Case Study

Collaboratively Modeling Reservoir Reoperation to Adapt to Earlier Snowmelt Runoff

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Abstract: Across many river basins in the arid Western United States, upstream surface water reservoirs store snowmelt runoff to meet downstream water demand. A collaborative modeling research program in the Truckee River Basin iteratively convenes researchers and local water managers to (1) assess water management challenges under climate change, (2) identify strategies to adapt water management, (3) prioritize research and modeling activities, and (4) collaboratively review findings. This paper presents selected research program results that identify fixed date–based reservoir operations based on stationary climate as a barrier to adapt to warmer temperatures, earlier Sierra Nevada snowmelt runoff, and shifts in streamflow timing. Using an integrated hydrologic and operations model tailored to the river basin, researchers demonstrate that under a warmer climate, earlier peak streamflow compromises reservoir storage. Simulations that allow for earlier storage absorb streamflow timing shifts, providing measurable benefits upstream in the reservoir and downstream for diverse water-use communities. Researchers review simulation results with managers to assess the on-the-ground potential and identify additional research opportunities that meet local information needs. This paper illustrates the utility of integrating local knowledge with applied climate science research to support adaptive water management in snow-fed river basins. **DOI: 10.1061/(ASCE)WR.1943-5452.0001136.**

Author keywords: Collaborative modeling; Climate stationarity; Reservoir reoperation; Snow-fed river basins; Adaptive water management.

Introduction

Snowpack remains one of the fastest changing hydrologic features (IPCC 2014; USGCRP 2017), altering water supply for arid regions across the Western United States (Harpold et al. 2017; Li et al. 2017; Mankin et al. 2015). 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, 2018; Trujillo and 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; McCabe et al. 2018; Stewart et al. 2004, 2005).

These changes have direct implications for river basin operations based on assumptions of climate stationarity (Ahmadi et al. 2014; Milly et al. 2008; Steimke et al. 2018; Steinschneider and Brown 2012; Watts et al. 2011; Willis et al. 2011). For example, across the Western United States, 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 (Mateus and Tullos 2017; Nava et al. 2016; Vogel et al. 2007). Under changing snowpack regimes, current fixed date–based operations can compromise reservoir storage (Ehsani et al. 2017; Gohari et al. 2014; Soundharajan et al. 2016), increasing competition for already scarce water supplies (Medellín-Azuara et al. 2007; Payne et al. 2004; Vanrheenen et al. 2004). Dynamic reservoir operations that account for earlier snowmelt runoff and streamflow timing have the potential to enhance water supply, adapting existing water management for climate change (Ehsani et al. 2017; Gohari et al. 2014; Mateus and Tullos 2017).

The Truckee River Basin in Nevada and California typifies such a river basin where upstream surface water reservoirs are operated according to fixed date–based flood-control criteria set by USACE. Current operations assume significant Sierra Nevada snowmelt does not occur before April 10 (Berris et al. 1998; USACE 1985). While management of these reservoirs has two objectives (i.e., mitigate flood risk and store runoff), current operations can prevent storage of earlier snowmelt runoff (Harpold et al. 2017), thereby exacerbating climate change impacts (Arheimer et al. 2017; Van Loon et al. 2016).

A participatory research approach, such as collaborative modeling, becomes useful in this context to understand how climate-induced water supply variability affects local water-use

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communities (Beall King and Thornton 2016; Langsdale et al. 2013; Singletary and Sterle 2017, 2018). Systematic and iterative interactions foster dialogue between researchers and local water managers to examine water management challenges (Sterle and Singletary 2017) and develop shared research questions to prioritize research and modeling activities that meet local information needs (Phillipson et al. 2012). This information exchange results in social learning (Ensor and Harvey 2015; McGreavy et al. 2015), where researchers and local water managers generate new knowledge of river basin function to support adaptive water management (Mills-Novoa et al. 2017; Niswonger et al. 2014; Parris 2016; Sandoval-Solis et al. 2013; Sterle and Singletary 2017). Incorporating local water managers in the research can also help identify local metrics that managers monitor and use in decision-making (Steimke et al. 2018). Reporting results as a function of these metrics enhances the utility of modeling results (Voinov et al. 2016; Voinov and Bousquet 2010), ultimately advancing applied climate science research (Clark et al. 2016; Fazey et al. 2018; Lemos and Morehouse 2005; Meadow et al. 2015; Singletary and Sterle 2018).

This paper features selected results from a 5-year collaborative modeling research program in the Truckee River Basin in the Western United States. The objectives are as follows:

1. Demonstrate how collaborative modeling fosters dialogue between researchers and local water managers to examine water management challenges and prioritize research and modeling activities.
2. Present results from iterative interactions that identify reservoir reoperation as one strategy to adapt existing water management for a warmer climate.
3. Quantify basin-wide implications of earlier reservoir storage using simulation results from an integrated hydrologic (PRMS) and operations (RiverWare) model tailored to the basin.
4. Summarize local water managers' responses to model results and opportunities identified for future research.

Methods

Truckee River Basin Case Study Area

Hydrogeography and Climate

The Truckee River originates as snowpack in the Sierra Nevada of eastern California and flows 195 km northeastward from Lake Tahoe, terminating in Pyramid Lake in northwestern Nevada's Great Basin (Fig. 1). The Sierra Nevada range creates a rain shadow effect resulting in two vastly different climates in the basin—an alpine forest in the upper basin (elevation 2,700 m) and arid-land desert in the lower basin (elevation 1,200 m). The upper basin receives 762 to 1,778 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 the Reno–Sparks metropolitan area (population 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 (population 19,200) to the river terminus at Pyramid Lake. Thirty-year (1981–2010) annual average temperatures for the region range from 8.8°C to 20.5°C in the upper elevations to 19.4°C 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 and 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 (7,925 km^2), with losing and gaining reaches of minor importance downstream (Huntington et al. 2013). Peak runoff typically occurs in June, with more than half the volume flowing from April to July sustaining streamflow to the lower reaches through August (USBOR 2015, 2016a). Notably, water years (WY) (October 1–30 September) 2015 and 2016, coincident with this case study, brought historically low snowpack in the upper watershed (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).

Water-Use Communities

The majority of water demand in the basin exists downstream in the Great Basin of northwestern Nevada, where water use is highly regulated through federal, tribal, state, and local water-sharing agreements based on 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).

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).

