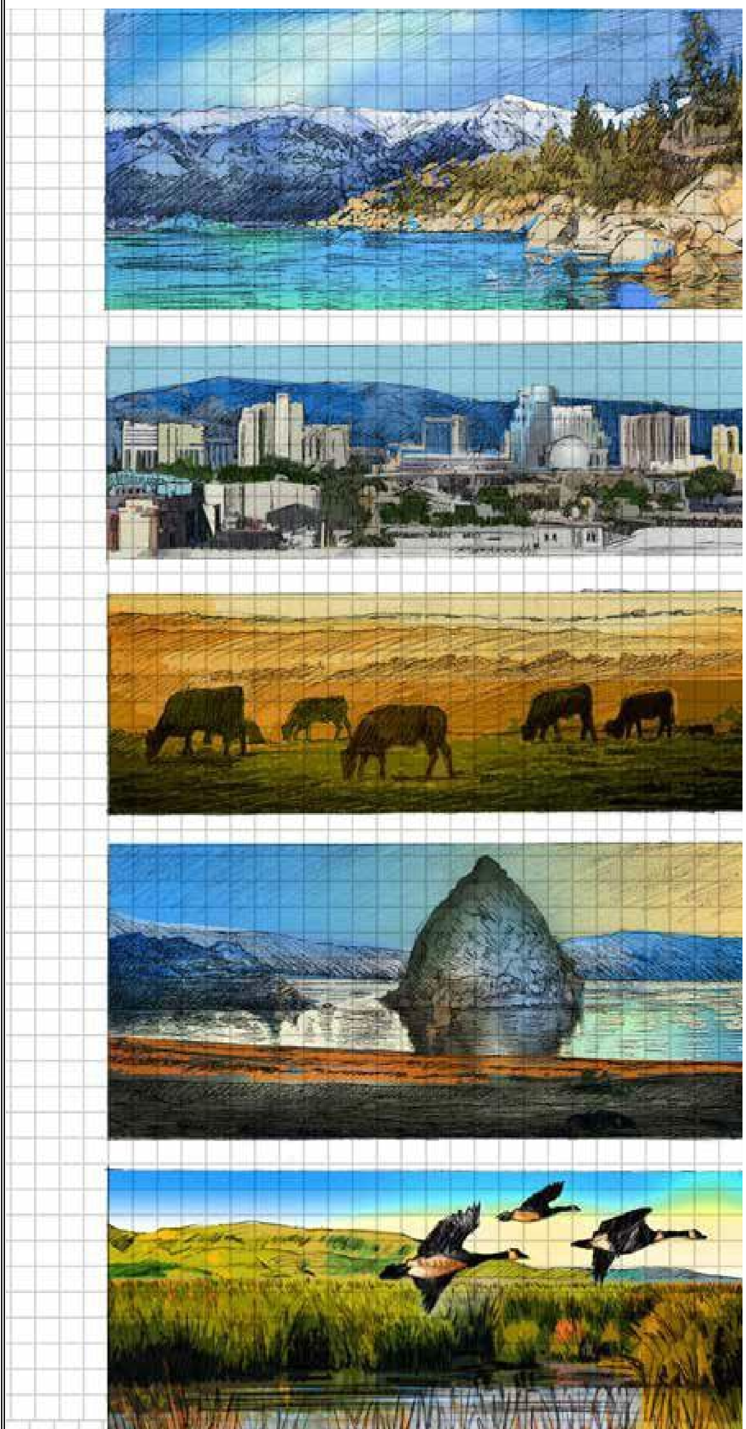
Water Sustainability and Climate in the Truckee-Carson River System, Western United States



10 Key Takeaways from the *Water for the Seasons* Collaborative Research Program

WATER For The SEASONS
"A Program for Sustaining Water Resources in a Changing Climate"

EXTENSION
College of Agriculture, Biotechnology & Natural Resources

PEER REVIEWED

Special Publication 20-02

A partnership of Nevada counties; University of Nevada, Reno; and U.S. Department of Agriculture

EXTENSION
College of Agriculture, Biotechnology & Natural Resources

PEER REVIEWED

Special Publication 20-02

Research Team

Kelley Sterle, Loretta Singletary, Gi-Eu Lee and Kim Rollins
University of Nevada, Reno

Greg Pohll, Maureen McCarthy, Shey Rajagopal, Christine Albano,
Will Boyer and Justin Huntington
Desert Research Institute

Michael Dettinger, Richard Niswonger, Eric Morway,
Wesley Kitlasten, and Murphy Gardner
U.S. Geological Survey

Shane Coors and Linnet Jose
Precision Water Resources Engineering

Derek Kauneckis
Ohio University

Stakeholder Affiliate Group

Kelvin Hickenbottom and Adam Sullivan
Nevada Division of Water Resources

Eddy Quaglieri
Carson City Public Works

Julie Regan and Dan Segan
Tahoe Regional Planning Agency

Mickey Hazelwood and Duane Petite
The Nature Conservancy

John Enloe, Shawn Stoddard, Bill Hauck,
Laine Christman and Kara Steeland
Truckee Meadows Water Authority

Nancy Hoffman and Carl Lunderstadt
Stillwater National Wildlife Refuge

Donna Marie Noel
Pyramid Lake Paiute Tribe

Norm Harry and Cale Pete
Washoe Tribe of California and Nevada

J.B. Lekumberry
Carson Valley Conservation District

Ed James
Carson Water Subconservancy District

Rusty Jardine
Truckee-Carson Irrigation District

Jennifer Derley and Dave Whalen
City of Fernley

Leanna Hale
Fallon Paiute-Shoshone Tribe

Table of Contents

Suggested citation:
Sterle. K., Singletary, L., Lee, GE., Rollins, K., Pohll, G., McCarthy, M., Rajagopal, S., Albano, C., Boyer, W., Huntington, J., Dettinger, M., Niswonger, R., Morway, E., Kitlasten, W., Gardner, M., Coors, S., Jose, L., Kauneckis, D. 2020. Water Sustainability and Climate in the Truckee-Carson River System, Western United States: 10 Key Takeaways from the Water for the Seasons Collaborative Research Program. University of Nevada, Reno Extension Special Publication SP-20-02.

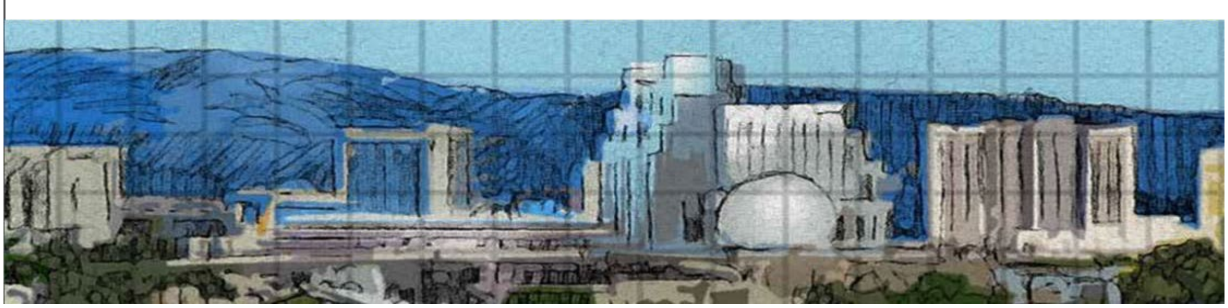
Water for the Seasons

Water for the Seasons is a five-year collaborative research program in the Truckee-Carson River System that partnered an interdisciplinary research team with the *Stakeholder Affiliate Group,* which represents the diverse and competing municipal, industrial, agricultural, environmental and regulatory water management organizations from headwaters to terminus. Funded by a grant from the National Science Foundation and United States Department of Agriculture Water Sustainability and Climate Program, this five-year integrated research and Extension initiative assessed the sustainability of water resources across the river system to climate change.

Hydrologists, climatologists, resource economists and political scientists worked alongside local water managers to:

1. Identify climate change impacts to water resources;
2. Develop and simulate climate scenarios that test river system resiliency; and
3. Examine the effectiveness of potential adaptation strategies to mitigate identified impacts.

Over the five-year period, researchers sought out and incorporated local water managers' knowledge and perspectives to model the effects of climate change on the river system's hydrology, river and reservoir operations, and related water management institutions that govern the allocation, diversion and use of water resources. This Special Publication briefly introduces the Truckee-Carson River System case study area, describes the *Water for the Seasons* research program, and presents 10 key takeaways from this five-year collaboration between local water managers and researchers.



The Truckee-Carson River System

The Truckee-Carson River System comprises the Truckee (121 km) and Carson (131 km) Rivers that originate as snowpack in Sierra Nevada of California and flow northeastward into the Great Basin in northwestern Nevada (Figure 1). The river system typifies water resource challenges observed across the arid western United States, where water supply is highly dependent on accumulated snow that melts through spring to fill reservoirs and recharge groundwater aquifers to meet summer demand. The 7,026 square-mile area encompasses multiple and historically contentious water management challenges common to snow-fed river dependent communities in the arid West. These include allocating water resources to:

1) support municipal and industrial development, population growth and recreation;
2) irrigate agricultural lands;
3) rehabilitate and protect ecological systems; and
4) sustain fisheries, agriculture, and municipal and industrial development on Native American reservation lands.

