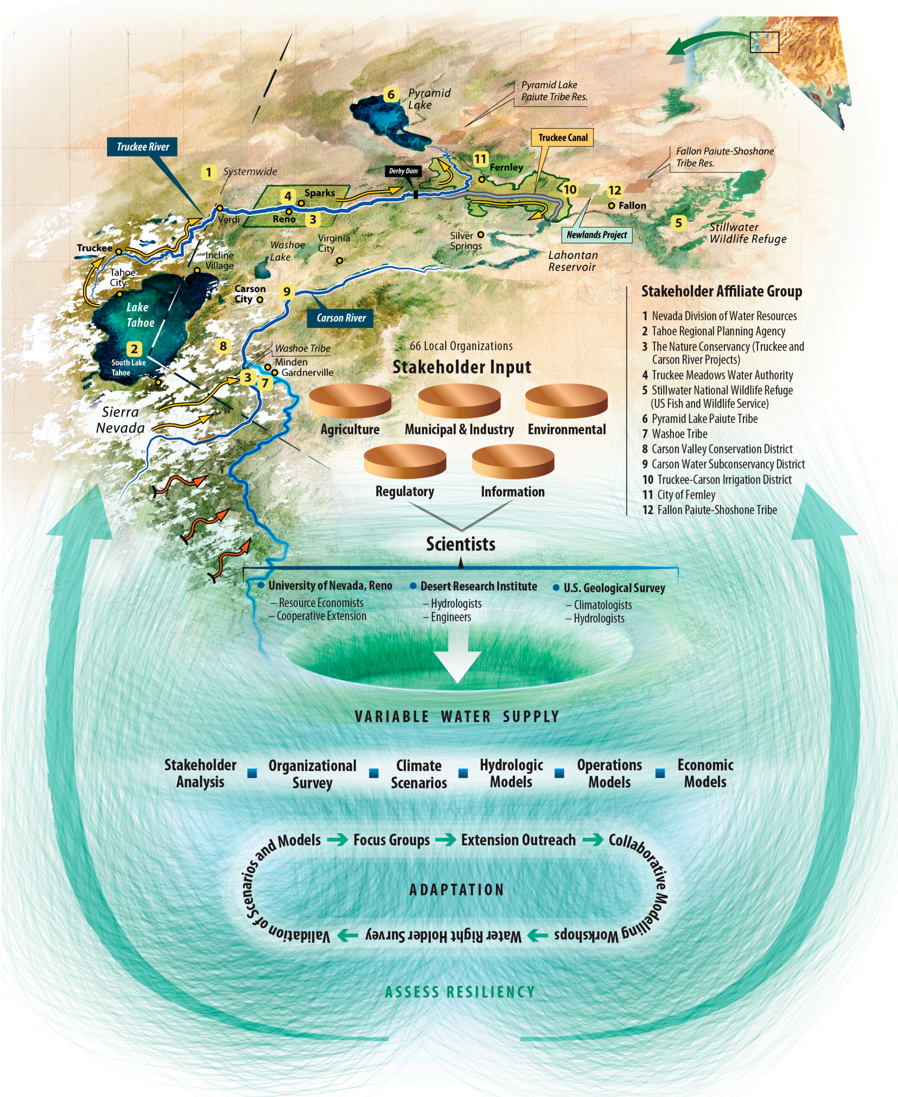

Figure 2. Collaborative Modeling Research Design, highlighting the location of *Stakeholder Affiliate Group* organizations [51].

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 the Newlands Irrigation Project, and system-wide) [51,79]. 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 (Appendix A). 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.

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 [80]. 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 [81].

Interview transcripts were analyzed using constant comparison analysis [82], a qualitative data analysis technique used to identify consistent patterns and relationships [77]. This method is useful particularly when data are collected at two or more points in time during the life of a case study [81] and when the key task is to compare one dataset with another to identify similarities or differences over time [77,83]. 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 then grouped into categories; and (3) selective coding, where one or more themes are developed to express the grouped content [81,84,85].

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 [86]. 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 Appendix B (Tables A1 and A2, respectively).

4. 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.

