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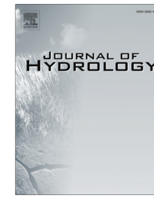

Collaborative modelling and integrated decision support system analysis of a developed terminal lake basin

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SUMMARY

A terminal lake basin in west-central Nevada, Walker Lake, has undergone drastic change over the past 90 yrs due to upstream water use for agriculture. Decreased inflows to the lake have resulted in 100 km^2 decrease in lake surface area and a total loss of fisheries due to salinization. The ecologic health of Walker Lake is of great concern as the lake is a stopover point on the Pacific route for migratory birds from within and outside the United States. Stakeholders, water institutions, and scientists have engaged in collaborative modeling and the development of a decision support system that is being used to develop and analyze management change options to restore the lake. Here we use an integrated management and hydrologic model that relies on state-of-the-art simulation capabilities to evaluate the benefits of using integrated hydrologic models as components of a decision support system. Nonlinear feedbacks among climate, surface-water and groundwater exchanges, and water use present challenges for simulating realistic outcomes associated with management change. Integrated management and hydrologic modeling provides a means of simulating benefits associated with management change in the Walker River basin where drastic changes in the hydrologic landscape have taken place over the last century. Through the collaborative modeling process, stakeholder support is increasing and possibly leading to management change options that result in reductions in Walker Lake salt concentrations, as simulated by the decision support system.

1. Introduction

Developed terminal-lake basins pose unique challenges for water resource managers. Terminal lakes are especially sensitive to changes in water availability and distribution because they rely on the residual of upstream water use, and are often given low priority. Decision support systems (DSSs) used in the context of collaborative modeling among resource stakeholders, managers, and scientists offers a pathway toward restoring complex systems like terminal-lake basins. A DSS provides a platform for establishing reference points among stakeholders, such as the current state of the system, and the response of the system to projected management change scenarios. Ultimately, stakeholders must have confidence in the DSS in order to establish mutual understanding and consensus on implementing changes for restoring the system. In this present work, we rely on state-of-the-art integrated management and hydrologic models as components of a DSS to improve the collaborative modeling process that is being used to restore the Walker Lake basin in west-central Nevada.

In the context of this work, the phrase collaborative modeling is used to describe collaboration between resource stakeholders, managers, and scientists to design and evaluate management change options through the use of a DSS for improving water resources (Langsdale et al., 2013). Central to the collaborative modeling process presented herein is the design and development of a DSS that can simulate the complex interactions between climate, hydrology, and water management. As the system being studied herein has changed drastically over the last century due to development, the DSS considers broad changes in the hydrologic landscape and the feedbacks associated with climate, hydrologic processes affecting water availability, and water management. Central to the DSS design are interactions between resource stakeholders, water managers, and scientist before, during, and after DSS development and application.

By their nature, terminal lakes persist due to long-term balances between inflow and outflow. Thus, if lake inflow is reduced by drought and/or by diversions from tributary streams, desiccation can occur (Cooper and Koch, 1984). Surface

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evaporation typically is the largest outflow from a terminal lake. Lake surface evaporation in amounts greater than lake inflow will result in evapo-concentration of salts and high total dissolved solid (TDS) concentrations, even for lakes that receive dilute inflow (Beutel et al., 2001). Among other issues, managing terminal lakes often requires maintenance of lake storage and TDS concentrations in order to avoid critical thresholds in lake water quality that can include degradation of drinking water supplies, reduction in recreational value, and deterioration of valuable fisheries and other ecological components (Galat et al., 1981). Adding to the difficulty of managing water resources, terminal lakes accumulate changes in flows throughout tributary basins, which may include thousands of square kilometers and diverse hydrogeologic settings. Also, storage in large lakes reflects climatic conditions over multiple years (Hunt et al., 2008; Virdi et al., 2012). Large regional-scale influences that occur over long time periods make managing water resources in terminal-lake basins very challenging.

Advancements in DSS design has focused on stakeholder interactions, system usability and interfacing, and to a lesser degree on rigorous coupling of policy, management, and hydrologic processes (Jamieson and Fedra, 1996b; Yates et al., 2005; Letcher et al., 2007; Koch and Grünewald, 2009; Langsdale et al., 2013). Meanwhile, research has been on-going to couple climate, terrestrial, hydrologic, and management processes (VanderKwaak and Loague, 2001; Maxwell and Miller, 2005; Therrien et al., 2006; Panday and Huyakorn, 2004; Markstrom et al., 2008; Kim et al., 2008; Paniconi and Wood, 1993; Hanson et al., 2010; Condon and Maxwell, 2013). Given these somewhat disparate lines of research, the use of integrated hydrologic models as components of a DSS is a logical next step for water resources management (Sophocleous et al., 1999; Rosegrant et al., 2000; Xu et al., 2001; Liu et al., 2008; Valerio et al., 2010). Here we stress the importance of coupling management and hydrologic processes to realistically represent feedbacks among water management operations and hydrologic processes, such as those associated with climate variability, conjunctive use of surface water and groundwater, and changes in land use and the hydrologic landscape. Previous works using DSSs typically have not focused on feedbacks among hydrologic components due to their simplistic representation of hydrologic processes or non-iterative coupling of system components (e.g., Arnold et al., 1998). Systems dynamics models have been used as DSSs for improving management of water resources (Langsdale et al., 2007; Letcher and Jakeman, 2003). Systems dynamics modeling has been a popular approach due to the general nature of the modeling platform that can be used to represent many different processes. However, this approach does not rely on physically-based governing equations, which limits its applicability to water resources problems, most notably the simulation of surface water and groundwater interactions and other diffusive processes related to aquifer flow and storage.