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 1,233 Mm^3. Three lakes in the basin have constructed dams to increase storage capacity. Lake Tahoe Dam (completed in 1913) controls the top 2 m of Lake Tahoe, increasing its storage capacity to 918 Mm^3, and is managed and operated by the Federal District Court Watermaster to meet the Floriston rate (discussed in detail in what follows). 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 US Bureau of Reclamation (USBOR) and operated in accordance with 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 April 10, a fixed operational date that assumes significant snowmelt does not begin earlier, and as late as May 25, 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

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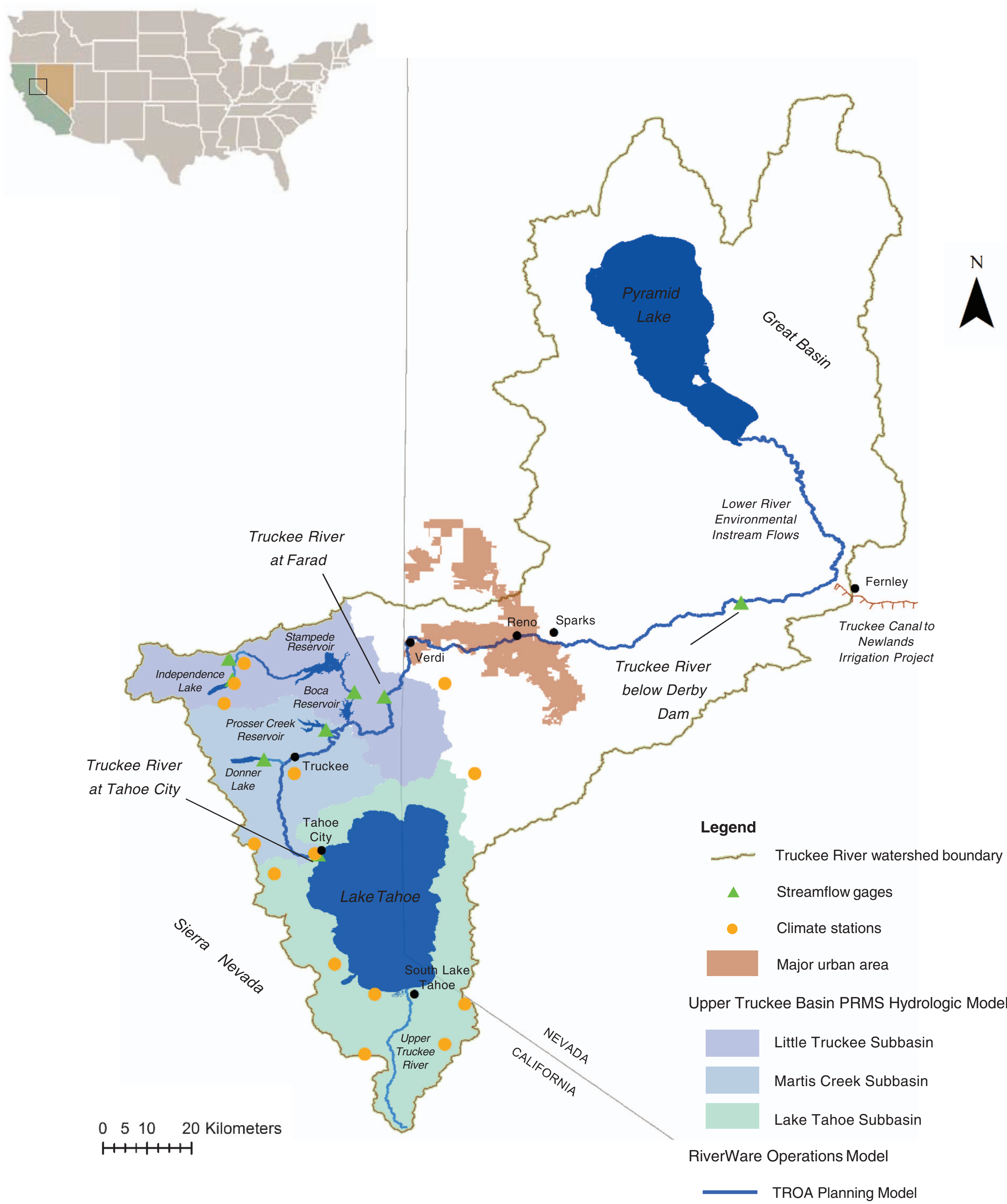

Fig. 1. (Color) Truckee River Basin case study area.

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 November 1 until April 10 (Berris et al. 1998; USACE 1985).

Lake Tahoe and upstream reservoirs are operated to meet federally established Floriston rates (established 1908), the most fundamental operational policy in the basin. The Floriston rates define the target rate of flow measured at the Farad gauge operated by the USGS at the California and Nevada state line west of Verdi (Fig. 1) to meet the needs of downstream agricultural, municipal, and environmental water users. As defined in the 1935 Truckee River Agreement, the Floriston rates specify a target rate of flow of (1) at least 11 m^3/s (400 ft^3/s) during winter between October 1 and February 28 and (2) 14 m^3/s (500 ft^3/s) during summer between March 1 and September 30 (USBOR 2016a). If natural flows and upstream reservoir releases are not sufficient to meet the 14 m^3/s target rate of flow, the dam at Lake Tahoe can be opened if lake level permits.

Between March 1 and September 30, when the Floriston rate is met, all downstream water rights are satisfied. When the Floriston rate is not met, Truckee Meadows agricultural users do not receive water, municipal and industrial water users must rely more upon groundwater supply, and environmental issues are amplified. In most years, the Floriston rate is met through September 30. The year 2015 broke a new record as the earliest date the Floriston rate was missed (April 17 compared to June 6, set in 1992). This was mostly the result of Lake Tahoe elevation falling below the dam, preventing releases.

Waters stored in Stampede and Prosser Creek reservoirs are designated specifically to maintain environmental instream flows that support spawning and recovery of native fish species and riparian habitat in the lower reach below Derby Dam to Pyramid Lake (Fig. 1). Six fish flow regimes (i.e., above average, average, below average, dry, very dry, extremely dry) and corresponding monthly instream flow targets were developed in the mid-1990s jointly by the Pyramid Lake Paiute Tribe and the US Fish and Wildlife Service. Flow regime selection occurs beginning March 1 and is based on two factors: Stampede Reservoir storage volume and forecasted inflows into Stampede Reservoir. The corresponding target flows are greatest during the April–July spawning period in order to mimic the natural hydrograph, while also optimally utilizing Stampede Reservoir storage during periods of extended drought (USFWS 2003). The Pyramid Lake Paiute Tribe adaptively manages the fishery, meaning that each month they have the ability to revise the fish flow regime selection should actual river and reservoir conditions be different than what was forecasted the month prior. Stampede and Prosser Creek reservoir releases historically helped to achieve the flow target for the selected regime until 2015, when the Pyramid Lake Paiute Tribe was forced to operate fisheries below the extremely dry (i.e., sub-6) regime to keep water in Stampede Reservoir.

Implemented December 1, 2015, the Truckee River Operating Agreement (TROA) is intended to increase the operational flexibility and efficiency of upstream reservoirs while honoring downstream water rights under existing decrees (i.e., Orr Ditch Decree 1944). The agreement, the result of a 26-year negotiated settlement process involving the Pyramid Lake Paiute Tribe, replaces the former management system and acknowledges decreasing agricultural water use and increasing municipal and industrial water demand in the region (USBOR 2016b). While TROA addresses long-standing conflict among diverse water users in the region, it does not explicitly address changes to reservoir storage under climate change.