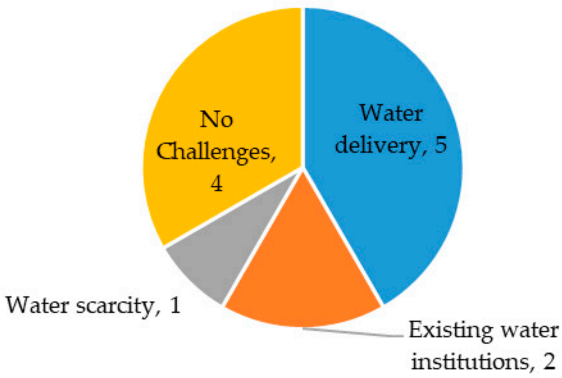

Figure 3. Baseline water supply challenges during normal water years, defined as years when snowpack is measured at 100% of normal, river flows are sustained through the summer irrigation season, or when all water rights and full allocations are met.

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 3.

Table 3. Moderate and severe drought 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 4 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 5 and include: (1) climate uncertainty; (2) existing water institutions; (3) lack of coordination; (4) water scarcity; and (5) water delivery.

Table 4. 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 5. 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

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.

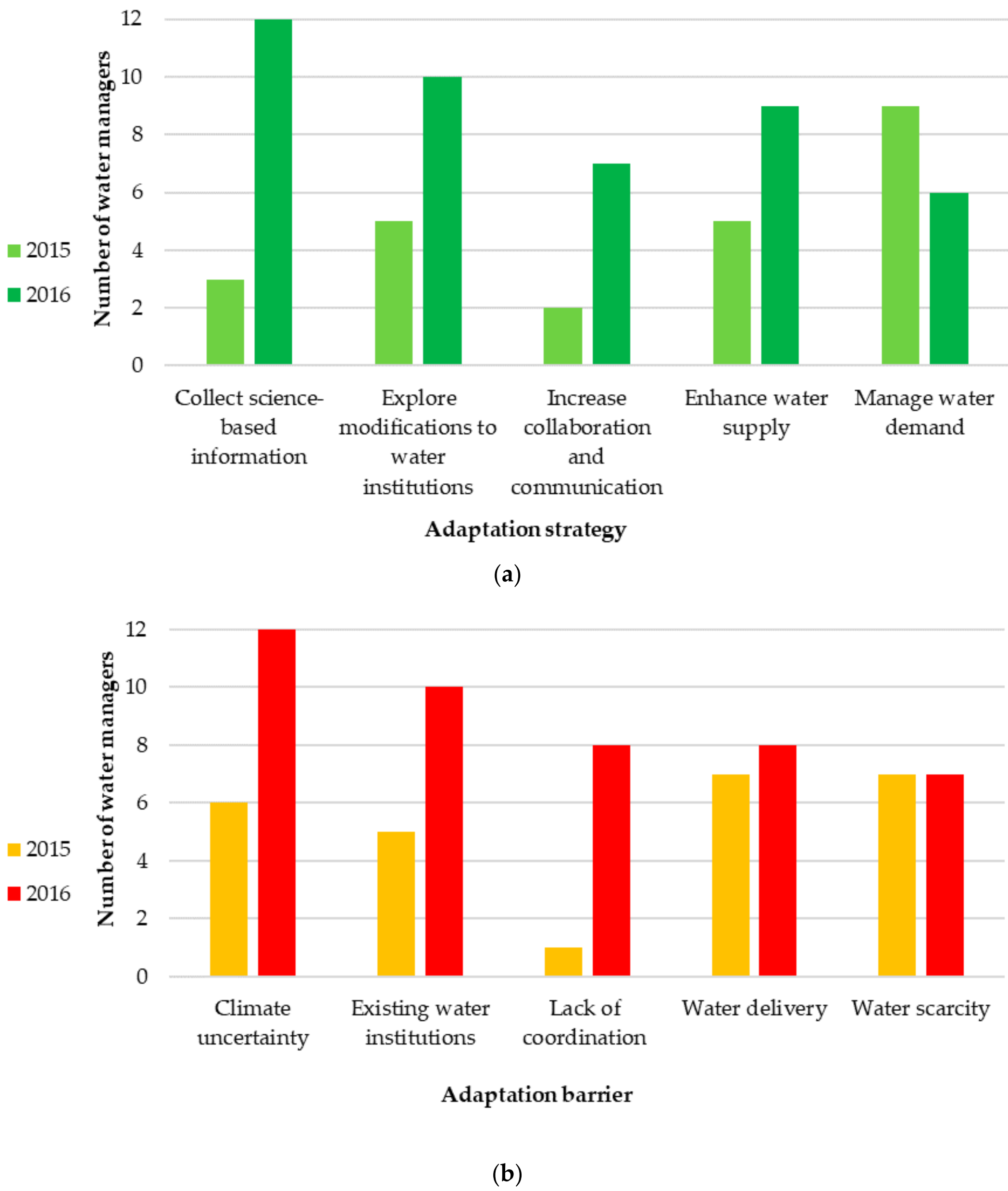

Figure 4. Shifts in adaptation strategies (**a**) and adaptation barriers (**b**) between 2015 and 2016.