Integrated models have not previously been used in the context of a DSS for collaborative modeling. Feedbacks between water use and hydrologic processes have been simulated using integrated models (i.e., Hanson et al., 2010; Rassam, 2011; Condon and Maxwell, 2013). However, these studies did not include the stakeholder component in the design and implementation of water management change within the DSS and were thus more hypothetical in nature. In the present work, collaborative modeling was used to design management change options; simulation capabilities needed to evaluate the management change were used to design the DSS, and DSS results were reviewed by stakeholders to further develop management change scenarios and for moving toward management change implementation. Stakeholders collectively referred to as the Walker Water Group include representatives from the Walker Federal Water Master, the Walker River Irrigation District, the Walker River Paiute Tribe, the Walker Lake Working Group, the U.S. Fish and Wildlife Service, the U.S. Geological Survey, the Nevada Department of Wildlife, the Mason/Smith Valley Conservation District, and Nevada State Engineer's Office. The Walker Water Group met 9 times since January, 2010 to collaborate on development, application, and evaluation of the DSS.

Integrated models provide a means of simulating all of the important hydrologic processes within regional systems within a single, coupled processes framework. Thus, unlike DSSs used previously that require separate modeling components for different parts of the hydrologic system and data conversion and transfer, the approach described herein represents all climatic, hydrologic, and management components internally and avoids the need to develop application-specific data compatibility and transfer. Benefits to this approach include a DSS that is applicable over a greater range of system behavior, including extreme climate conditions, and feedbacks between water supply and demand. For example, during water scarcity, there are feedbacks between water management and water availability that are very difficult to simulate using a conventional, uncoupled DSS design. For the integrated approach, constraints on water allocation caused by water scarcity are simulated implicitly. Thus, a more realistic and seamless representation of coupled components of the DSS adds greater flexibility to the collaborative modeling process and therefore results in a more usable DSS. There is some increase in computational time associated with using integrated models as components of a DSS. However, due to the design of the integrated model presented herein, additional computation time is insignificant relative to other aspects of collaborative modeling process (i.e., information transfer, analysis of results, and consensus building with stakeholders) and the time savings associated with added richness of information provided by an integrated model. Furthermore, external linkages must be developed and modified when using a conventional DSS to consider management change, whereas this is not necessary for a DSS consisting of integrated modeling components.

Humans alter nearly all components of the hydrologic landscape, and these alterations cascade through tributary basins, and have a cumulative impact on terminal lakes. Humans control flow and storage in reservoirs, streams, and wetlands, and release contaminants and nutrients into these systems. Similarly, water availability, and indirectly, climatic conditions affect how water is managed. For example, during periods of water scarcity, water may not be delivered to low priority users, and thus, the location and rate of diversions or reservoir releases depend on flow and storage in the system. Feedbacks between water availability and water management are complicated when a diversion or release is dependent on water availability at a distant, downstream location in the system due to the established delivery rules or water rights priority. Similarly, reservoir releases are dependent on complex feedbacks between water supply and demand. Management and hydrologic models must be properly coupled to simulate these complicated interactions, which are apparent in developed terminal lake basins (Brooks et al., 2012). Properly simulating the effects of drought or population growth during periods of water scarcity requires simulating nonlinear feedbacks between supply and demand.

DSSs used for water management include representation of key system components, typically categorized into climatic, hydrologic, ecologic, management, institutional, and socio-economic components (Jamieson and Fedra, 1996a). The climatic and hydrologic component of a DSS considers relations among climate, surface water, and groundwater. Ecologic components represent wildlife habitat and water quality, natural vegetation, and associated linkages to water resources, such as stream and groundwater dependent ecosystems. Management components represent human controls on the hydrologic system, typically including reservoir storage and release, diversions from streams, and groundwater pumping. Institutional components represent governing bodies and jurisdictional parties that enact water policy and laws. Socio-economic components represent water pricing and transfers, human response, and their influence on other components of the DSS. Ultimately, a DSS assists in the collaborative modeling process through the development of management change scenarios that are informed by plausible simulated outcomes (Renger et al., 2008). Management change scenarios typically consist of water rights transfers, improved water-use efficiencies, and water quality and water banking trading markets. Stakeholders and institutions inform the process by developing and proposing management changes, and directing policy and climatic scenarios testing.