Collaborative Modeling Research Program

The collaborative modeling research program developed for and implemented in this case study systematically and iteratively convenes researchers and local water managers through a set of primary data collection methods (Singletary and Sterle 2017, 2018). Broadly, these interactions serve to (1) assess water management challenges under climate change, (2) identify strategies to adapt water management, (3) prioritize research and modeling activities, and (4) collaboratively review findings to identify additional research opportunities that meet local information needs (Sterle et al. 2019; Sterle and Singletary 2017). The following sections describe the primary data collection and modeling methods featured in this paper.

Primary Data Collection

Table 1 summarizes the primary data collection methods used to harness local knowledge and assess local information needs. Researchers followed a consistent protocol pertaining to human subject research reviewed and approved by the University of Nevada, Reno, Office of Research Integrity, which includes participant recruitment, data collection, and analysis.

During the 2015 summer irrigation season at the case study's outset, an interdisciplinary research team conducted face-to-face semistructured interviews to establish a baseline understanding of river basin function (Singletary and Sterle 2017). Water managers were selected for interviews if their organizations (1) consume, deliver, protect, or supply surface or groundwater; (2) participate in water resource planning and management; (3) regulate or have the potential to influence water management; or (4) possess technical and scientific knowledge about local water resources. This resulted in 66 total interviews with managers representing the diverse municipal and industrial ($n = 15$), agricultural ($n = 8$), and environmental ($n = 18$) water-use communities, as well as planning ($n = 14$) and regulatory ($n = 11$) organizations. The sample was intended also to achieve uniform geographical representation from headwaters to terminus.

The 21-question survey instrument, developed by the interdisciplinary research team, featured 4 questions that aimed to (1) characterize water management challenges faced during drought years, (2) evaluate whether warmer temperatures impact water management, (3) identify desired changes that would improve water management, and (4) gather input on local strategies to adapt water management. Interviews were conducted at managers' offices and lasted approximately 90 min. A researcher, other than the facilitator, transcribed the discussion using a laptop computer. Qualitative data resulting from the open-ended questions were analyzed using content analysis, a method commonly used to objectively identify key themes (Rossman and Rallis 2016). The data were descriptively coded (Miles et al. 2014) and analyzed using basic descriptive statistics. Researchers conducted an intercoder reliability assessment to minimize coder bias and finalize codes (Kurasaki 2000)

Table 1. Primary data collection methods

Method	Participants and procedure	Purpose
Face-to-face semistructured interviews	Conduct interviews with 66 water managers representing diverse water-use communities geographically distributed from headwaters to terminus at project outset (2015)	Characterize water management challenges faced during drought years, evaluate warmer temperatures impacts, and gather local input on strategies to adapt water management
Stakeholder Affiliate Group workshops	Convene interdisciplinary research team and 12 "key informant" water managers, identified through a stakeholder analysis	Consistent forum to discuss and consider input of local water managers, review and validate model simulations, and prioritize ongoing research activities

(see Supplemental Data for featured question items and coding categories).

Following the 2015 interviews with 66 water managers, researchers met with 12 key local water managers who voluntarily participated in workshops held biannually at the Desert Research Institute, Reno, Nevada. These 12 key managers, identified through a stakeholder analysis (Prell et al. 2009; Reed et al. 2009), represent the diverse water-use communities spatially distributed across the basin and meet with researchers through the life of the research program (Singletary and Sterle 2017). While workshops follow a semistructured agenda, facilitated information exchange between managers and researchers achieves a deeper understanding of climate change impacts on water management. Research activities are identified, prioritized, and revised accordingly to reflect this new knowledge and to meet managers' climate adaptation information needs. Managers also provide local technical expertise to help to further focus researchers' modeling efforts.

Integrated Hydrologic and Operations Model

Concurrent with primary data collection, researchers integrated an existing hydrologic and operations model tailored to the Truckee River Basin to facilitate a basin-wide assessment of water management under climate change. Hydrologic processes in the Upper Truckee Basin are simulated using the Precipitation Runoff Modeling System (PRMS) surface water model (Fig. 1 for model boundary) (Huntington et al. 2013; Rajagopal et al. 2015; USBOR 2015). PRMS is 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). The model was calibrated using historical daily precipitation and temperature data (WY 1980–2010) from 14 climate stations located in the upper basin (for calibration, see Supplemental Data). Locally informed climate scenarios provide inputs of temperature and precipitation that drive the Upper Truckee PRMS model, producing daily streamflow outputs at seven streamflow gauges that are then passed as inputs to the TROA Planning Model (Fig. 1).

The TROA Planning Model was developed in the RiverWare modeling framework and simulates Truckee River Basin operations from headwaters to terminus according to TROA river basin policy (for calibration, see Supplemental Data). RiverWare is a river operations and accounting model that simulates river and reservoir operations and water diversions (Rieker et al. 2005; Zagona et al. 2001). Using daily inputs of streamflow from the Upper Truckee PRMS model, reservoir physical contents, and reservoir account storages, the TROA Planning Model distributes water based on scheduled water demands to meet reservoir storage and release targets according to USACE flood-control criteria space, maintenance of the Floriston rate, and environmental instream flow targets.

Results

Fig. 2 outlines the content presented in the results section, highlighting facilitated discussions between researchers and key water managers that served to identify the research and modeling activities featured in this paper.