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. 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 [29,31,36,45,88–90]. 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 [31]. 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 [29]. 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 [36].

As adaptation barriers related to climate change emerge, increasingly adaptation strategies incorporate cooperation to mitigate the risk of uncertainty [91]. 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 [45]. 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 [89].

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 [89], mobilize regional knowledge exchange to balance adaptive capacity [29], and institutionalize resilience and adaptive management in advance of a potential water management crisis [45]. Thus, collaborative research that facilitates increased communication and coordination should inform future climate planning so that it meets the needs of diverse water users [90].

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 in other snow-fed inland river systems that are highly regulated and where operations are based on historical climate records [31,92,93].

6. 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 [51,95]. 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 [96], constructing a reservoir in the Carson River headwaters to store snowmelt for downstream agricultural irrigation [97], and exploring managed aquifer recharge in the Carson Valley through off-season/winter irrigation in agricultural areas [98].

As warmer drought conditions are projected to increase in duration, frequency and intensity [4,99], 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) [100]. 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 [5].

Acknowledgments: Research is funded by a grant from the National Science Foundation (NSF) Division of Earth Sciences Water Sustainability and Climate program (award# 1360506). The grant covers the cost of this publication. The authors acknowledge local water managers across the Truckee-Carson River System who contributed substantively to this study.

Author Contributions: Kelley Sterle led the design and implementation of this qualitative interview and research component of the collaborative modeling case study. Loretta Singletary assisted with data collection, coding, analysis, and reporting.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Open-ended question items analyzed for this study.

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

Appendix B

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		

References

1. Bond, N.A.; Cronin, M.F.; Freeland, H.; Mantua, N. Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophys. Res. Lett.* **2015**, *42*, 3414–3420. [CrossRef]