Prior Appropriation Doctrine is the institution governing water allocation across the river system, which includes federally operated reservoirs and an interbasin transfer that diverts Truckee River flows to Carson River flows via the Truckee Canal to support the first federal desert reclamation project for irrigated agricultural development.

Collaborative Research Approach

Collaborative modeling incorporates local stakeholder knowledge into applied research. At the program's outset, an interdisciplinary research team collaborated with key local water managers identified through a *stakeholder analysis*. This analysis identified the primary water use organizations on the system whose managers were willing to work with the research team through the life of the program. The *Stakeholder Affiliate Group* included representatives from 12 organizations representing diverse and competing water users across the river system from its headwaters to terminus, and included regulatory, municipal and industrial, agricultural, and environmental interests. Figure 2 illustrates the location of the *Stakeholder Affiliate Group* representatives' water management areas.

Ongoing interaction between the research team and *Stakeholder Affiliate Group* water managers served to guide the research and validate outcomes. Biannual workshops provided a forum for learning and relationship-building. Interviews and focus groups served as additional opportunities for researchers and water managers to exchange information and further prioritize program research activities. Figure 3 illustrates the various components of the *Water for the Seasons* collaborative research program.

Figure 1. The Truckee-Carson River System. Graphic by Ron Oden and Kelley Sterle, University of Nevada, Reno Extension.

Figure 2. Stakeholder Affiliate Group water managers and their location in the river system. Graphic by Ron Oden and Kelley Sterle, University of Nevada, Reno Extension.

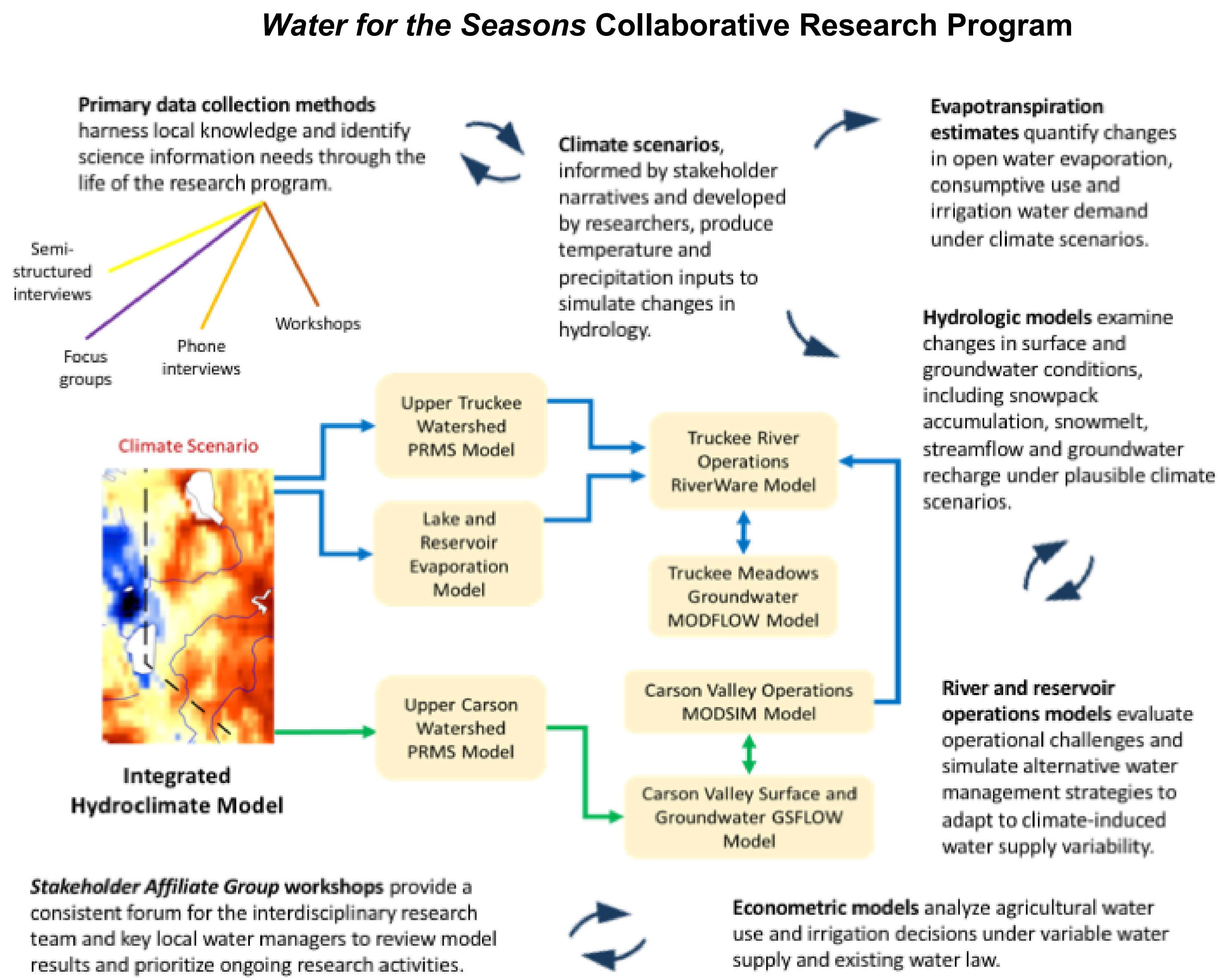


Figure 3. Collaborative modeling research design illustrating how local knowledge informs research and modeling activities.

10 Key Takeaways

#1. Climate projections across the river system generally show warmer temperatures and increased precipitation variability.

The Intergovernmental Panel on Climate Change, National Climate Assessment and California Climate Assessment[1] report with high confidence levels that:

- The future will be warmer;
- Precipitation variability will be more extreme;
- Mountain snowpack will decline; and
- Dry years will become more frequent.

> *"In the last couple years, [climate change] has entered our discussions about water. We talk about timing of water coming off the mountains, water delivery, less snowpack. We also have big floods, so it's not about the drought." – Local regulatory water manager.*

The graphic below (Figure 4) illustrates the projected changes in temperatures under two greenhouse gas scenarios, suggesting an average temperature increase of 2.5 degrees Celsius (4.5 degrees Fahrenheit) by mid-century (2050) and 4.3 degrees Celsius (7.7 degrees Fahrenheit) by late-century (2080). Despite certainty in a warmer future climate, there remains a high degree of uncertainty surrounding future precipitation amounts.

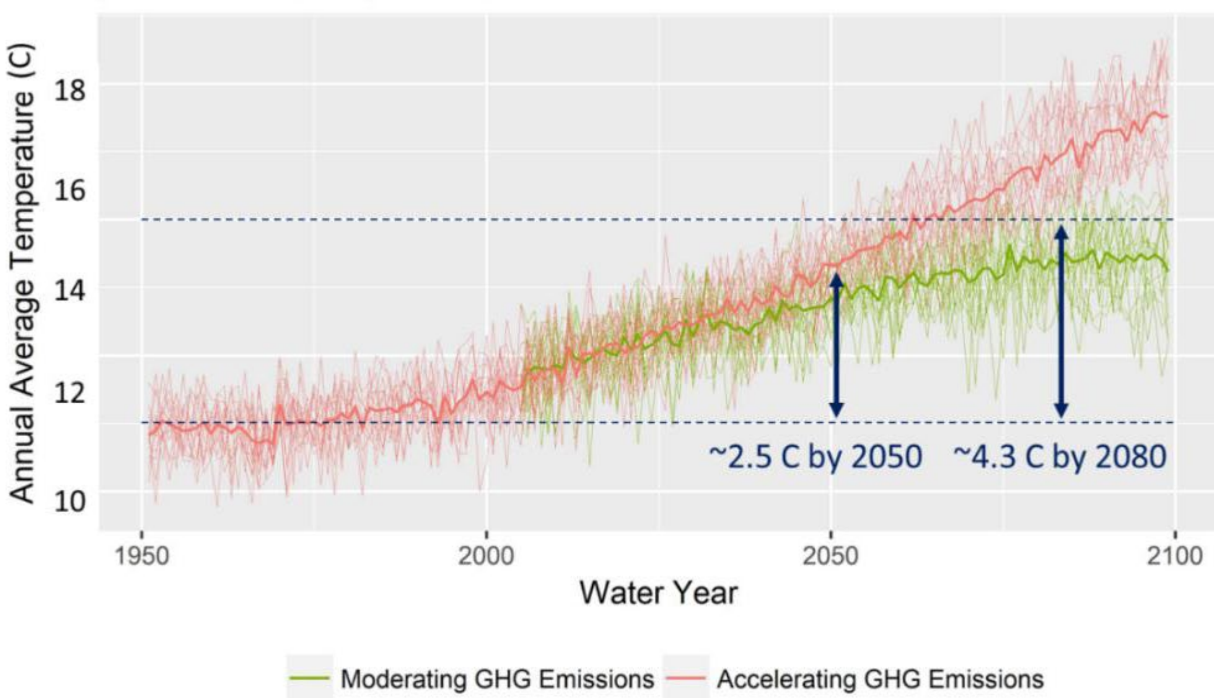


Figure 4. Climate change projections under moderate and accelerated greenhouse gas emission scenarios.