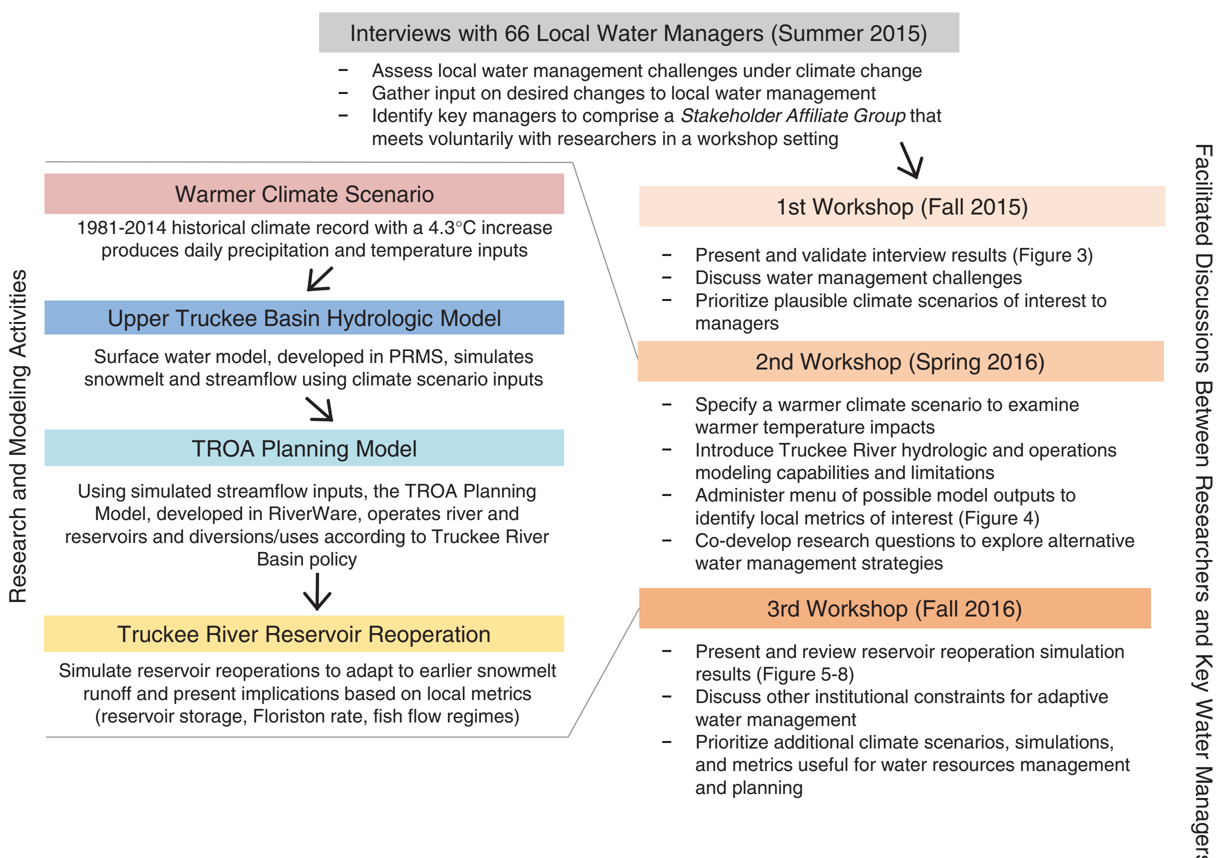

Fig. 2. (Color) Facilitated discussions between researchers and key water managers that identify the research and modeling activities featured in this paper and compose part of a larger collaborative modeling research program in the Truckee River Basin case study area.

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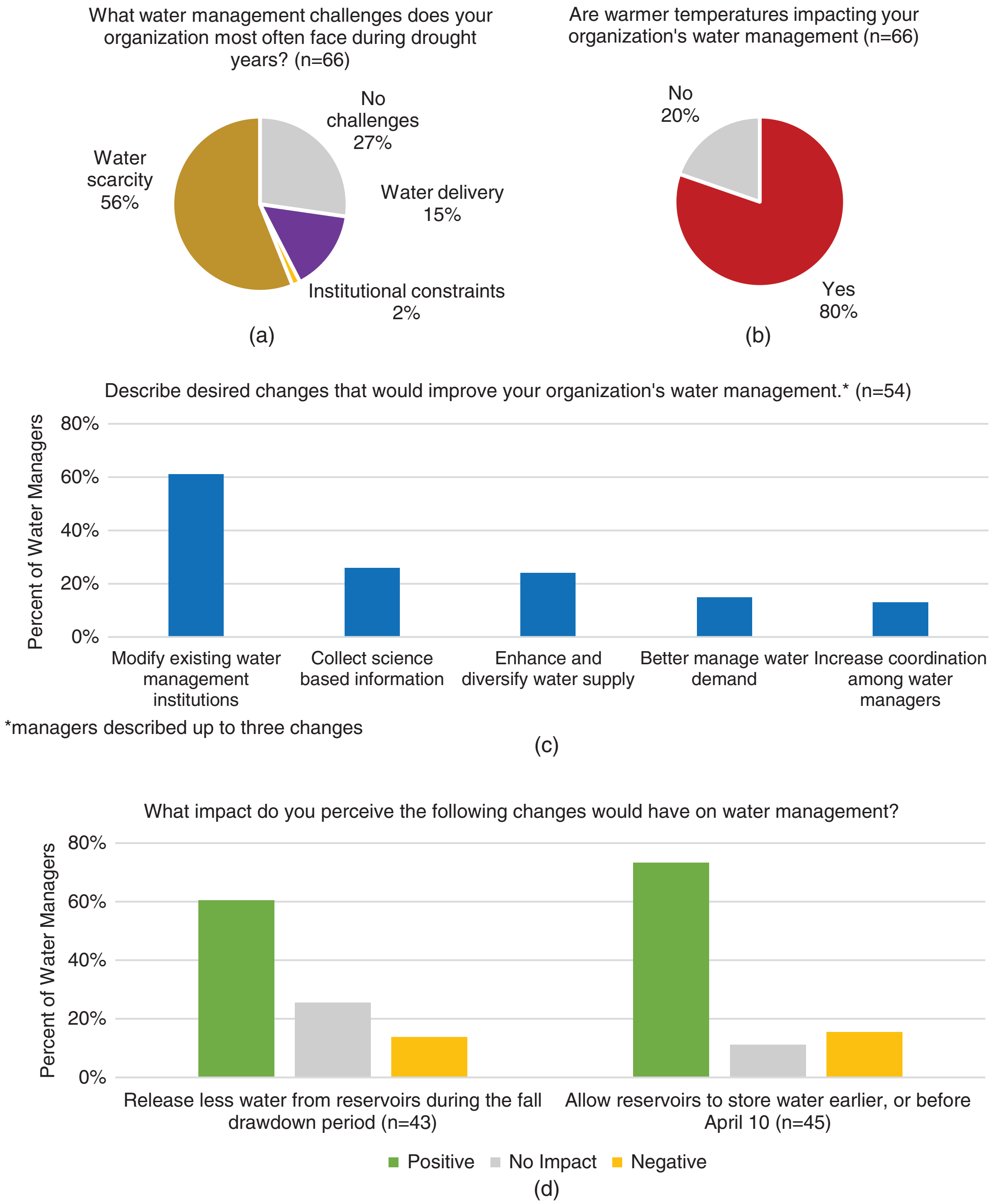

Fig. 3. (Color) Selected results of interviews conducted during summer 2015 with 66 local water managers that demonstrate the percentage of water managers who (a) face challenges during drought years; (b) describe impacts of warmer temperature; (c) desire changes to improve water management; and (d) perceive positive impacts as a result of revised reservoir operations.

Assessing Water Management Challenges

Fig. 3 presents selected results from interviews conducted with 66 water managers to gather baseline understanding of the river basin. Of those who experience water management challenges during drought years, water scarcity was cited most frequently (56%, $n = 66$), defined as conditions inherent to arid lands and exacerbated by climate change [Fig. 3(a)]. Eighty percent of managers ($n = 66$) reported that warmer temperatures impact their organization's water management [Fig. 3(b)], and when asked to describe desired changes, the majority (59%, $n = 46$) indicated the need to modify existing water management institutions to account for climate change [Fig. 3(c)]. When presented with specific strategies that would modify reservoir operations, the majority of managers anticipated positive impacts under climate change [Fig. 3(d)]. That is, 60% of managers ($n = 43$) perceived positive impacts if less water was released during the fall drawdown period and 73% of managers ($n = 45$) perceived positive impacts if reservoirs could store water before April 10.