2. Cayan, D.R.; Dettinger, M.D.; Pierce, D.; Das, T.; Knowles, N.; Ralph, F.M.; Sumargo, E. Natural Variability, Anthropogenic Climate Change, and Impacts on Water Availability and Flood Extremes in the Western United States. In *Water Policy and Planning in a Variable and Changing Climate*; Miller, K.A., Hamlet, A.F., Kenney, D.S., Redmond, K.T., Eds.; CRC Press: Boca Raton, FL, USA, 2016; pp. 17–42.
3. Belmecheri, S.; Babst, F.; Wahl, E.R.; Stahle, D.W.; Trouet, V. Multi-century evaluation of Sierra Nevada snowpack. *Nat. Clim. Chang.* **2016**, *6*, 2–3. [CrossRef]
4. Cook, B.I.; Ault, T.R.; Smerdon, J.E. Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Sci. Adv.* **2015**, *1*, 1–7. [CrossRef] [PubMed]
5. Harpold, A.; Dettinger, M.; Rajagopal, S. Defining Snow Drought and Why It Matters. *Eos* **2017**, *98*. [CrossRef]
6. Dettinger, M.D.; Udall, B.; Georgakakos, A. Western water and climate change. *Ecol. Appl.* **2015**, *25*, 2069–2093. [CrossRef] [PubMed]
7. Trujillo, E.; Molotch, N. Snowpack regimes of the Western United States. *Water Resour. Res.* **2014**, *527*, 137–170. [CrossRef]
8. Mote, P.W.; Hamlet, A.F.; Clark, M.P.; Lettenmaier, D.P. Declining Mountain Snowpack in Western North America. *Bull. Am. Meteorol. Soc.* **2005**, *86*, 39–49. [CrossRef]
9. Fritze, H.; Stewart, I.T.; Pebesma, E. Shifts in Western North American Snowmelt Runoff Regimes for the Recent Warm Decades. *J. Hydrometeorol.* **2011**, *12*, 989–1006. [CrossRef]
10. Regonda, S.K.; Rajagopalan, B.; Clark, M.; Pitlick, J. Seasonal Cycle Shifts in Hydroclimatology over the Western United States. *J. Clim.* **2005**, *18*, 372–384. [CrossRef]
11. Knowles, N.; Dettinger, M.D.; Cayan, D.R. Trends in snowfall versus rainfall in the western United States. *J. Clim.* **2006**, *19*, 4545–4559. [CrossRef]
12. Mankin, J.S.; Viviroli, D.; Singh, D.; Hoekstra, A.Y.; Diffenbaugh, N.S. The potential for snow to supply human water demand in the present and future. *Environ. Res. Lett.* **2015**, *10*, 114016. [CrossRef]
13. Godsey, S.E.; Kirchner, J.W.; Tague, C.L. Effects of changes in winter snowpacks on summer low flows: Case studies in the Sierra Nevada, California, USA. *Hydrol. Process.* **2014**, *28*, 5048–5064. [CrossRef]
14. Barnhart, T.B.; Molotch, N.P.; Livneh, B.; Harpold, A.A.; Knowles, J.F.; Schneider, D. Snowmelt rate dictates streamflow. *Geophys. Res. Lett.* **2016**, *43*, 1–8. [CrossRef]
15. Jasechko, S.; Birks, S.J.; Gleeson, T.; Wada, Y.; Fawcett, P.J.; Sharp, Z.D.; McDonnell, J.J.; Welker, J.M. The pronounced seasonality of global groundwater recharge. *Water Resour. Res.* **2014**, *50*, 8845–8867. [CrossRef]
16. Harpold, A.A. Diverging sensitivity of soil water stress to changing snowmelt timing in the Western U.S. *Adv. Water Resour.* **2016**, *92*, 116–129. [CrossRef]
17. Georgakakos, A.; Fleming, P.; Dettinger, M.; Peters-Lidard, C.; Richmond, T.; Reckhow, K.; White, K.; Yates, D. *Chapter 3 Water Resources*; Melillo, J.M., Richmond, T.C., Yohe, G.W., Eds.; U.S. Global Change Research Program: Washington, DC, USA, 2014.