[1] See Climate Change Projections references in Additional Materials.

#2. Local stakeholders are concerned about climate change impacts on water resources.

At the program's outset, researchers conducted face-to-face interviews with 66 local water managers of which 90% believe climate change is important to the Truckee-Carson River System. Over the course of the program, researchers continued to meet with *Stakeholder Affiliate Group* water managers to identify their greatest climate change concerns and conditions that affect their organization's water management. Local water managers' current climate impact concerns were:

- Increased temperatures;
- Extended drought conditions;
- Precipitation variability, such as dry years punctuated with wet years; and
- Extreme storms and floods.

> "*This [2012-15] drought is a warm drought. Temperature has added its own flavor, but this might be the hallmark of our future." – Local regulatory water manager.*
>
> *"Warmer ambient temperatures affect water temperature, which affects fish and wildlife. Water earlier in the year can mean less later in the year, so the timing also affects sustained availability." – Environmental water manager.*

Managers also expressed concerns about future climate change impacts. The most frequently mentioned was climate change effects on Lake Tahoe surface elevation; Lake Tahoe has the largest average annual inflow and largest average annual release volume of seven Truckee River reservoirs.

Over the five-year research program, the Truckee-Carson River System experienced a high degree of water supply variability that included extreme drought and high-flow years paired with warmer than normal temperatures. These variable water years are illustrated below (Figure 5) in terms of snow water equivalent measured at two SNOTEL (SNOwpack TELemetry) stations in the Sierra Nevada headwaters. These conditions created a heightened sense of urgency among managers to explore plausible climate scenarios tailored to the river system.

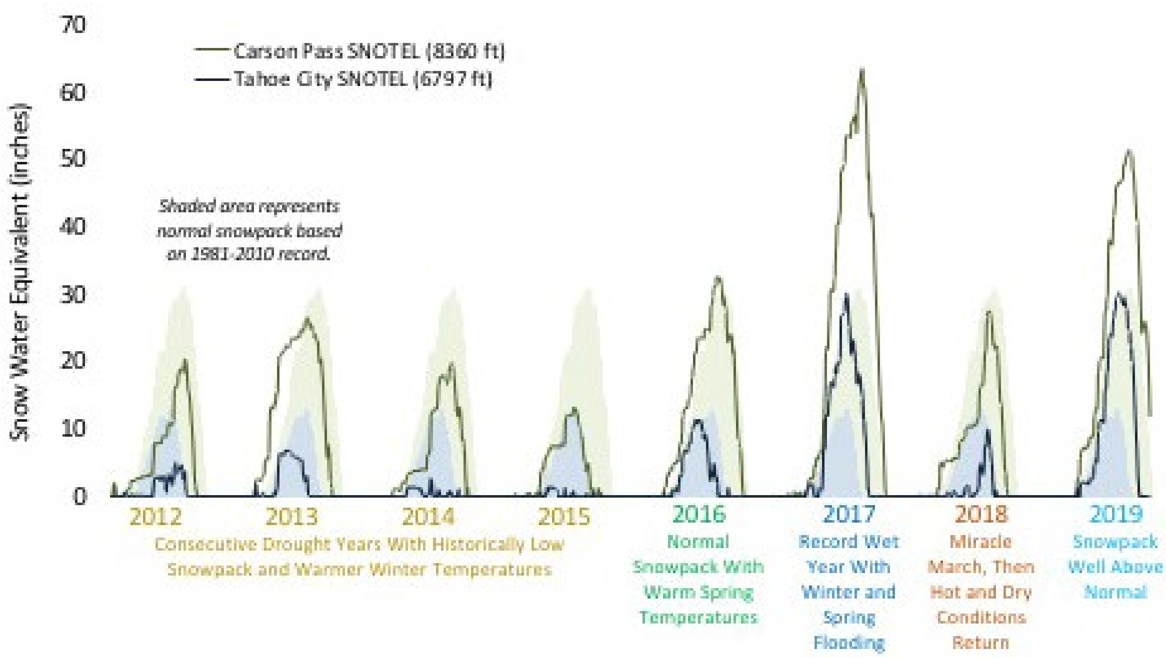


Figure 5. Recent water years in the Truckee-Carson River System as indicated by snow water equivalent measured at two SNOTEL sites in the Sierra Nevada headwaters. Source: Natural Resource Conservation Service (NRCS) SNOTEL station data https://www.wcc.nrcs.usda.gov/snow/.

#3. Scenarios of a warmer climate demonstrate measurable snowpack changes that affect the timing and availability of water supply.

The Truckee-Carson River System is dependent on snow for the majority of its water supply. Historically, snowpack accumulated from November to March and melted from April to June supplies water to downstream water users, including agricultural water rights holders.[2] Hydrologic model simulations suggest that scenarios of a warmer climate alter snowpack accumulation and snowmelt processes, increase evaporation and shift streamflow timing to earlier in the year. Key observations for the Truckee and Carson Rivers under a multi-decadal (34-year) 4.3-degrees Celsius warmer climate scenario are presented in Figure 6, including models used to produce featured results. The blue and green lines indicate models were tailored to either the Truckee or Carson Rivers, respectively.

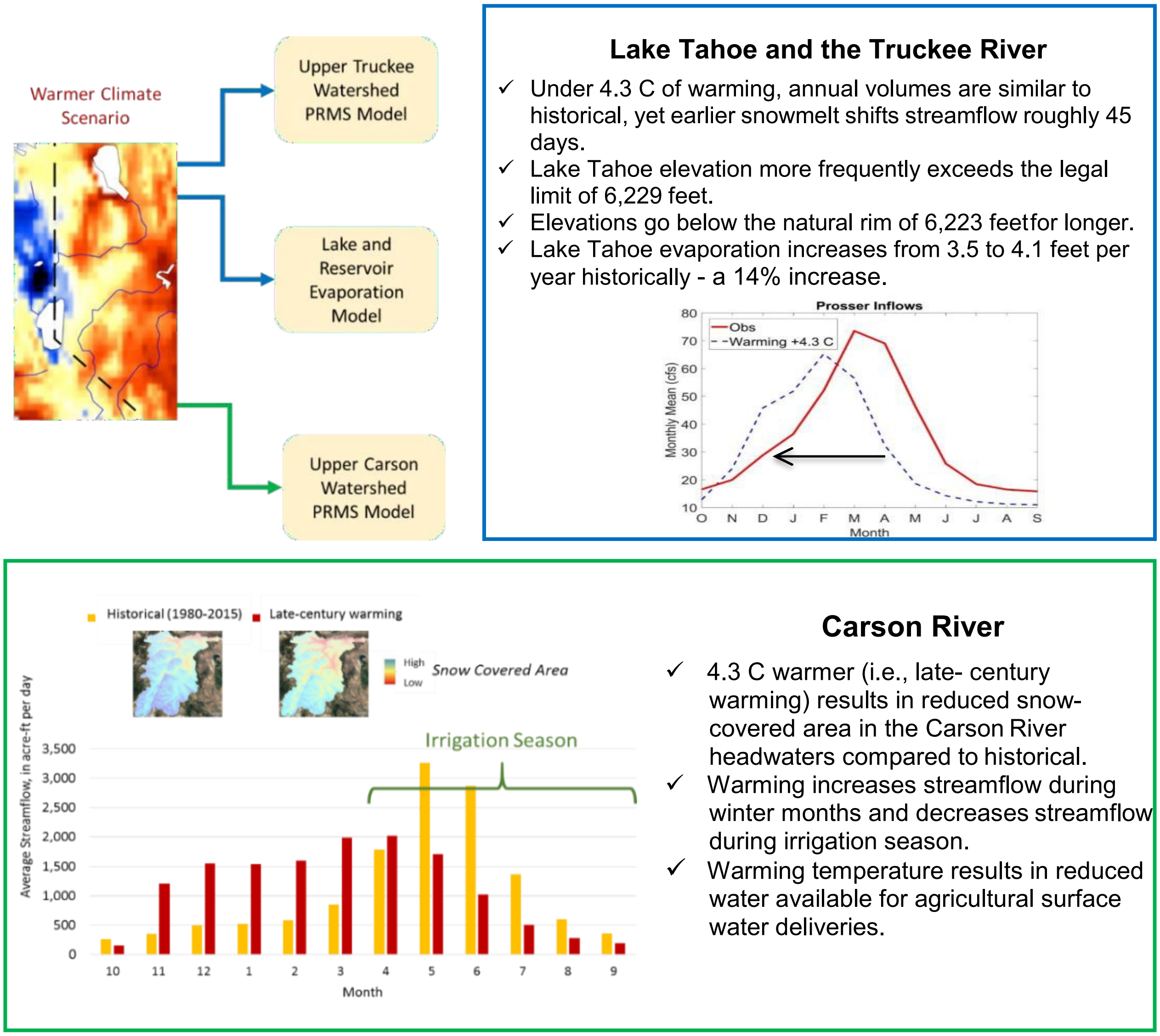


Figure 6. Hydrologic impacts of a warmer climate scenario in the Truckee-Carson River System. The schematic shows the models used to simulate hydrologic impacts on Lake Tahoe and the Truckee River (blue box) and the Carson River (green box).

