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Collaboratively Modeling Water Resources in the Truckee-Carson River System

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Introduction

The Truckee-Carson River System, comprising approximately 7,026 square miles (18,197 square kilometers), supplies water to the high desert communities of northwestern Nevada primarily through spring snowmelt runoff originating as winter snowpack in the Sierra Nevada. The river system community includes diverse water users comprising municipal, industrial, environmental and agricultural demand. Typically, snowmelt accumulates in winter and begins melting in late spring, sustaining streamflow through the summer, and recharging groundwater aquifers utilized as both primary and supplemental sources of water for municipal, agricultural and environmental uses.

In the Truckee River Basin, snowmelt is stored in natural and manmade reservoirs that release water throughout the year to satisfy downstream water use needs. In contrast, the Carson River Basin does not have upstream water storage reservoirs, making groundwater an especially important resource to satisfy downstream demand.

Though the Truckee and Carson River Basins are two separate watersheds, they are connected via the Truckee Canal, which diverts Truckee River surface flows away from the natural terminus at Pyramid Lake to supplement Carson River flows. These flows are stored in Lahontan Reservoir to be released for agricultural irrigation in the Newlands Project Area, the nation's first Bureau of Reclamation project (1906), and for environmental use on the Stillwater National Wildlife Refuge (Wilds, 2014). Thus, the river "system" aspect derives from this man-made diversion.

Changes to snowpack accumulation, the timing and rate of snowmelt, and warmer temperatures bringing winter precipitation in the form of rain versus snow alter water supply for municipal, agricultural and environmental uses. Prolonged warmer drought conditions paired with shifting snowmelt may require modifications to existing water management institutions reliant on historical runoff timing in order to better manage supply and demand under variable conditions. Understanding future water supply in the river system involves incorporating not only the climatic drivers of change, such as varying precipitation and temperature, but also nonclimatic drivers, such as population growth and shifting water demand.

This Special Publication explains efforts underway to collaboratively model water resources in the Truckee-Carson River System, focusing on climate-induced drivers of change. It reviews the hydrologic and operations models developed and integrated as part of this research program and the use of these models to examine climate-induced water supply variability in the study area.

Collaboratively Modeling Water Resources

Participatory research approaches, such as collaborative modeling, acknowledge that local stakeholders have an interdependent and vested interest in developing and implementing water resources research. The collaborative modeling research design implemented in the Truckee-Carson River System convenes researchers and local water managers to develop relevant research questions and evaluate alternative water management scenarios that may alleviate the compounding effects of prolonged warmer drought conditions (Singletary & Sterle, 2017).

Researchers include climatologists and hydrologists, specializing in both surface and groundwater, from the Desert Research Institute and the U.S. Geological Survey, as well as resource economists and Extension outreach specialists from the University of Nevada, Reno. Local stakeholders include water managers representing municipal, industrial, planning, environmental, agricultural and government organizations.

Models are useful in scientific and participatory research to explain and predict the behavior of systems in a conceptual yet objective way. While models cannot provide a perfect simulation of real-world situations and challenges, researchers and local water managers can use models as tools to help conceptualize complex environmental systems with human-derived infrastructure and management.

Multiple models are required to simulate climate-induced changes to water supply across this river system. For example, to understand water supply change in the snow-dominated headwaters of the Truckee River requires a hydrologic model that incorporates surface processes such as snowmelt and streamflow, as well as contributions of shallow groundwater to streamflow.

Each river also requires different operations models. For example, Carson River operations are regulated according to the Alpine Decree, a prior appropriation-based adjudication of surface water rights to predominately individual agricultural parties. Thus, the operations model for the Carson River must account for diversions and return flows based on agricultural water rights and use information. The Truckee River operates according to the Truckee River Operating Agreement, and includes seven upstream reservoirs that store and release water to meet a variety of surface water demands, including environmental in-stream flow requirements. Thus, the operations model for the Truckee River must account for the date-based rules governing reservoir storage and releases regulating flow in the Truckee River.

In the Truckee-Carson River System, water resources and operations are simulated using a **suite of hydrologic and operations models** integrated to explore systemwide implications of water supply variability. Models are integrated by passing data from one model to the next at specific points (described further in the next section). The output of one model acts as the boundary condition for the next model, referred to as cascading models.