18. Das, T.; Hidalgo, H.G.; Pierce, D.W.; Barnett, T.P.; Dettinger, M.D.; Cayan, D.R.; Bonfils, C.; Bala, G.; Mirin, A. Structure and Detectability of Trends in Hydrological Measures over the Western United States. *J. Hydrometeorol.* **2009**, *10*, 871–892. [CrossRef]
19. Dettinger, M.D. Atmospheric Rivers as Drought Busters on the U.S. West Coast. *J. Hydrometeorol.* **2013**, *14*, 1721–1732. [CrossRef]
20. Hatchett, B.J.; Boyle, D.P.; Putnam, A.E.; Bassett, S.D. Placing the 2012–2015 California-Nevada drought into a paleoclimatic context: Insights from Walker Lake, California-Nevada, USA. *Geophys. Res. Lett.* **2015**, *42*, 8632–8640. [CrossRef]
21. Howells, M.; Hermann, S.; Welsch, M.; Bazilian, M.; Segerström, R.; Alfstad, T.; Gielen, D.; Rogner, H.; Fischer, G.; van Velthuizen, H.; et al. Integrated analysis of climate change, land-use, energy and water strategies. *Nat. Clim. Chang.* **2013**, *3*, 621–626. [CrossRef]
22. Diffenbaugh, N.S.; Swain, D.L.; Touma, D. Anthropogenic warming has increased drought risk in California. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 3931–3936. [CrossRef] [PubMed]
23. Intergovernmental Panel on Climate Change (IPCC). Annex II: Glossary. In *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Mach, K.J., Planton, S., von Stechow, C., Eds.; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2014; pp. 117–130.
24. Berrang-Ford, L.; Ford, J.D.; Paterson, J. Are we adapting to climate change? *Glob. Environ. Chang.* **2011**, *21*, 25–33. [CrossRef]
25. Keskitalo, E.C.H.; Westerhoff, L.; Juhola, S. Agenda-setting on the environment: The development of climate change adaptation as an issue in European states. *Environ. Policy Gov.* **2012**, *22*, 381–394. [CrossRef]
26. Coleman, J.M.A.; Sosa-Rodriguez, F.S.; Mortsch, L.D.; Deadman, P.J. Assessing stakeholder impacts and adaptation to low water-levels: The Trent-Severn waterway. *Clim. Chang.* **2016**, *134*, 115–129. [CrossRef]
27. Haden, V.R.; Niles, M.T.; Lubell, M.; Perlman, J.; Jackson, L.E. Global and Local Concerns: What Attitudes and Beliefs Motivate Farmers to Mitigate and Adapt to Climate Change? *PLoS ONE* **2012**, *7*, e52882. [CrossRef] [PubMed]
28. Jackson, L.E.; Wheeler, S.M.; Hollander, A.D.; O'Geen, A.T.; Orlove, B.S.; Six, J.; Sumner, D.A.; Santos-Martin, F.; Kramer, J.B.; Horwath, W.R.; et al. Case study on potential agricultural responses to climate change in a California landscape. *Clim. Chang.* **2011**, *109*, S407–S427. [CrossRef]
29. Engle, N.L. Adaptation Bridges and Barriers in Water Planning and Management: Insight from Recent Extreme Droughts in Arizona and Georgia. *J. Am. Water Resour. Assoc.* **2012**, *48*, 1139–1150. [CrossRef]
30. Eisenack, K.; Moser, S.C.; Hoffmann, E.; Klein, R.J.T.; Oberlack, C.; Pechan, A.; Rotter, M.; Termeer, C.J.A.M. Explaining and overcoming barriers to climate change adaptation. *Nat. Clim. Chang.* **2014**, *4*, 867–872. [CrossRef]
31. Burnham, M.; Ma, Z.; Endter-Wada, J.; Bardsley, T. Water Management Decision Making in the Face of Multiple Forms of Uncertainty and Risk. *J. Am. Water Resour. Assoc.* **2016**, *52*, 1–19. [CrossRef]
32. Kates, R.W.; Travis, W.R.; Wilbanks, T.J. Transformational adaptation when incremental adaptations to climate change are insufficient. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 7156–7161. [CrossRef] [PubMed]
33. Gallaher, S.; Heikkila, T.; Patterson, W.; Frank, V.; Weible, C. Adapting water policy tools to new issues: Lessons from Colorado's experience over time. *Water Policy* **2013**, *15*, 43–60. [CrossRef]
34. Bierbaum, R.; Smith, J.B.; Lee, A.; Blair, M.; Carter, L.; Chapin, F.S.; Fleming, P.; Ruffo, S.; Stults, M.; McNeeley, S.; et al. A comprehensive review of climate adaptation in the United States: More than before, but less than needed. *Mitig. Adapt. Strateg. Glob. Chang.* **2013**, *18*, 361–406. [CrossRef]
35. Global Commons Institute. *Climate Uncertainty and Policymaking: A Policy Maker's View*; All Party Parliamentary Group on Climate Change: London, UK, 2010.
36. McNeeley, S.M. A "toad's eye" view of drought: Regional socio-natural vulnerability and responses in 2002 in Northwest Colorado. *Reg. Environ. Chang.* **2014**, *14*, 1451–1461. [CrossRef]
37. Pulwarty, R.S.; Maia, R. Adaptation Challenges in Complex Rivers Around the World: The Guadiana and the Colorado Basins. *Water Resour. Manag.* **2015**, *29*, 273–293. [CrossRef]
38. Nava, L.F.; Brown, C.; Demeter, K.; Lasserre, F.; Milanés-Murcia, M.; Mumme, S.; Sandoval-Solis, S. Existing opportunities to adapt the Rio Grande/Bravo basin water resources allocation framework. *Water* **2016**, *8*, 291. [CrossRef]