During the first Stakeholder Affiliate Group workshop (Fall 2015) with key water managers, researchers presented these interview results. Managers affirmed the findings, validating that hypothetical yet plausible climate scenarios that resemble a series of warmer drought years like those recently experienced in the region would be most useful to understand constraints within existing

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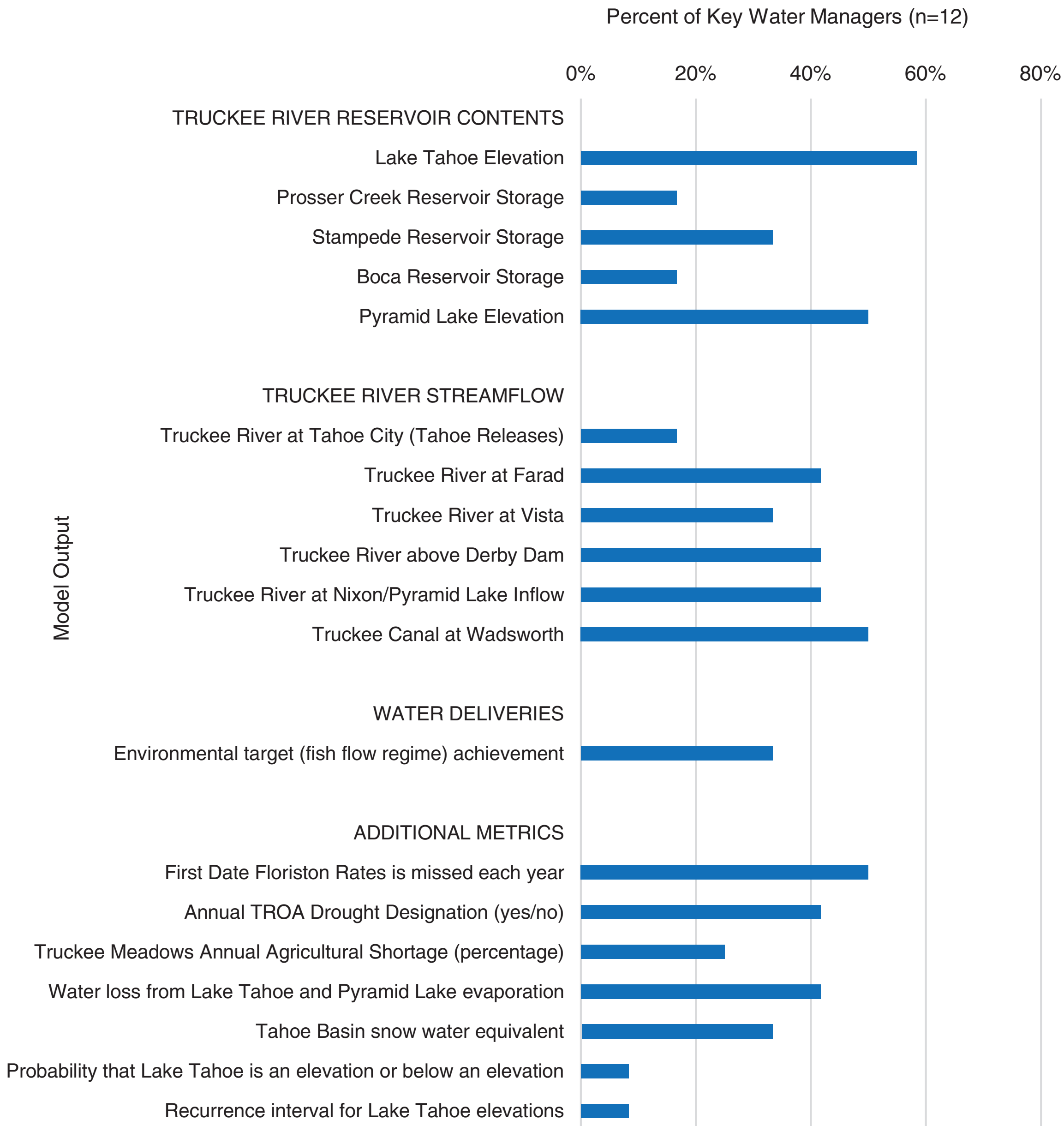

Fig. 4. (Color) Truckee River Basin model outputs requested by key water managers.

water management practices (Dettinger et al. 2017). During the second workshop (Spring 2016), researchers introduced managers to the Upper Truckee Basin Hydrologic Model and the TROA Planning Model and explained how climate scenarios are used to examine climate change impacts on water management (Fig. 2). To establish credibility and trust in the models, the introduction included a synopsis of the model boundaries, calibration, inputs, and outputs, as well as model capabilities and limitations. To ensure simulation results were useful to managers, researchers administered the Truckee River Basin Model Outputs Menu to identify local metrics of interest (see Supplemental Data for output menu instrument). Briefly, this instrument lists a possible menu of outputs that managers monitor and use in decision-making. The selected outputs that water managers requested most frequently are shown in Fig. 4.

After having synthesized the interview results and modeling capabilities, researchers and managers prioritized reservoir reoperation as the first integrated model simulation. They codeveloped three research questions: (1) Under plausible future warming, what are the impacts of fixed date–based Truckee River Reservoir operations on water supply? (2) To what extent does reservoir reoperation that allows for storage before April 10 increase reservoir storage? (3) What are the implications of earlier reservoir storage for downstream municipal, agricultural, and environmental water users?

Specifying Research and Modeling Activities

Answering these three questions required researchers to (1) develop a warmer climate scenario to generate simulated streamflow; (2) define reservoir reoperation simulations within the TROA Planning Model that allows Truckee River reservoirs to store water earlier; and (3) select local metrics using the model outputs menu to present results. The warmer climate scenario was developed using the incremental technique for sensitivity analysis (Mearns et al. 2001). A 4.3°C temperature increase was applied to the historical climate

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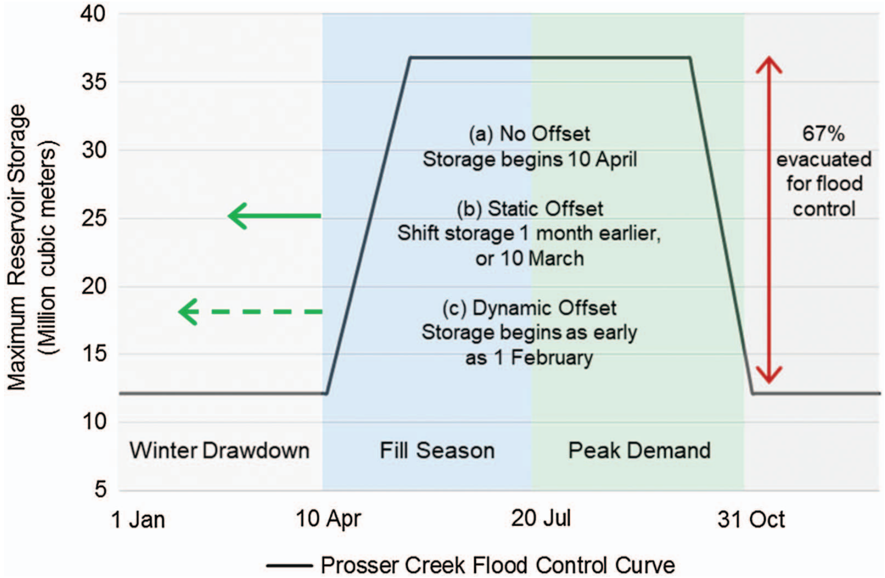

Fig. 5. (Color) Truckee River Reservoir operation simulations, illustrating reoperation for Prosser Creek Reservoir: (a) no offset defines the current operations that do not allow for reservoir storage before April 10; (b) static offset reoperation shifts the flood control curve to allow for storage 1 month earlier, or March 10; and (c) dynamic offset reoperation calculates the spring fill date based on simulated inflows, but occurs no earlier than February 1.

record for the basin (WY 1981–2014 + 4.3°C), creating a hypothetical yet plausible 34-year scenario. The degree of warming was selected from the 4th California Climate Change Assessment's 10-general circulation model average end of the 21st-century warming (i.e., 2080–2089) (Dettinger et al. 2016).