Hydrologic models simulate physical hydrologic processes and estimate components of the hydrologic cycle, such as snowmelt, runoff and evaporation, at a defined spatial scale within the landscape or basin. Hydrologic models are useful to understand and predict hydrologic processes under current and future climate, and subsequent changes in the water balance equation. The water balance equation describes the flow of water into and out of a system, such as a watershed or groundwater aquifer, or a smaller spatial scale such as a sub-basin or urban area. The change in water storage of the system equates to the difference of water in (precipitation) and water out (streamflow and evapotranspiration, a measure of the combined water loss from lakes, reservoirs, soil or agricultural croplands due to evaporation and plant transpiration).

Hydrologic models are developed according to regional (or subregional) topography, geologic formations, surface and groundwater flow directions, hydrologic boundaries (such as rivers, lakes, wetlands and recharge areas), and hydrogeology (such as aquifer properties and soil porosity). These models are calibrated using observations from climate stations (precipitation,

snow depth and temperature), hydrologic gauges (streamflow), and wells (groundwater levels) within the model boundary.

Precipitation and temperature are key climate inputs that "drive" these hydrologic models. Hydrologic model outputs depict surface and groundwater fluxes and states, such as streamflow, snowpack accumulation and melt, evapotranspiration, groundwater levels, and groundwater flow to and from streams. These models are also used to simulate changes in runoff, river stage and groundwater levels. These outputs are passed to operations models to examine implications for local water managers.

Figure 1 provides a map of the Truckee-Carson River System, watershed boundaries (green outline), and call-outs for where hydrologic models exist (red and green shaded areas). Yellow arrows indicate flow of water through the Truckee River and to either the river's natural terminus (Pyramid Lake) or to the system terminus through the Truckee Canal. Orange arrows represent snowmelt from the Sierra Nevada driving Carson River flow. To focus results on the impacts of changing urban water demand on groundwater resources, as illustrated, the Truckee Meadows Groundwater Model incorporates the Reno-Sparks urban areas. The Fernley Groundwater Model incorporates the City of Fernley.

Figure 1. Truckee-Carson River System and hydrologic model boundaries.
Graphic design by Kelley Sterle and Ron Oden, University of Nevada, Reno.

To improve simulation of connected processes, such as surface water and groundwater, two hydrologic models can be coupled. By coupled models, we mean that a two-way connection or flow of information is established between models. For example, coupled surface and groundwater models can simulate stream and aquifer interactions. Coupled is different from integration because there is information flow in both directions, as opposed to flow only in the forward direction.

In some reaches of the river system, such as the headwaters of the Truckee River and Carson Valley, the interactions between surface and groundwater are important for estimating streamflow because aquifers in the headwaters are relatively shallow as compared to the valleys. An important interplay exists between snowmelt-derived streamflow and the zone of surface and groundwater interactions, referred to as the unsaturated or vadose zone. Thus, the shallow groundwater-discharge areas are important for understanding streamflow that has important implications for operations in both the Truckee and Carson Rivers. Therefore, in these reaches, researchers have updated existing models to incorporate this interaction, as shallow alluvial aquifers are more susceptible to climate fluctuations.

Operations models are developed to gain insight into how the river operates based on hydrologic changes under current and future climate. For example, under less streamflow and warmer temperatures, are water right allocations met in all reaches of the Carson River? Thus, these models "operate" the system based on the available water as indicated by the flow outputs from the hydrologic models to determine how changes in water supply translate to changes in water allocations. Operations models incorporate the built infrastructure, such as reservoirs, canals or ditches, that stores and/or routes water, and operational rules that dictate water releases through the system.

When outputs from one model are passed as inputs to the next, these cascading models are able to simulate the daily hydrologic conditions and operating rules to deliver water supply throughout the interconnected system. This is particularly useful when evaluating downstream implications of prolonged drought that are highly dependent on upstream snowpack conditions and flows. For example, estimating storage in Lahontan Reservoir requires an understanding of how both Truckee River and Carson River flows and demands are altered when supply is scarce.