39. López-Hoffman, L.; Breshears, D.D.; Allen, C.D.; Miller, M.L. Key landscape ecology metrics for assessing climate change adaptation options: Rate of change and patchiness of impacts. *Ecosphere* **2013**, *4*, 1–18. [CrossRef]
40. Van Loon, A.F.; Gleeson, T.; Clark, J.; Van Dijk, A.I.J.M.; Stahl, K.; Hannaford, J.; Di Baldassarre, G.; Teuling, A.J.; Tallaksen, L.M.; Uijlenhoet, R.; et al. Drought in the Anthropocene. *Nat. Geosci.* **2016**, *9*, 89–91. [CrossRef]
41. Stoutenborough, J.W.; Vedlitz, A. Public attitudes toward water management and drought in the United States. *Water Resour. Manag.* **2014**, *28*, 697–714. [CrossRef]
42. Adger, W.N.; Dessai, S.; Goulden, M.; Hulme, M.; Lorenzoni, I.; Nelson, D.R.; Naess, L.O.; Wolf, J.; Wreford, A. Are there social limits to adaptation to climate change? *Clim. Chang.* **2009**, *93*, 335–354. [CrossRef]
43. Moser, S.C.; Ekstrom, J.A. A framework to diagnose barriers to climate change adaptation. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 22026–22031. [CrossRef] [PubMed]
44. Parris, A. *Climate in Context: Science and Society Partnering for Adaptation*, 1st ed.; Parris, A.S., Garfin, G.M., Dow, K., Meyer, R., Close, S.L., Eds.; John Wiley & Sons Ltd: West Sussex, UK, 2016.
45. Beall King, A.; Thornton, M. Staying the Course: Collaborative Modeling to Support Adaptive and Resilient Water Resource Governance in the Inland Northwest. *Water* **2016**, *8*, 232. [CrossRef]
46. Reed, M.S. Stakeholder participation for environmental management: A literature review. *Biol. Conserv.* **2008**, *141*, 2417–2431. [CrossRef]
47. Meadow, A.M.; Ferguson, D.B.; Guido, Z.; Horangic, A.; Owen, G.; Wall, T. Moving Toward the Deliberate Co-Production of Climate Science Knowledge. *Weather Clim. Soc.* **2015**, *7*, 179–191. [CrossRef]
48. Adger, W.N.; Arnell, N.W.; Tompkins, E.L. Successful adaptation to climate change across scales. *Glob. Environ. Chang.* **2005**, *15*, 77–86. [CrossRef]
49. Barnett, J.; Graham, S.; Mortreux, C.; Fincher, R.; Waters, E.; Hurlimann, A. A local coastal adaptation pathway. *Nat. Clim. Chang.* **2014**, *4*, 1103–1108. [CrossRef]
50. Ekstrom, J.A.; Moser, S.C. Identifying and overcoming barriers in urban adaptation efforts to climate change: Case study findings from the San Francisco Bay Area, California, USA. *Urban Clim.* **2014**, *9*, 54–74. [CrossRef]
51. Singletary, L.; Sterle, K. Collaborative Modeling to Assess Drought Resiliency of Snow-fed River Dependent Communities in the Western United States: A Case Study in the Truckee-Carson River System. *Water* **2017**, *9*, 99. [CrossRef]
52. Bureau of Reclamation (BOR). *Truckee Basin Study*; Bureau of Reclamation: Washington, DC, USA, 2015.
53. Wilds, L.J. *Water Politics in Northern Nevada: A Century of Struggle*, 2nd ed.; University of Nevada Press: Reno, NV, USA, 2014.
54. Nevada Division of Water Planning (NDWP). *Nevada State Water Plan*; Nevada Division of Water Planning: Carson City, NV, USA, 1999.
55. Truckee Meadows Water Authority (TMWA) Where Does TMWA Get Their Water Supply? Available online: http://tmwa.com/article/where-does-tmwa-get-their-water-supply/ (accessed on 1 November 2016).
56. Horton, G. *A Chronological History of Lake Tahoe and the Truckee River and Related Water Issues: A Publication in the Nevada Water Basin Information and Chronology Series*; Division of Water Planning: Carson City, NV, USA, 1997.
57. Mihevc, T.; Pohll, G.; Niswonger, R.; Stevick, E. *Truckee Canal Seepage Analysis in the Fernley/Wadsworth Area*; University and Community College System of Nevada: Reno, NV, USA, 2002.
58. Cobourn, J. *An Introduction to Our Home Watershed: The Carson River Basin (FS-01-85)*; The Southwestern Naturalist: Reno, NV, USA, 2001.
59. Carson City Public Works (CCPW) Carson City: Daily Water Supply and Demand. Available online: http://www.carson.org/government/departments-g-z/public-works/water/daily-water-supply-demand (accessed on 14 February 2017).
60. Townley, J.M. *Turn This Water Into Gold: The Story of The Newlands Project*, 2nd ed.; Nevada Historical Society: Reno, NV, USA, 1998.
61. Kleppe, J.A.; Brothers, D.S.; Kent, G.M.; Biondi, F.; Jensen, S.; Driscoll, N.W. Duration and severity of Medieval drought in the Lake Tahoe Basin. *Quat. Sci. Rev.* **2011**, *30*, 3269–3279. [CrossRef]
62. Kahil, M.T.; Dinar, A.; Albiac, J. Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. *J. Hydrol.* **2015**, *522*, 95–109. [CrossRef]