Researchers then defined two reservoir reoperation simulations: (1) static offset that shifts reservoir storage 1 month earlier to March 10 and (2) dynamic offset that determines the fill date based on inflows to Boca, Stampede, and Prosser Creek reservoirs, but occurs no earlier than February 1 (Fig. 5). In the case of dynamic offset, the number of offset days is not fixed from year to year but optimized based on reservoir inflows and the volume of water required to fill each reservoir to its storage capacity in order to maximize water supply for downstream users. If inflows are not sufficient to fill the reservoir to capacity (i.e., peak streamflow occurs before April 10), the number of days before prior to April 10 is determined and the offset is set to that date. This simplification does not consider additional operational considerations that may determine whether inflows are legally storable in the reservoir or are required to be passed through to meet higher priority water rights (i.e., flows to meet the Floriston rate). However, it does allow researchers to isolate the potential benefits of dynamic offset. Note that reoperation does not alter dates associated with the fall precautionary drawdown season but rather explores only changes to the spring fill season.

Utilizing the model output menu results, researchers selected three metrics of interest to respond to managers' information needs. To quantify changes in upstream storage, researchers selected Prosser Creek Reservoir Storage because it is comparatively more susceptible to climate change impacts than the other federally managed reservoirs. That is, 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 reservoir capacity, respectively. Additionally, Prosser Creek Reservoir (elevation 1,750 m) drains mid-elevation (2,000 m) terrain, where changes in precipitation phase from snow to rain are most pronounced (e.g., Hatchett et al. 2017). Researchers selected the Floriston rate to evaluate implications for downstream municipal and industrial water users, and the fish flow regime target achievement to evaluate implications for downstream environmental water users (described in detail in the section "Reservoir Operations and Water Management").

Simulating Reservoir Reoperation under a Warmer Climate

Comparison of historical Prosser Creek Reservoir inflows (WY 1981–2014) to simulated inflows under the 34-year warmer climate scenario (WY 1981–2014 + 4.3°C) reveals an approximately 45-day shift in peak streamflow timing from mid-March to early February. This is consistent with other studies in the region (Barnhart et al. 2016; Coats 2010; Lundquist and Flint 2006; Steimke et al. 2018; Stewart et al. 2004, 2005). During the current April–June spring fill season, inflows decrease 47% (44 to 21 Mm^3) on average, resulting in decreased reservoir storage.

Table 2 presents the average maximum storage attained in Prosser Creek Reservoir at the peak fill date under historical climate (WY 1981–2014) as compared to reoperation under the warmer climate scenario. Historically, Prosser Creek Reservoir filled an average of 76% of capacity (28 Mm^3). Under a warmer climate, current

Table 2. Average maximum storage attained in Prosser Creek Reservoir at peak fill date historically and under warmer climate scenario

Climate scenario	Reservoir operation	Average maximum reservoir storage at peak fill date (Mm^3)	Percentage of reservoir capacity (%)
Historical climate (WY 1981–2014)	No offset	28	76
Warmer climate scenario (WY 1981–2014 + 4.3°C)	No offset	17	46
	Static offset	24	64
	Dynamic offset	28	76

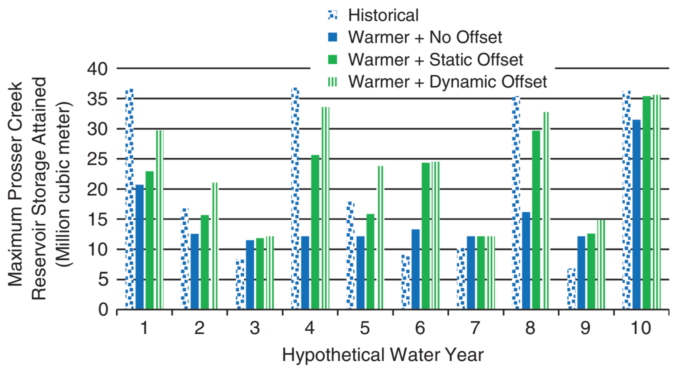

Fig. 6. (Color) Maximum storage attained in Prosser Creek Reservoir for a hypothetical 10-year period illustrating increased annual storage with static and dynamic offset reoperation under a warmer climate.

reservoir operations failed to capture shifts in peak streamflow timing, resulting in reduced reservoir storage, or an average of 46% of capacity (17 Mm^3) over the 34-year simulation period. Reoperation under a warmer climate increased average maximum storage to 64% of capacity (24 Mm^3) under static offset and 76% of capacity (28 Mm^3) under dynamic offset, retaining the historical average maximum storage.

Fig. 6 presents the annual storage attained in Prosser Creek Reservoir based over a hypothetical 10-year period, illustrating decreased storage under a warmer climate compared to historical storage levels (Fig. 6). Reoperation under a warmer climate increases storage typically greater under dynamic offset as compared to static offset (Fig. 6). Fig. 7 further presents these results for three water years, illustrating how reoperation captured earlier runoff under both static offset [Fig. 7(c)] and dynamic offset [Fig. 7(d)] as compared to current operations [Fig. 7(b)].

Evaluating the implications of earlier reservoir storage upstream reveals measurable benefits to downstream water users. Under current operations, the Floriston rate is met through the end of September 49% of years under a warmer climate as compared to 84% of years historically (WY 1981–2014). Under dynamic offset, 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. This equates to Truckee Meadows agricultural water users receiving their water more often and municipal and industrial water users drawing from groundwater supplies less often.