[2] The Truckee River is managed according to the Truckee River Operating Agreement with upstream reservoirs to capture snowmelt runoff. The Carson River is managed according to the Alpine Decree and lacks upstream storage, making shifts in streamflow timing a potential challenge to ensure adequate irrigation water deliveries.

#4. The sequencing of wet and dry years matters for evaluating future basin supply conditions and operations.

Managers often describe water supply conditions in terms of: *annual inflow volume* and *timing of inflows.*

> *"It's the mismatch in the timing that has a lot of us concerned. Normally, we get the snowmelt in the summer when the critters and the ranchers are prepared to utilize it." - Environmental water manager.*
> *"In these snow-dominated systems, I think that a few years of bad drought can cause a severe impact. Back in time, a few dry years and then some wet years… we would rebound. But the cumulative impact over the past few years [2012- 2016] has put us in a place that we are in now… we are in this [drought] pretty deep." – Municipal and industrial water manager.*

Increasingly, water managers described the cumulative and compounding effects of consecutive drought years signaling that *frequency* of variable precipitation is also important. Researchers and water managers explored further whether the sequencing of dry and wet years is as important as annual inflow volume and streamflow timing.

Researchers developed two 20-year warmer climate scenarios that have differing precipitation frequency under late-century (2080, or 4.3 degrees Celsius) warming. Precipitation variability was characterized as:

- *Low frequency* with longer periods (~5 years) of sustained dry and wet years; and
- *High frequency* with more often (~2 years) swings between wet and dry years.

To assess with local water managers long-term water supply and evaluate the performance of existing river and reservoir operations, researchers presented model simulation results in terms of common river system indicators, such as water surface elevations and streamflow at key locations. Figure 7 illustrates the modeling framework used to simulate precipitation variability scenarios and the river system indicators identified as most useful to present results.

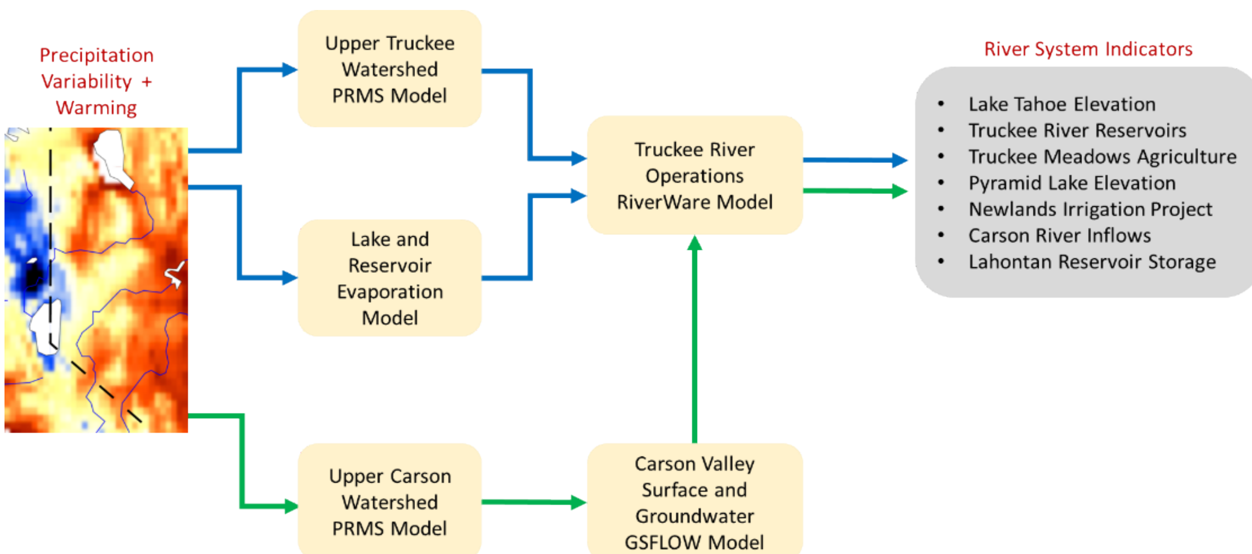


Figure 7. Modeling framework illustrating the hydrologic and operations models used to simulate precipitation variability scenarios, and subsequent river system indicators identified to present results.

Key findings from the simulation results suggest that:

- Timing and frequency have a significant impact on water supply and river system operations;

- Earlier snowmelt runoff impacts river basin operational policy based on historical runoff timing; and
- Impacts are greater on the Carson versus Truckee River due to lack of upstream storage.

Results of low- and high-precipitation frequency scenarios based on local river system indicators are presented in Table 1 and Figure 8.

Table 1. Results of low- and high-precipitation frequency scenarios based on local river system indicators. Numbers correspond to location on the map presented on the right. Numbers correspond to locations shown in Figure 8.

		Low frequency scenario…	***High frequency scenario…***
Lake Tahoe and Truckee River	1 - Lake Tahoe Elevation	*increases time periods below the rim, affecting Lake Tahoe's water storage*	*results in conditions generally above the rim as Lake Tahoe is less sensitive to timing of runoff given its volume*
	2 - Truckee River Reservoirs	*adversely affects reservoir storage, and under current operations, fail to capture earlier snowmelt runoff*	*indicates reservoirs remain full as a result of punctuated wet years*
	3 - Truckee Meadows Agriculture	*increases the frequency and magnitude of surface water delivery shortages*	*reveals little impact to agricultural deliveries*
	4 - Pyramid Lake Elevation	*increases streamflow to Pyramid Lake due to decreased storage and use upstream*	*results in more water making it to Pyramid Lake due to less efficient storage upstream*
Carson River	5 - Newlands Irrigation Project	*simulates Truckee Canal flows near historical scenarios*	*enhances deliveries via Truckee Canal under the defined Operating Criteria and Procedures*[3]
	6 - Carson River Inflows	*emphasizes water shortages and related water management challenges due to lack of upstream storage*	*results in significant increase in flows at Ft. Churchill due to earlier runoff*
	7 - Lahontan Reservoir Storage	*introduces greater stress to reservoir infrastructure as a result of increased runoff volume*	*reveals shifts in timing of streamflow before irrigation season that benefit reservoir substantially*

[3] Referred to as OCAP, this federal rule defines how the Newlands Project is operated by regulating the timing and amount of water that can be diverted from the Truckee River to serve Newlands Project water rights. It ensures these water rights are served while also minimizing the use of the Truckee River and maximizing the use of the Carson River.

Figure 8. Corresponding low and high frequencies scenario indicator based on Truckee-Carson River System. Graphic by Ron Oden and Kelley Sterle, University of Nevada, Reno Extension.

#5. Local water management organizations are adapting to climate-induced water supply variability, and in doing so, encounter barriers to implementing desired strategies.

Interviews conducted over a five-year period with *Stakeholder Affiliate Group* water managers identified shifts over time in adaptation strategies, defined as actions devised or taken in response to climate-induced water supply variability. That is, managers described emergent barriers that impede their organization’s ability to implement desired adaptation strategies. Shifts in climate adaptation strategies and implementation barriers as described by *Stakeholder Affiliate Group* water managers are presented in Figure 9.

> Restoration work is making our [river] system more resilient to climate change.” – Environmental water manager.

To summarize, we learned from local water managers on the river system that:

- Warmer drought conditions exacerbate water supply challenges inherent to this water-scarce region;
- Even during above-average years, managers described drought management strategies;
- Variable water supply conditions challenge existing water management and operations that are based on historical climate records;
- Efforts have increased to collect climate data and monitor climate impacts, re-evaluate existing water management strategies and enhance water supplies for increasing demands due to population growth;
- Over time, climate uncertainty and lack of coordination among water managers are described less often as barriers to climate adaptation; and
- Recent water years that demonstrate considerable water supply variability is the “new normal climate” for which they should plan.