63. Natural Resource Conservation Service (NRCS) Nevada Water Supply Outlook Reports. Available online: https://www.nrcs.usda.gov/wps/portal/nrcs/main/nv/snow/ (accessed on 17 September 2017).
64. Natural Resource Conservation Service (NRCS). *Nevada Water Supply Outlook Report April 1, 2015*; Natural Resource Conservation Service: Reno, NV, USA, 2015.
65. Natural Resource Conservation Service (NRCS) Natural Resource Conservation Service Basin Snowpack Graphs. Available online: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/nv/snow/products/?cid=nrcseprd1298705 (accessed on 9 September 2017).
66. NOAA National Centers for Environmental Information. *State of the Climate: National Overview for March 2015*; NOAA National Centers for Environmental Information: Asheville, NC, USA, 2015.
67. Natural Resource Conservation Service (NRCS). *Nevada Water Supply Outlook Report May 1, 2015*; Natural Resource Conservation Service: Reno, NV, USA, 2015.
68. Natural Resource Conservation Service (NRCS). *Nevada Water Supply Outlook Report April 1, 2016*; Natural Resource Conservation Service: Reno, NV, USA, 2016.
69. Natural Resource Conservation Service (NRCS). *Nevada Water Supply Outlook Report March 1, 2016*; Natural Resource Conservation Service: Reno, NV, USA, 2016.
70. Nevada State Climate Office. *Quarterly Report and Outlook April–June 2016*; Nevada State Climate Office: Reno, NV, USA, 2016.
71. Natural Resource Conservation Service (NRCS). *Nevada Water Supply Outlook Report May 1, 2016*; Natural Resource Conservation Service: Reno, NV, USA, 2016.
72. NOAA National Centers for Environmental Information. *State of the Climate: Drought for Annual 2016*; NOAA National Centers for Environmental Information: Asheville, NC, USA, 2017.
73. Langsdale, S.; Beall, A.; Bourget, E.; Hagen, E.; Kudlas, S.; Palmer, R.; Tate, D.; Werick, W. Collaborative modeling for decision support in water resources: Principles and best practices. *J. Am. Water Resour. Assoc.* **2013**, *49*, 629–638. [CrossRef]
74. Reed, M.S.; Graves, A.; Dandy, N.; Posthumus, H.; Hubacek, K.; Morris, J.; Prell, C.; Quinn, C.H.; Stringer, L.C. Who's in and why? A typology of stakeholder analysis methods for natural resource management. *J. Environ. Manag.* **2009**, *90*, 1933–1949. [CrossRef] [PubMed]
75. Prell, C.; Hubacek, K.; Reed, M. Stakeholder Analysis and Social Network Analysis in Natural Resource Management. *Soc. Nat. Resour.* **2009**, *22*, 501–518. [CrossRef]
76. Kaplowitz, M.D.; Hoehn, J.P. Do focus groups and individual interviews reveal the same information for natural resource valuation? *Ecol. Econ.* **2001**, *36*, 237–247. [CrossRef]
77. Krueger, R.A.; Casey, M.A. *Focus Groups: A Practical Guide for Applied Research*, 5th ed.; Sage Publications: Thousand Oaks, CA, USA, 2015.
78. Rossman, G.B.; Rallis, S.F. *An Introduction to Qualitative Research. Learning in the Field*, 4th ed.; Sage Publications: Thousand Oaks, CA, USA, 2016.
79. Singletary, L.; Sterle, K.; Simpson, K. *Assessing the Climate Resiliency and Adaptive Capacity of the Truckee-Carson River System: Results of a Survey of Local Organizations (SP-16-03)*; University of Nevada Cooperative Extension: Reno, NV, USA, 2016.
80. Sandelowski, M. Whatever happened to qualitative description? *Res. Nurs. Health* **2000**, *23*, 334–340. [CrossRef]
81. Onwuegbuzie, A.J.; Dickinson, W.B.; Leech, N.L.; Zoran, A.G. A Qualitative Framework for Collecting and Analyzing Data in Focus Group Research. *Int. J. Qual. Methods* **2009**, *8*, 1–21. [CrossRef]
82. Glaser, B.G.; Strauss, A.L. *The Discovery of Grounded Theory: Strategies for Qualitative Research*; Routledge: Abingdon-on-Thames, UK, 1999.
83. Thorne, S. *Interpretive Description: Qualitative Research for Applied Practice*, 2nd ed.; Routledge: Abingdon-on-Thames, UK, 2016.
84. Strauss, A.; Corbin, J. *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*; SAGE Publications, Inc.: Thousand Oaks, CA, USA, 2008.
85. Miles, M.B.; Huberman, A.M.; Saldana, J. *Qualitative Data Analysis: A Methods Sourcebook*, 3rd ed.; Sage Publications: Thousand Oaks, CA, USA, 2014.
86. Kurasaki, K.S. Intercoder Reliability for Validating Conclusions Drawn from Open-Ended Interview Data. *Field Methods* **2000**, *12*, 179–194. [CrossRef]