To assess the implications for downstream environmental water users, the benefits of earlier storage were evaluated based on fish flow regime selection and occurrence of the sub-6 regime (i.e., below extremely dry, or fail). Recall that this selection indicates the target flow was not achieved. Fig. 8 illustrates the distribution of time spent in each of the fish flow regimes historically [Fig. 8(a)] as

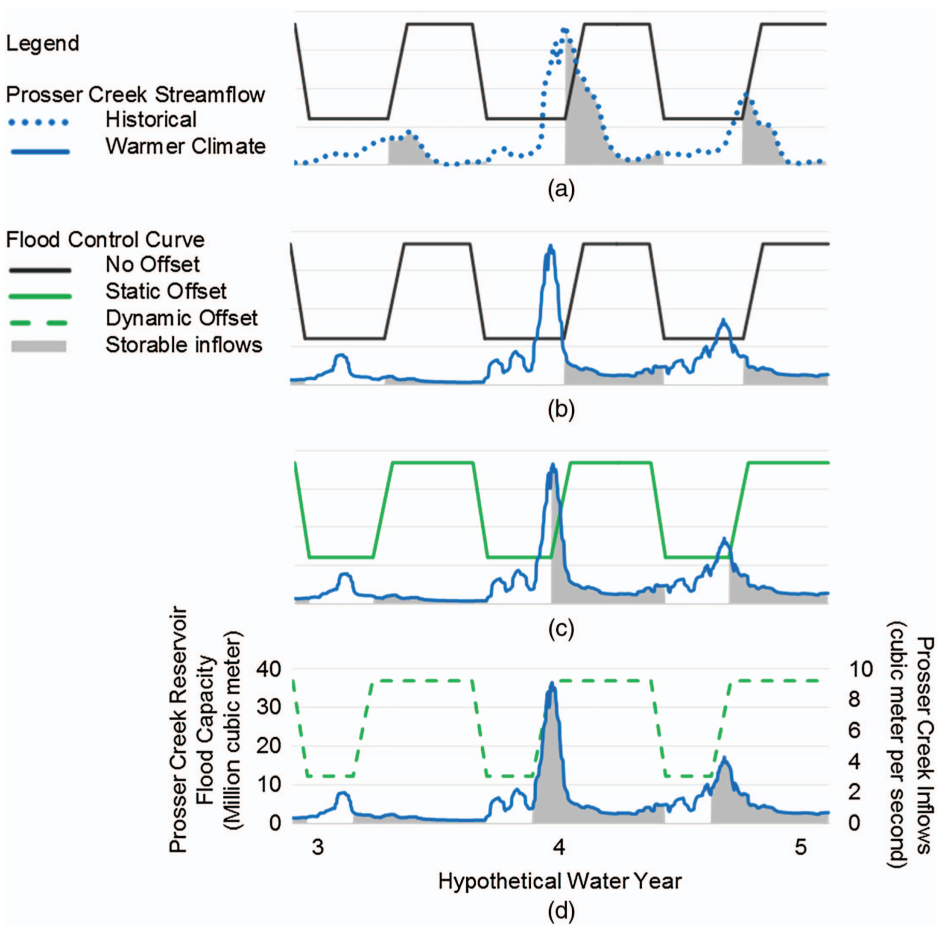

Fig. 7. (Color) Prosser Creek Reservoir inflows storable under current operations compared to reoperation for three water years (inclusive of hypothetical 10-year period presented in Fig. 6). Gray shading illustrates Prosser Creek inflows storable for (a) current operations (dark gray curve) under historical climate and streamflow (blue dotted line); (b) current operations under a warmer climate (blue solid line); (c) static offset reoperations (green solid curve) under a warmer climate; and (d) dynamic offset reoperations (green dashed) under a warmer climate.

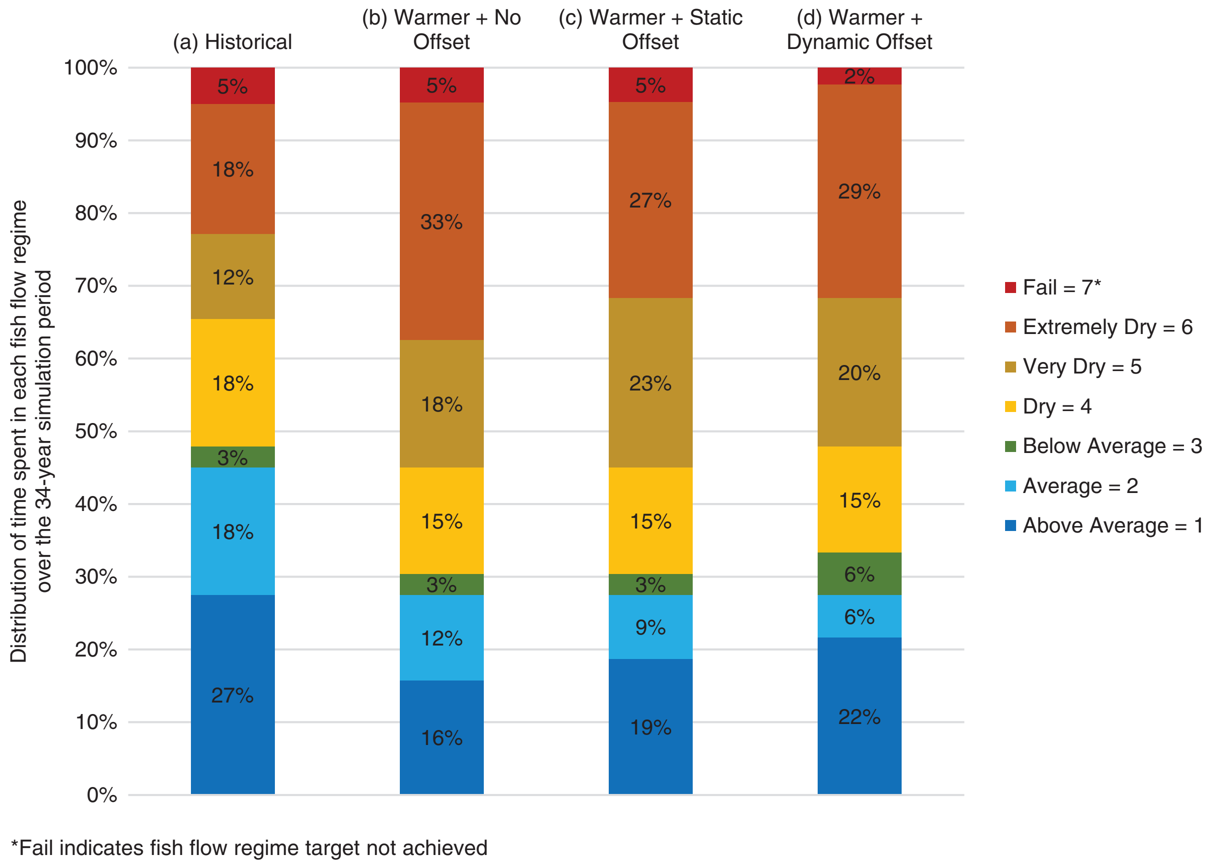

Fig. 8. (Color) Comparison of distribution of time spent in each fish flow regime over 34-year simulation period under reservoir reoperation.

compared to a warmer climate over the 34-year simulation period [Figs. 8(b and c)]. Under the warmer climate scenario, reoperation improved the fish flow regime distribution, with low flow regimes happening less often. Dynamic offset [Fig. 8(d)] improved the distribution to a greater extent than static offset [Fig. 8(c)], with the above-average flow regime (Regime 1) happening 6% more often and the extremely dry regime (Regime 6) happening 4% less often. Also under dynamic offset, failure to achieve target flow happened 3% less often as a result of more effective storage during low-flow years, thus improving fish habitat conditions.