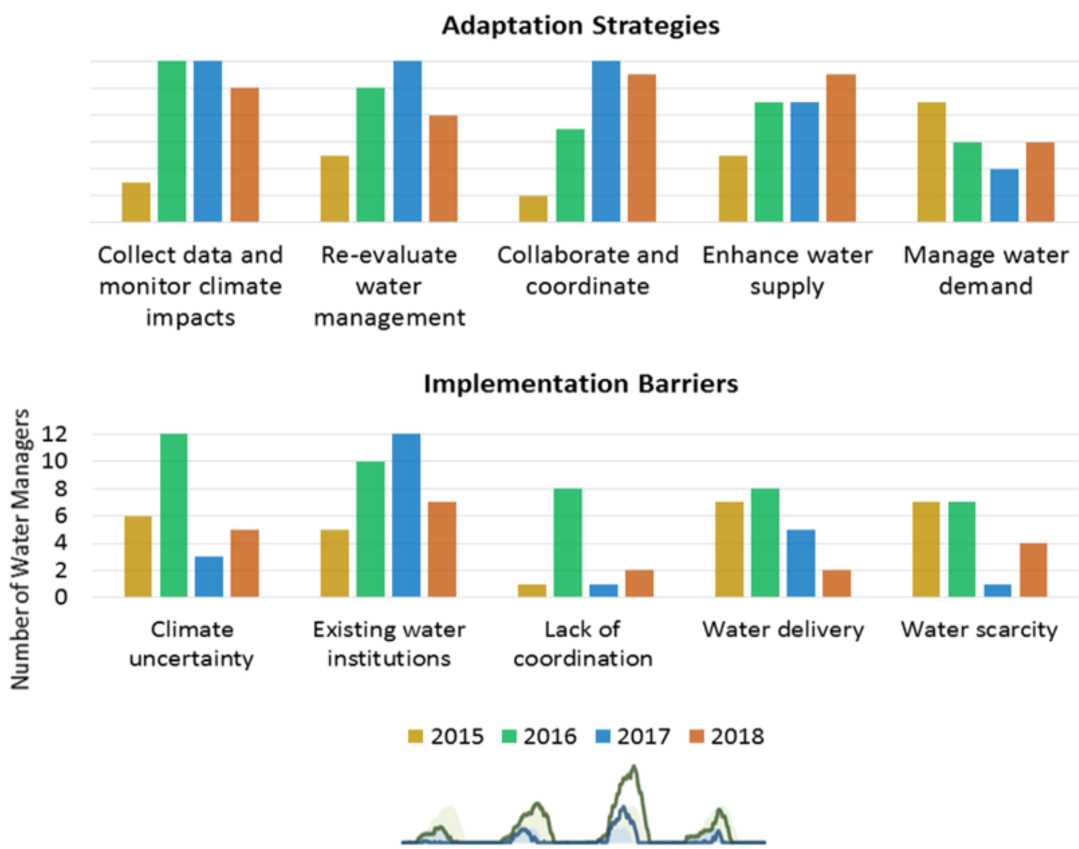


Figure 9. Shifts in adaptation strategies and implementation barriers as described by 12 key local water managers in the river system. Bar colors correspond to water years as indicated in Figure 5.

To assess the viability of climate adaptation strategies, researchers and local water managers worked together to explore the following:

- Changes to operations of Truckee River reservoir that allow for earlier storage to capture earlier streamflow runoff;
- Managed aquifer recharge in the Carson River to allow for storage while enhancing groundwater sustainability; and
- Increased flexibility under Prior Appropriation Doctrine to facilitate the temporary transfer of water rights during drought periods.

"These [Truckee River] reservoirs were designed using historic [climate and hydrologic] data and the patterns have changed and will be different moving forward."– Municipal and industrial water manager.

"A warm snap that melts off the snowpack early [in the Carson River]? We don't have facilities to grab that. What about storage underground?" – Agricultural water manager.

#6. Allowing Truckee River reservoirs to store water earlier in the year has the potential to enhance water supply.

How are Truckee River reservoirs currently operated?

The U.S. Bureau of Reclamation operates Stampede, Boca and Prosser Creek reservoir waters according to dates set by the U.S. Army Corps of Engineers flood control criteria. These criteria ensure sufficient reservoir space exists during the winter and spring to capture potential floodwaters in order to mitigate downstream flood risk. The reservoirs begin storing water April 10, a date set based on historical peak streamflow and the assumption that significant snowmelt does not begin earlier. Reservoir releases are managed to meet particular river basin policy, including:

- Floriston rate, which defines a target rate of streamflow at the Farad gage located at the California and Nevada state line; and
- U.S. Fish and Wildlife Service environmental instream flow targets that support fish spawning and riparian health in the lower reach of the Truckee River from Derby Dam to Pyramid Lake.

What are the perceived limitations of existing reservoir operations?

Model simulation results suggest that under a warmer climate, peak streamflow timing generally occurs before April 10, resulting in decreased reservoir storage (see Key Takeaway #3). One strategy that local water managers considered was whether allowing Truckee River reservoirs to store snowmelt runoff earlier than April 10 might enhance or sustain water supply in summer months. Researchers used the Truckee River operations River Wear Model to evaluate under reservoir reoperation the benefits in terms of commonly used water supply indicators, as illustrated in Figure 10.

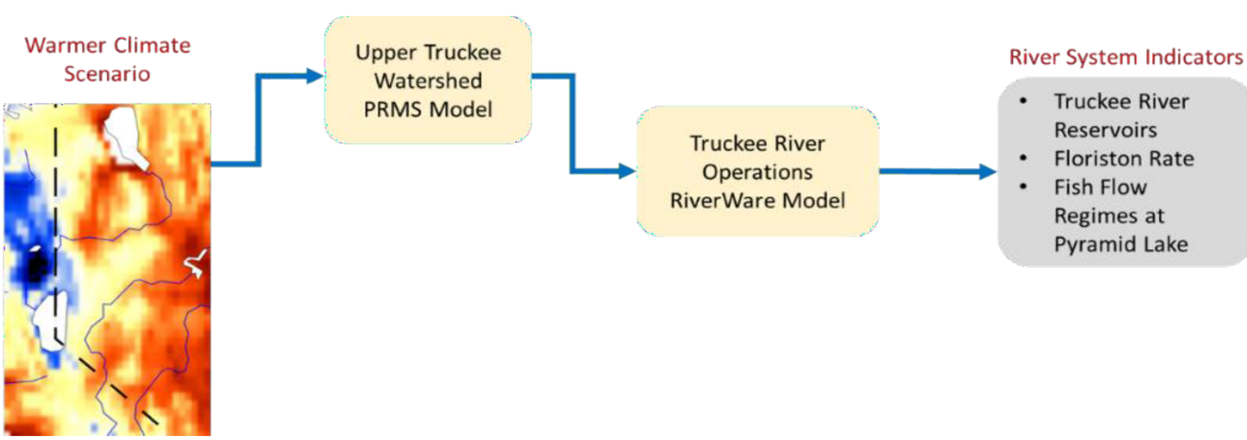


Figure 10. Modeling framework to evaluate reservoir reoperation impacts on water supply.

What do model simulations that allow for earlier reservoir storage suggest?
Allowing for earlier reservoir storage alleviates the impacts of earlier snowmelt and absorbs shifts in streamflow timing. Figure 11 presents simulation results for Prosser Creek Reservoir, illustrating:

a) Inflows stored under current reservoir operations based on historical streamflow record;
b) Inflows stored under current operations and a warmer climate scenario; and
c) Inflows under reoperation and a warmer climate scenario.