Table 1 describes the hydrologic and operations models used in this study, the spatial extent of these models, and model inputs and outputs, including how evapotranspiration (ET) is incorporated. Note that in some cases, the same model is used more than once. For example, GSFLOW is used as the hydrologic model for both the headwaters of the Truckee River as well as in the Carson Valley. The same groundwater model, MODFLOW, also exists for the Truckee Meadows and the City of Fernley. Tailoring models to each of these regions produces more realistic outputs to better inform local water managers' decisions.

Table 1. Hydrologic and operations models comprising the integrated model.

Model	Location	Definition	Model Inputs and Outputs
PRMS	Upper Carson Watershed	A hydrologic model of surface water that simulates watershed response to changes in precipitation, climate and land use (USGS, 2015). PRMS, or Precipitation Runoff Modeling System, simulates snowmelt- and rain-generated runoff, and is used only in the Carson River headwaters to explicitly capture dominant snowmelt processes contributing to streamflow downstream.	Hydrologic model inputs include daily precipitation and temperature data collected from climate stations (i.e., SNOTEL sites) and USGS stream gages, providing instantaneous streamflow rates in the river and basin tributaries.
MODFLOW	Truckee Meadows	A hydrologic model that simulates groundwater flow into the deeper unsaturated zone (USGS, 2016). MODFLOW, or the Modular Groundwater Flow model, is used in the Truckee Meadows and City of Fernley where deep valley aquifers are present, to improve understanding of groundwater levels under changing water supply, and potential increased demand on supplemental groundwater pumping.	Historical groundwater levels from observation wells in the Truckee Meadows, and from the Middle and Lower Carson Valleys are also used where groundwater processes are incorporated.
	Fernley		
GSFLOW	Upper Truckee Watershed	A coupled surface-groundwater model developed by combining the MODFLOW groundwater model with the PRMS watershed model to improve simulation of surface-groundwater interactions occurring in the unsaturated zone. The model simultaneously accounts for climatic conditions, runoff across the land surface, and flow from the surface to groundwater aquifers, as well as connections with terrestrial systems, streams, lakes, wetlands and groundwater (USGS, 2016). The surface-groundwater interactions are notable in shallow alluvial aquifers particularly sensitive to climate change.	Outputs depict surface and groundwater supplies under resultant changes in precipitation and temperature, driving subsequent changes to rainfall versus snowpack accumulation, timing of melt and evapotranspiration. Model outputs reflect simulated changes in runoff, streamflow, groundwater levels, and groundwater flow to and from streams.
	Carson Valley and Middle Carson Valley		
MODSIM	Carson Valley and Middle Carson Valley	A decision support model designed to help river operations managers with water rights planning and water resources management, including scheduling diversions from rivers to irrigation ditches. MODSIM can incorporate water management constraints, such as legal agreements, contracts, federal regulations and interstate compacts (Labadie, 2016). MODSIM is coupled with GSFLOW, providing a two-way exchange between water demand and water supply, respectively.	Operations model inputs include both observed and simulated streamflow and evapotranspiration from the hydrologic models.

Outputs typically present water availability based on water rights at points of interest within the system, reservoir elevations and storage capacity, irrigation diversion amounts, or basin-specific measures, such as the day a legally required flow rate is no longer met. |
| RiverWare | Truckee River | A river-system modeling tool that incorporates the hydrologic conditions to determine whether certain operations criteria and water demands are met. These operations include reservoir releases and minimum instream flow requirements. Under reduced flows, for example, the model will optimize storage and releases (CADSWES, 2016). RiverWare's groundwater objects are calibrated to MODFLOW in the Truckee Meadows to more accurately depict pumping impacts on surface water flows. | |
| Evapo-transpiration (ET) | Open surface water and irrigated lands | Evapotranspiration estimation produces open water evaporation from Lake Tahoe, Pyramid Lake, Truckee River reservoirs, and irrigated agriculture throughout the Carson Valley and Newlands Project. | ET estimates incorporate precipitation and temperature, as well as crops, to estimate crop water demand. Revised coefficients are estimated. |