87. Economic Development Authority of Western Nevada (EDAWN). *Northern Nevada Regional Growth Study 2015–2019*; Economic Development Authority of Western Nevada: Reno, NV, USA, 2015.
88. Jenni, K.; Graves, D.; Hardiman, J.; Hatten, J.; Mastin, M.; Mesa, M.; Montag, J.; Nieman, T.; Voss, F.; Maule, A. Identifying stakeholder-relevant climate change impacts: A case study in the Yakima River Basin, Washington, USA. *Clim. Chang.* **2014**, *124*, 371–384. [CrossRef]
89. Endter-Wada, J.; Selfa, T.; Welsh, L.W. Hydrologic Interdependencies and Human Cooperation: The Process of Adapting to Droughts. *Weather Clim. Soc.* **2009**, *1*, 54–70. [CrossRef]
90. Sandoval-Solis, S.; Teasley, R.L.; Mckinney, D.C.; Thomas, G.A.; Patiño-Gomez, C. Collaborative Modeling to Evaluate Water Management Scenarios in the Rio Grande Basin. *J. Am. Water Resour. Assoc.* **2013**, *49*, 639–653. [CrossRef]
91. Lach, D.; Rayner, S.; Ingram, H. Taming the waters: Strategies to domesticate the wicked problems of water resource management. *Int. J. Water* **2005**, *3*, 1. [CrossRef]
92. Wehlage, G. The Purpose of Generalization in Field-Study Research. In *A Study of Schooling: Field-Based Methodologies in Educational Research and Education*; Popkewitz, T., Tabachnick, R., Eds.; Praeger: New York, NY, USA, 1981; pp. 211–226.
93. Creswell, J.W.; Poth, C.N. *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*, 4th ed.; Sage Publications: Thousand Oaks, CA, USA, 2017.
94. Lee, G.-E.; Rollins, K.; Singletary, L. An Empirical Analysis of Water Allocation Efficiency through the Prior Appropriation Doctrine: A Case Study in the Carson River Valley, Nevada. In Proceedings of the Agricultural and Applied Economics Association (AAEA) Annual Meeting, Chicago, IL, USA, 30 July–1 August 2017.
95. Sterle, K.; Singletary, L.; Pohll, G. *Collaboratively Modeling Water Resources in the Truckee-Carson River System (SP-17-04)*; University of Nevada Cooperative Extension: Reno, NV, USA, 2017.
96. Sterle, K.; Singletary, L.; Rajagopal, S.; Jose, L.; Coors, S.; Pohll, G.; Thomas, J. Adapting to Earlier Snowmelt through Reservoir Reoperation. In Proceedings of the 2017 Annual Conference of the Italian Society for Climate Sciences (SISC), Bologna, Italy, 26–27 October 2017.
97. Morway, E.D.; Niswonger, R.G.; Triana, E. Toward improved simulation of river operations through integration with a hydrologic model. *Environ. Model. Softw.* **2016**, *82*, 255–274. [CrossRef]
98. Niswonger, R.G.; Morway, E.D.; Triana, E.; Justin, L. Huntington Managed Aquifer Recharge through Off-Season Irrigation in Agricultural Regions. *Water Resour. Res.* **2017**, *53*. [CrossRef]
99. Dai, A. Drought under global warming: A review. *Wiley Interdiscip. Rev. Clim. Chang.* **2011**, *2*, 45–65. [CrossRef]
100. Natural Resource Conservation Service (NRCS). *Nevada Water Supply Outlook Report April 1, 2017*; Natural Resource Conservation Service: Reno, NV, USA, 2017.