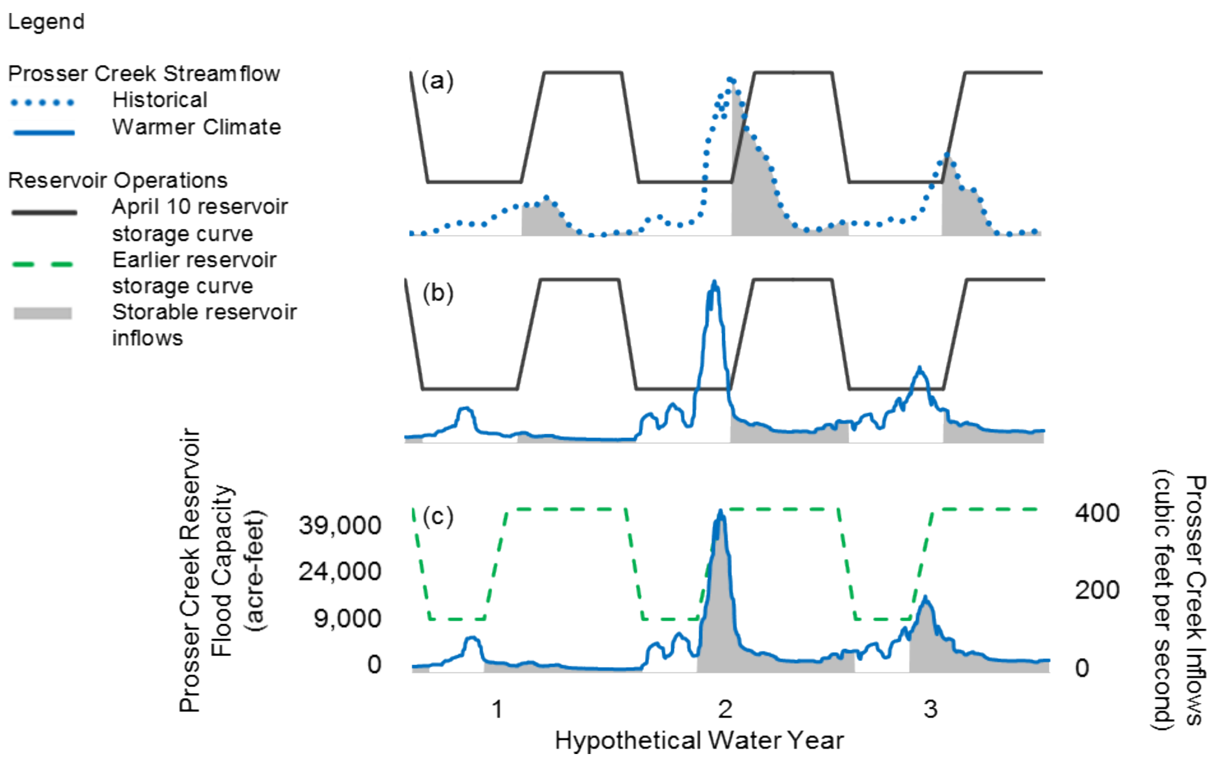


Figure 11. Simulation results for Prosser Creek Reservoir, illustrating (a) inflows stored under current reservoir operations based on historical streamflow record; (b) inflows stored under current operations and a warmer climate scenario; and (c) inflows under reoperation and a warmer climate scenario.

Using the storage capacity of Utilization of Truckee River reservoirs results in measurable benefits for downstream water users, including:

- Floriston rate water is met an additional 14 days, resulting in Truckee Meadows agricultural water delivery shortages less often; and
- Environmental instream flowsand riparian habitat benefit as a result of increased water upstream for releases to maintain downstream instream flow requirements.

With earlier storage, can reservoirs still mitigate flood control?
Truckee River upstream reservoirs were constructed to bridge the gap in timing between low and high water years. Extended dry periods under the low precipitation frequency climate scenario strains the ability of the reservoirs to bridge this gap. Additionally, when the Truckee River Basin experiences extended wet periods, surplus water cannot be captured adequately which may increase flood risk to downstream communities. Further research is needed to address flood control operations and flood risk under changing reservoir operations, as well as how earlier storage could be adapted under the existing water law.[4]

[4] The Truckee River is managed according to the Truckee River Operating Agreement (TROA), implemented in 2015, with the intent to increase the operational flexibility and efficiency of upstream reservoirs while honoring downstream water rights under existing decrees. While TROA addresses long-standing conflict among diverse water users in region, it does not explicitly address changes to reservoir storage under climate change.

#7. Managed aquifer recharge may help mitigate long-term climate change impacts by increasing groundwater storage, equating to an overall increase in water availability.

What is managed aquifer recharge?
Managed aquifer recharge is the intentional recharge of water into the groundwater system. As illustrated in Figure 12, runoff generated from the Sierra Nevada snowmelt is diverted across agricultural lands. Recharge could occur by injection into the aquifer through existing wells, or diversions through delivery networks and existing conveyance structures to be spread over agricultural lands.

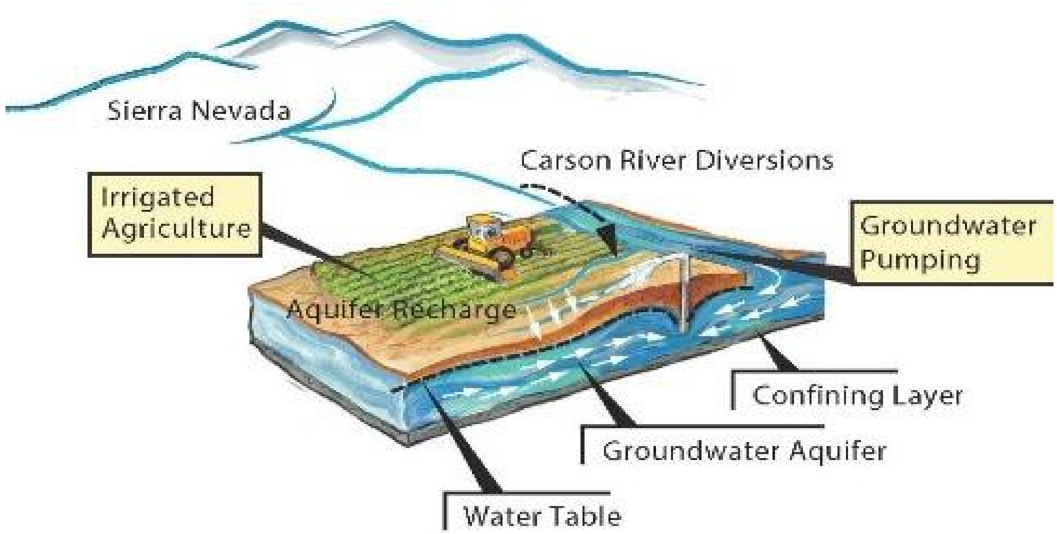


Figure 12. Schematic of managed aquifer recharge in the Carson River Basin.

How might managed aquifer recharge help Carson River water managers adapt to climate change?
Climate change scenarios indicate that reduced snowpack accumulation and earlier snowmelt runoff reduce water available during the summer irrigation season (see Key Takeaway #3). Water managers repeatedly shared with researchers their concerns about changing snowpack impacts on surface water deliveries and reliance on groundwater, as the region's population and economy continue to grow.

Researchers introduced to the *Stakeholder Affiliate Group* the concept of managed aquifer recharge during water surplus years as a potential strategy to enhance regional water sustainability. Using the integrated hydrologic and operations model tailored to the Carson River Basin illustrated in Figure 13, researchers simulated managed aquifer recharge to explore the extent that this strategy mitigates earlier snowmelt timing impacts on water availability.

What assumptions did researchers make?
The hypothetical scenario seeks to "follow the changing hydrograph" and assumes no legal constraints. This means that:

- **During "wet" or above-average water years,** irrigators in the Upper Carson Valley could divert high flows and spread these waters over their agricultural lands. Assuming these earlier flows are abundant, diversions would begin prior to the growing season.
- **During "dry" years or drought periods,** when surface water availability is less, irrigators in the Upper Carson Valley could augment shortages in surface water deliveries with

groundwater, allowing any available surface water to flow downstream. This assumes that upper valley irrigators can access groundwater through pumping.

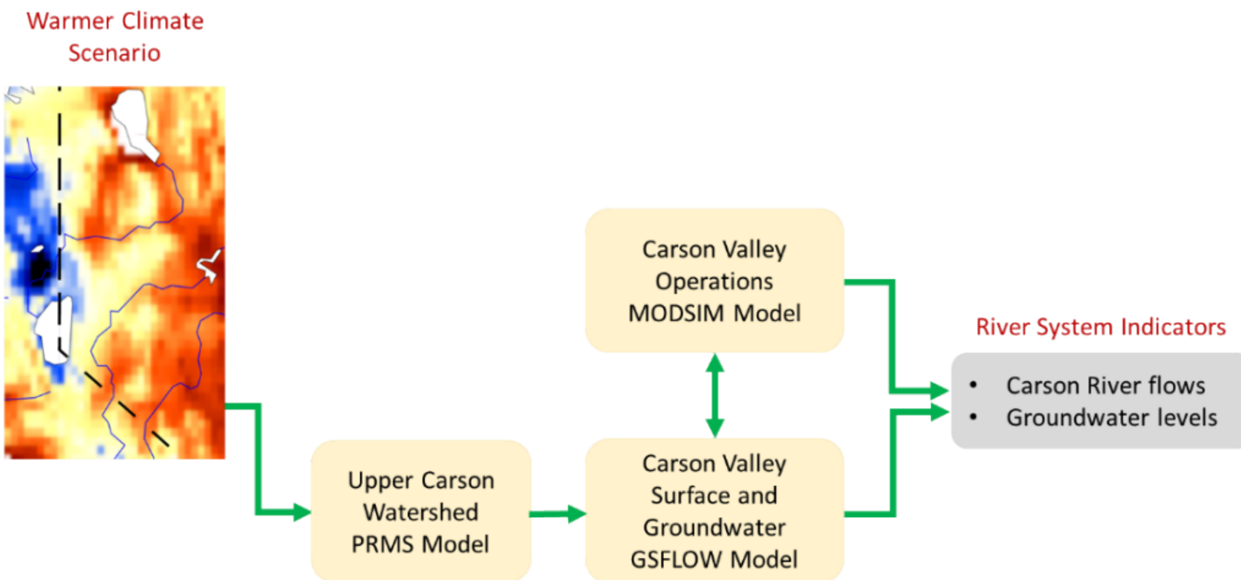


Figure 13. Modeling framework to evaluate managed aquifer recharge impacts on surface and groundwater supply.