Assessing Changes in Water Supply

Climate inputs drive the hydrologic models in the upper Truckee and Carson watersheds, and pass flow information sequentially to models developed for downstream areas. The operations models then simulate operations and water rights on the Truckee and Carson Rivers, respectively under relative conditions. **Figure 2** illustrates this cascade of information through the integrated model, the exchange of inputs and outputs between models.
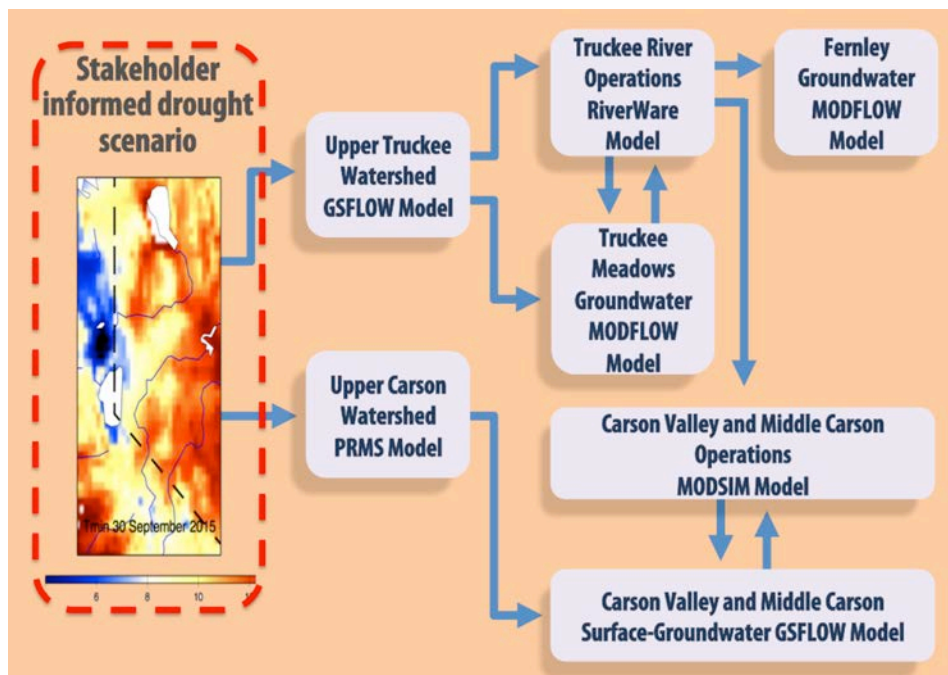

Figure 2. Integrated model conceptual schematic.
Graphic design by Kelley Sterle and Ron Oden, University of Nevada, Reno.