Collaboratively Reviewing Simulation Results and Identifying Future Research

Researchers reviewed simulation results with local water managers during the third Stakeholder Affiliate Group workshop (Spring 2016). Managers affirmed that under a warmer climate, reservoir reoperation has the ability to capture earlier streamflow timing and provide measureable benefits basin-wide. To implement this strategy, managers and researchers agreed additional simulations were necessary to incorporate potential trade-offs of earlier reservoir storage with increased flood events indicative of climate change in the region (e.g., Willis et al. 2011). For example, as one manager asked, "How might dynamic reservoir reoperations [that allow for storage as early as February 1] be updated to prepare for a rain-on-snow event during the fill period?" To respond to managers' additional simulation requests, researchers explained the need to develop additional modeling tools that would more accurately predict flood magnitude and timing as opposed to only the occurrence of such events. To prioritize ongoing research activities, managers requested that researchers continue to develop plausible climate scenarios and report impacts as a function of locally preferred metrics that managers monitor and use in decision-making (Fig. 4). Researchers proposed investigating the implications of earlier storage on downstream flood risk and developing climate scenarios that explore variable precipitation in addition to warmer temperatures.

Discussion

In regions dependent on snow for water supply, examining potential modifications to existing water management institutions that assume a stationary climate remains a key strategy to adapt to climate change (Ho et al. 2017; Mateus and Tullos 2017; Steinschneider and Brown 2012; Willis et al. 2011). Other case studies that evaluate reservoir reoperation 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 and Brown 2012), and around the world (e.g., Ahmadi et al. 2014; Diogo et al. 2016; Gohari et al. 2014; Minville et al. 2009; Soundharajan et al. 2016; Sun and Fu 2016; Vonk et al. 2014) illustrate the importance of place-based research to characterize local water management challenges and quantify benefits as it pertains to the diverse local water-use communities within any particular river basin.

In this paper, the authors demonstrate how collaborative modeling facilitates an understanding of local water management challenges under climate change. Using the Truckee River Basin in the Western United States as a case study, it is illustrated how systematic and iterative discussions between water managers and researchers can harness local knowledge to ensure research and modeling results are useful. Face-to-face interviews with 66 water managers across the basin, followed by workshops with 12 key representative local managers, identified reservoir operations tied to fixed calendar dates based on stationary climate as a key water management challenge in adapting to earlier snowmelt runoff and streamflow timing recently observed in the basin. As a result of facilitated discussions, researchers prioritized model simulations of interest to local managers and examined the performance of earlier reservoir storage under a plausible warmer climate scenario as a function of locally relevant metrics. Working together to develop research questions also ensured that researchers understood the local water managers' needs and that managers understand the capabilities of the integrated hydrologic and operations model utilized for this program.

The simulation results reported here, which indicate earlier storage enhances water supply, are consistent with other climate change studies that evaluate 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). While other studies use integrated hydrologic and operations models (e.g., Mateus and Tullos 2017; Vano et al. 2010) to illustrate the effects of reservoir reoperation (e.g., Wheeler et al. 2002, 2016), evaluating these effects with water managers enhanced the immediate utility of research results to support adaptive water management (Beall King and Thornton 2016; Jurgilevich et al. 2017; Meadow et al. 2015; Paolisso and Trombley 2017; Singletary and Sterle 2017).

While researchers increasingly solicit local input through participatory research approaches to support local climate adaptation (e.g., Verkerk et al. 2017), this paper demonstrates how collaborative modeling that incorporates focused participation of key constituents facilitates a more intensive form of participatory research (Basco-carrera et al. 2017). That is, collaboration that occurs systematically and frequently around a common research goal enhances model utility, helps researchers to refine model outputs (Voinov et al. 2016; Voinov and Bousquet 2010), and ultimately informs adaptive water management under climate change (Basco-carrera et al. 2017; Klenk et al. 2015). For example, researchers quantified the effects of changes in upstream reservoir storage operations in terms of downstream metrics that managers monitor and use in decision-making. As a result, managers expressed a sense of ownership in the modeling activities and outcomes (Singletary and Sterle 2018).

The results reported here provide empirical evidence that changes to reservoir operations offer managers a strategy to enhance basin-wide resilience to climate change (Ehsani et al. 2017). A review of these results with local water managers identified additional research opportunities, including developing additional climate scenarios that explore variable precipitation and increased atmospheric river strength (e.g., Espinoza et al. 2018; Lavers et al. 2015) and reporting results as a function of other metrics useful to water managers. As described, workshops will continue to provide a forum for managers to provide input that enables researchers to advance modeling applications to assess climate resiliency and provide information useful for adaptive water management (Singletary and Sterle 2017; 2018).

An evaluation of the research program to date provides some insight into best practices for collaborative modeling in arid snow-fed river basins. For example, interviews with managers served as a key forum to harness local information needs early, while workshop discussions paired with hands-on activities (i.e., completing the model outputs menu) involving researchers and managers were critical to develop research questions, identify local river system metrics, and prioritize and review model simulation results. An overview of the integrated hydrologic and operations model was necessary to facilitate effective dialogue and to build confidence in model representation (Falconi and Palmer 2017). In this environment of social learning, local water managers asked researchers questions about modeling capabilities and limitations, while researchers asked managers questions about salient water management challenges to help identify the most effective use of limited time and resources available in the research program. As a result, researchers reviewing results with managers led to a shared vision for how to improve climate scenario–driven model simulations to inform managers' decision-making (Holman et al. 2018; Whateley et al. 2015).

Conclusion

A collaborative modeling research program in the Truckee River Basin, Western United States, systematically and iteratively convenes researchers and local water managers to assess water management challenges under climate change and prioritize research that supports adaptive water management. The results reported here demonstrate how this program identified reservoir reoperation as one strategy to adapt existing water management for a warmer climate. Using an integrated hydrologic (PRMS) and operations (RiverWare) model tailored to the river basin, researchers simulate water management implications under a 4.3°C warmer climate scenario. Results suggest current reservoir operations that assume stationary climate conditions compromise storage of earlier snowmelt runoff and shifts in streamflow timing. Shifting the flood control curve to allow for earlier storage effectively absorbs earlier streamflow timing, increasing annual average reservoir storage to historical levels and providing measurable benefits to downstream water-use communities. These benefits include extended periods to fulfill water right allocations for municipal and agricultural water users, and improved fish and riparian habitat conditions in the lower river reach. As warming temperatures continue to impact snow-fed regions around the globe (Georgakakos et al. 2014; Musselman et al. 2017; Sturm et al. 2017), collaborative research can facilitate and foster an understanding of local challenges and information needs (Cosgrove and Loucks 2015; Van Loon et al. 2016). Future research should examine additional climate scenarios and other potentially viable strategies that support adaptive water management.

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Supplemental Data

Survey data collection instruments used in this study, model calibration, and data generated during this study are available online in the ASCE Library (www.ascelibrary.org).

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