<u>What are the possible outcomes of model simulations?</u>

- As a result of reduced surface water flows during the irrigation season, irrigators may need to rely on supplemental groundwater pumping to meet historical deliveries;
- The aquifer would then be impacted further by increased withdrawals over time;
- Diverting surface water prior to the start of the irrigation seasons (i.e., February and March) may reduce surface outflows; and
- Managed aquifer recharge may help mitigate long-term climate change impacts by increasing groundwater levels, equating to an overall increase in water availability.

Future considerations of managed aquifer recharge will include identifying operational decision points for implementation, such as low winter flow criteria that would prohibit recharge, as well as exploring flexibility within existing water law. Finally, trade-offs associated with higher winter flows under climate change should be considered to ensure flood risks are mitigated.

#8. Prior Appropriation Doctrine has allocated water over time to higher valued economic uses.

<u>What is Prior Appropriation Doctrine?</u>

In Nevada, irrigated agriculture accounts for approximately 67% of groundwater and 65% of surface water withdrawals. Prior Appropriation Doctrine is the primary water allocation mechanism in Nevada and most western states. Prior Appropriation follows a general set of rules:

- First in time, first in right - earliest water claimants have more senior rights, receiving their water duty prior to other more junior water right holders on the river;
- Place of use - each water right claim is attached to a specific land parcel;
- Water duty - the basis, measure and the limit of the quantity of water allocated;
- Beneficial use - intended purpose of a water right as established by State water law;
- Use it or lose it - failure to use a water right consistently over time can result in

forfeiture of that water right; and
- Permitted water rights transfer - state permitted relocation of water right priority date and water duty to another land parcel or place of use, provided that no other water right holders will be negatively impacted by the transfer.

> *"To adapt to climate change… what about a revision to Prior Appropriation Doctrine to address this use-it-or-lose-it issue. Could look to conservation credits? Or, more flexibility to determine higher and best use, rather than just Prior Appropriation alone." – Regulatory Water Manager.*

How has Prior Appropriation Doctrine performed over time?
As in most western river basins, the earliest water claims were assigned to lands closest to the river to facilitate access to surface flows for agricultural irrigation. Because more profitable alfalfa hay was introduced decades after water rights had already been established for grass hay, senior water rights may be attached to lands with comparatively lower valued water use and therefore receive water even in drought years.

Researchers developed an econometric model to:
1) Determine whether over time Prior Appropriation has resulted in less valued, less profitable agricultural lands being mismatched with senior, more secure water rights; and
2) Evaluate whether permitted permanent water transfers realign high-valued agricultural lands and profits with more senior water rights, thereby improving water allocation efficiency.

Econometric model results suggest that over time with permitted permanent water transfers, more senior, secure water rights are realigned with more profitable agricultural lands, such as those with higher alfalfa yield potential. As a result of these permanent transfers in the Carson Valley, for example, agricultural revenue may increase by 42%. Facilitating the transfer application process to effectively demonstrate hydrologic impacts on other users from such transfers may further improve Prior Appropriation water allocation efficiency and thus agricultural profitability.

Additionally, using satellite land use data, economists examined the extent of temporary, small-scale water transfers, wherein no permit is required, that occur during drought years as a result of farmers' cooperative water-sharing arrangements. Econometric models verify that temporary transfers of senior water rights occur in drought years, allowing for more alfalfa production on lands with junior water rights than would otherwise be possible, thereby increasing agricultural profitability. These results reaffirm that temporary water transfers, particularly during droughts, can improve Prior Appropriation allocation efficiency.

#9. *Water for the Seasons* facilitated stakeholder-driven collaborative research and social learning.

The *Water for the Seasons* collaborative research program facilitated stakeholder-driven science discovery and learning, resulting in new knowledge, including hydrologic and econometric models, analytical techniques and climate information services to support local climate adaptation. This report summarizes these climate information services that include:
- Direct input of local managers into the research agenda, collected over five years, that demonstrate local managers' adaptation strategies, implementation barriers and information needs
- Climate scenarios, intended to test the resiliency of the river system's water resources to climate change, informed through local water managers' narratives and climate scientists' expertise;
- Hydrologic and river operations models and simulations that assess the effects of climate

scenarios on water availability and associated challenges of the system's capacity to meet diverse and competing water demands; and
- Econometric models and data that assess the economic performance over time of Prior Appropriation Doctrine to allocate water to higher-valued land use and its flexibility in allocating water efficiently during periods of drought.

"Now is the perfect time to get other tribal leadership more informed about what's going on [with climate change]. The more they are informed, the better decisions they can do." – Tribal water manager.

#10. Local water managers voiced the need for additional collaborative research to investigate climate change impacts and support ongoing climate adaptation across the river system.

Additional research is necessary to assess and adapt to climate change impacts across the river system using the models and datasets program tailored to the Truckee-Carson River System that were developed during this program. Researchers acknowledge that some degree of uncertainty is inherent with analytical models designed to represent reality. However, they present their findings from this program with high levels of confidence and seek ongoing collaboration with local water managers to refine their research models, methods and results. Coincidently, local water managers voice the need for additional collaborative research and outreach in support of local climate adaptation efforts, including:

- Incorporate economic development scenarios across the river system that forecast population growth and increased municipal water demands coupled with climate scenario stressors;
- Further downscale systemwide climate projections sufficiently to better inform local climate adaptation planning;
- Explore potential threats to water quality under climate change;
- Identify potential surface water storage sites in the Carson River Basin, wherein none exist presently; and
- Educate the public about water sustainability in the context of climate change impacts and the need for adaptation in an arid environment.

"It would be nice to know where you have large aquifers that could take additional water [from managed aquifer recharge and aquifer storage and recovery]. That is part of what you would look at, the science there. A lot of it will be policy and land use." – Agricultural water manager.
"We want to know more about the groundwater quality. If you start putting down a lot of water, are you moving contaminants? "– Urban water manager.
"Agencies are always juggling climate science. Projections of the new normal would be helpful." – Regulatory water manager.

Acknowledgements

The research team acknowledges the steadfast commitment and involvement of the local Truckee-Carson River System water managers who contributed substantively to this study, especially representatives of the *Stakeholder Affiliate Group,* who voluntarily participated consistently over the five- year (2014-2019) period. Additional acknowledgement is given to Olga Ilchuk for program administrative support, preparation for and coordination of program workshops, and educational materials and publications copyediting; and to Ron Oden for graphic design. Both are with the University of Nevada, Reno. The *Water for the Seasons* collaborative research program was funded by a Water Sustainability and Climate program grant from the National Science Foundation (#1360506) and the U.S. Department of Agriculture National Institute of Food and Agriculture (#2014-67003-22105).

Additional Information

Water for the Seasons Collaborative Research Program

McCarthy, M., Singletary, L., Sterle, K., Simpson, K., Fitzgerald, K., Pohll, G., Rajagopal, S., Huntington, J., Dettinger, M. & Niswonger, R. (2016). Sustaining Water and Climate Resiliency in the Truckee-Carson River System. University of Nevada, Reno Extension Special Publication SP-16-01. Visit a link to the above publication here.

Collaborative Research Design

Singletary, L. (2016). Collaborative Modeling to Assess and Enhance Community Climate Resiliency University of Nevada, Reno Extension Fact Sheet FS-16-04. Visit a link to the above publication here.

Singletary, L. & Sterle, K. (2017). 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, 9*(2). Visit a link to the above publication here.

Singletary, L. & Sterle, K. (2018). Participatory Research to Assess the Climate Resiliency of Snow-fed River Dependent Communities: A Collaborative Modeling Case Study in the Truckee-Carson River System. In P. R. Lachapelle & D. Albrecht (Eds.), Addressing Climate Change at the Community Level in the United States. New York, NY: Routledge. Visit a link to the above publication here.

Sterle, K. (2018). Collaborative Modeling to Assess Climate Adaptation and Science Information Needs in Snow-fed River Systems (Doctoral dissertation). University of Nevada, Reno. Visit a link to the above publication here.

Sterle, K., Singletary, L. & Pohll, G. (2017). Collaboratively Modeling Water Resources in the Truckee-Carson River System. University of Nevada, Reno Extension Special Publication SP-17-04. Visit a link to the above publication here.

Singletary, L. & Sterle, K. (Accepted pending revisions). Supporting Local Adaptation through the Co-Production of Climate Information: An Evaluation of Collaborative Research Processes and Outcomes *Climate Services.*

Local Water Managers' Perspectives

Singletary, L., Sterle, K. & Simpson, K. (2016). Assessing the Climate Resiliency and Adaptive Capacity of the Truckee-Carson River System: Results of a Survey of Local Organizations. University of Nevada, Reno Extension Special Publication SP-16-03. Visit a link to the above publication here.