Climate inputs can be generated using either: 1) observed historical climate data collected at nearby stations, or 2) future forecasted climate conditions packaged as "climate scenarios." Ongoing and iterative engagements with local water managers knowledgeable about the river system inform these climate scenarios. For example, interviews in the summer of 2015 with 66 local water managers, coincident with worsening drought conditions, revealed that the majority of water managers, regardless of organization or location, were concerned about the effects of prolonged drought events (Singletary, Sterle & Simpson, 2016). Thus, the first climate scenario explored the implications of a 13-year prolonged drought on water resources in the system. **Figure 3** illustrates how climate data (black dots) are downscaled to the nearest climate stations (blue dots) and used to calibrate hydrologic models in the Upper Truckee Watershed.
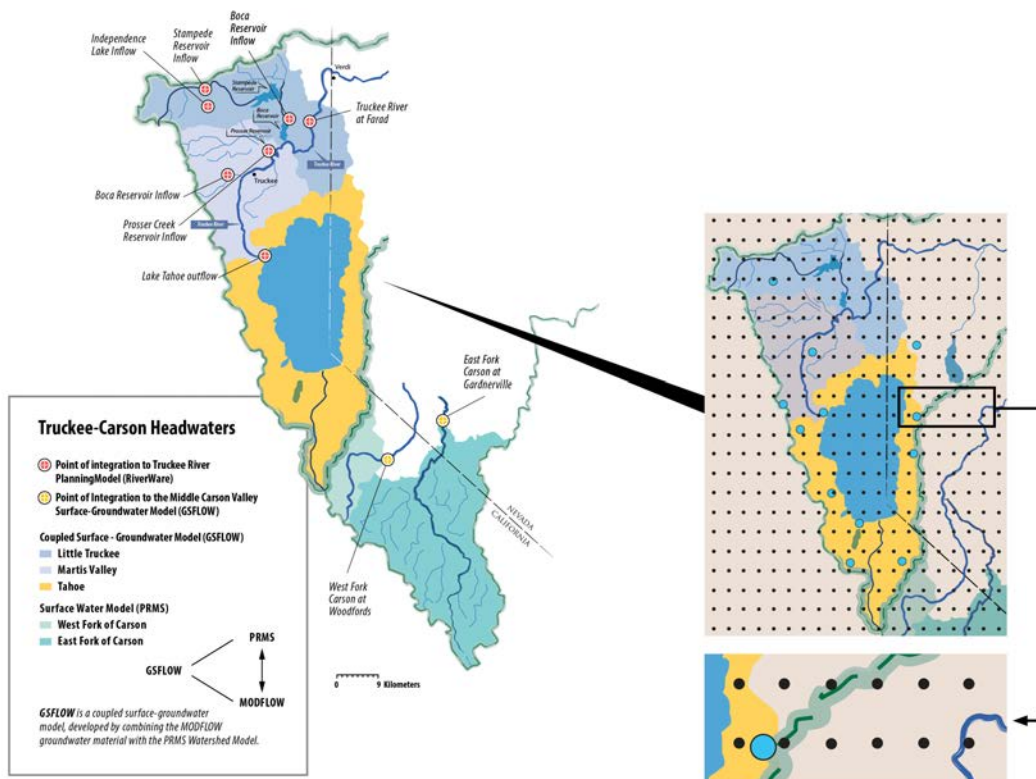
**Figure 3: Points of integration in the Truckee and Carson River headwaters.
Graphic design by Kelley Sterle and Ron Oden, University of Nevada, Reno.**

As described above, the suite of hydrologic and operations models is integrated by passing data outputs from one model into the next model (as inputs). Thus, implications are cascading from hydrologic models in the headwaters to downstream hydrologic and operations models. This occurs at specific points, defined as **points of integration**. **Figure 3** illustrates the location of these points in the Truckee and Carson River headwaters. Note, the Upper Truckee River model is comprised of three smaller models (Little Truckee, Martis Valley and Tahoe). The RiverWare model inputs include flow measured at seven river gages, indicated by the red points. The two yellow points indicate the gage locations where flows from the Upper Carson River model are passed downstream.

Evapotranspiration or ET, a component of the water balance typically estimated based on fixed crop coefficients, is particularly sensitive to changes in precipitation and increases in temperature. Given the low humidity characteristic of arid climates, the low moisture content in the air as compared to the soil causes increased levels of ET. Water from open lakes also evaporates more readily. Thus, ET is re-estimated based on the climate scenario of interest and incorporated into both the hydrologic and operations model estimations (Huntington et al., 2015).

Towards Adaptation Strategies

As part of this collaborative modeling research design, local water managers continue to inform research activities, including prioritization of climate scenarios of interest such as the climate conditions needed to return to "normal" and recurring atmospheric river events bringing winter precipitation in the form of rain versus snow.

As researchers simulate hydrologic change under variable precipitation and temperature, results from operations models suggest locations where water supply shifts translate to reduced water storage, decreased water allocations, and increased reliance on groundwater pumping to supplement surface water shortages. Examining these losses systemwide puts these changes in a context relevant to local water managers, and serves to identify adaptation strategies that may alleviate continued years of warmer drought conditions.

While local water managers propose some strategies that would improve their ability to operate, researchers contribute their knowledge by suggesting the water management alternatives they can simulate to examine the net benefits across the system. For example, researchers explored how shifting date-based operations on Truckee River reservoirs would help to sustain flows through late summer. Similarly, researchers shared a series of alternative management scenarios with Carson River agricultural producers to better understand under what conditions producers would fallow croplands or change crops. These discussions address the interests of local stakeholders while fully demonstrating the capabilities of these models to assess both climatic-induced water supply variability, as well as nonclimatic drivers that influence water demand and future supply.

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