Sterle, K., Hatchett, B.J., Singletary, L. & Pohll, G. (2019). Hydroclimate Variability in Snow-fed River Systems: Local Water Managers' Perspectives on Adapting to the New Normal. *Bulletin of the American Meteorological Society, 100*(6): 1031–1048. Visit a link to the above publication here.

Sterle, K. & Singletary, L. (2017). Adapting to Variable Water Supply in the Truckee-Carson River System: Results of Focus Groups Conducted in 2016 With Local Water Managers. University of Nevada, Reno Extension Special Publication SP-17-15. Visit a link to the above publication here.

Sterle, K. & Singletary, L. (2017). Adapting to Variable Water Supply in the Truckee-Carson River System, Western USA. *Water, 9*(10). Visit a link to the above publication here.

Sterle, K. & Singletary, L. (2018). Shifts in Local Climate Adaptation Strategies over the 2015-2017 Water Years: A Case Study in the Truckee-Carson River System. University of Nevada, Reno Extension Fact Sheet FS-18-04. Visit a link to the above publication here.

Climate Change Projections

IPCC (2014). 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 [Core Writing Team, R.K. Pachauri & L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. Visit a link to the above publication here.

Thorne, J.H., Wraithwall, J. & Franco, G. (2018). California's Changing Climate 2018. California's Fourth Climate Change Assessment. California Natural Resources Agency. Visit a link to the above publication here.

USGCRP. (2018). Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II: Report-in-Brief [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock & Stewart B.C (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 186 pp. Visit a link to the above publication here.

Climate Change Scenarios

Albano, C.M. (2019). Atmospheric Rivers and Climate Stresses: Retrospective and Prospective Assessments of the Impacts of Storm Variability, Climate Changes, and Extremes in the Western US (Doctoral dissertation). University of Nevada, Reno.

Albano, C.M., Sterle, K., Dettinger, M.D. & Singletary, L. (2019). Four Climate Scenarios Developed to Explore Adaptation Strategies for the Truckee-Carson River System. University of Nevada, Reno Extension Fact Sheet FS-19-09. Visit a link to the above publication here.

Albano, C.M., Dettinger, M.D. & Harpold, A.A. (2020). Patterns and Drivers of Atmospheric River Precipitation and Hydrologic Impacts Across the Western US. *Journal of Hydrometeorology, 21*: 143–159. Visit a link to the above publication here.

Albano, C.M., McCarthy, M.I., Dettinger, M.D. & McAfee, S.A. (In review). Techniques for Specifying Climate Stress-test Scenarios for Climate Adaptation Planning. Submitted to *Climatic Change.*

Dettinger, M.D., Sterle, K., Simpson, K., Singletary, L., McCarthy, M. & Fitzgerald, K. (2017). Climate Scenarios for the Truckee-Carson River System. University of Nevada, Reno Extension Special Publication SP-17-05. Visit a link to the above publication here.

Climate Impacts to Water Supply and System Operations

Dettinger, M.D., Udall, B. & Georgakakos, A. (2015). Western water and climate change. *Ecological Applications, 25*(1), 2069–2093. Visit a link to the above publication here.

Harpold, A., Rajagopal, S., Crews, J. B., Winchell, T. & Schumer, R. (2017). Relative Humidity Has Uneven Effects on Shifts from Snow to Rain Over the Western *U.S. Geophysical Research Letters*, *44*(19). Visit a link to the above publication here.

Harpold, A., Dettinger, M. & Rajagopal, S. (2017). Defining Snow Drought and Why It Matters. *Eos, 98.* Visit a link to the above publication here.

Rajagopal, S. & Harpold, A.A. (2016). Testing and Improving Temperature Thresholds for Snow and Rain Prediction in the Western United States. *Journal of the American Water Resources Association, 52*(5):1142-1154. Visit a link to the above publication here.

Raynor, D., Rajagopal, S. & Sterle, K. (2018). Quantifying Contributions of Snow to Water Supply in The Western U.S. *Journal of Nevada Water Resources Association, Winter 2018*, 5-17.

Truckee River Adaptation Strategies

Boyer, W. (2018). A Dynamic Decision Support System for Drought Resiliency and Climate Change (Masters thesis). University of Nevada, Reno.

Boyer, W., Christman, L. & McCarthy, M. (2019). A Dynamic Decision Support System for Assessing the Impacts of Drought and Climate Change to Water Supply and Demand within the Truckee Meadows. Division of Hydrologic Sciences, Desert Research Institute (Publication No. 71002), Reno, NV, USA.

Sterle, K., Jose, L., Coors, S., Singletary, L., Pohll, G. & Rajagopal, S. (2020). Collaboratively Modeling Reservoir Reoperation to Adapt to Earlier Snowmelt Runoff. *Journal of Water Resources Planning and Management, 46*(1). Visit a link to the above publication here.

Sterle, K. & Singletary, L. (2018). Adapting Truckee River Reservoir Operations for a Warmer Climate. University of Nevada, Reno Extension Fact Sheet FS-18-06. Visit a link to the above publication here.

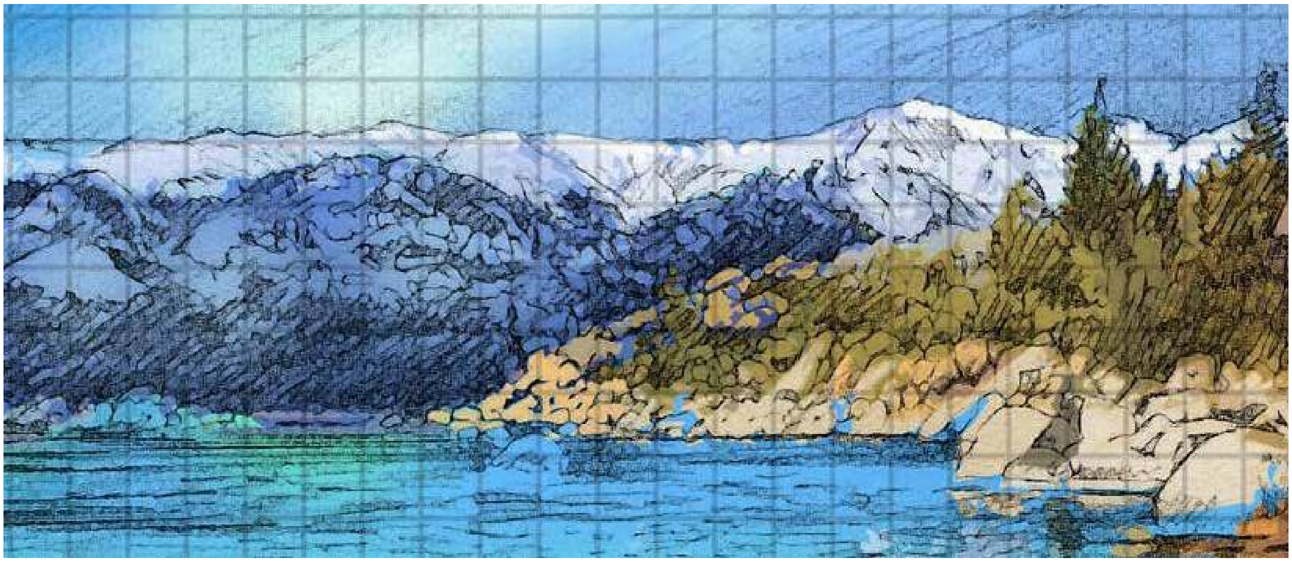
Carson River Adaptation Strategies

Lee, G.E., Rollins, K. & Singletary, L. (forthcoming, August 2020) An Empirical Analysis of the Influence of Permitted Place of Use Transfers on the Performance of Prior Appropriations Water Rights. *Land Economics, 96*(3): 384-398. Visit a link to the above publication here.

Morway, E.D., Niswonger, R.G. & Triana, E. (2016). Toward Improved Simulation of River Operations Through Integration with a Hydrologic Model. *Environmental Modelling and Software, 82*: 255–274. Visit a link to the above publication here.

Niswonger, R.G., Morway, E.D., Triana, E. & Huntington, J.L. (2017). Managed Aquifer Recharge through Off-Season Irrigation in Agricultural Regions. *Water Resources Research, 53*(8): 6970-6992. Visit a link to the above publication here.

Sterle, K., Kitlasten, W., Morway, E., Niswonger, R.G. & Singletary, L. (2019). Managed Aquifer Recharge in Snow-fed River Basins: What, Why and How? University of Nevada, Reno Extension Fact Sheet FS-19-10. Visit a link to the above publication here.



The University of Nevada, Reno is committed to providing a place of work and learning free of discrimination on the basis of a person's age, disability, whether actual or perceived by others (including service-connected disabilities), gender (including pregnancy related conditions), military status or military obligations, sexual orientation, gender identity or expression, genetic information, national origin, race, or religion. Where discrimination is found to have occurred, the University will act to stop the discrimination, to prevent its recurrence, to remedy its effects, and to discipline those responsible.