Here we apply various management change scenarios developed through collaborative modeling to improve water quality in a terminal lake basin in west-central Nevada (LWRB; Fig. 1). The LWRB provides a useful test basin for evaluating the added benefits provided by tight coupling among modeling components as part of the DSS. This work relies on deterministic implementation of water policy changes and is focused on the effectiveness of management strategies for improving Walker Lake. The LWRB provides a challenging test case because Walker Lake has experienced a long-term inflow deficit that has resulted in 45 m of water-level decline and large increases in total dissolved solids (TDS) over the last century. Although the fisheries have completely died off due to high TDS levels in the last decade, there is a new commitment by the State

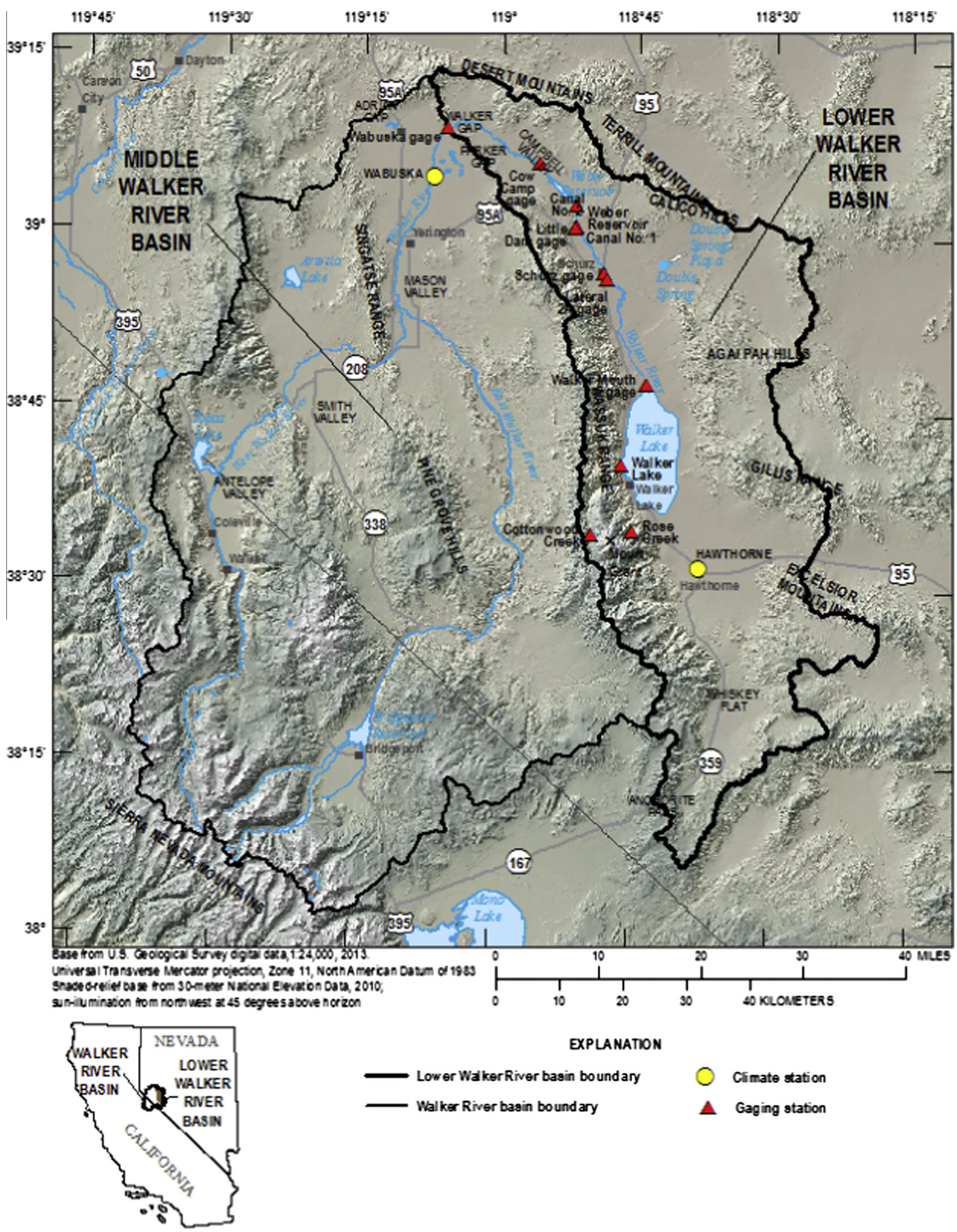

Fig. 1. Map of study area showing model boundaries, lakes, rivers, stream gages, and climate stations.

of Nevada to restore Walker River and Walker Lake through implementation of water quality standards (NDEP, 2005). Managing water resources throughout the entire Walker Lake basin to achieve these lake water quality standards will require innovative management solutions; this paper evaluates some of these proposed management change options in the LWRB to demonstrate the use of integrated management and hydrologic models as components of a DSS.

We use an integrated hydrologic model, GSFLOW, which has been modified to simulate management of reservoir releases, river diversions, and irrigation within the LWRB. GSFLOW is combined with model components that generate future climate conditions that are input to GSFLOW, and a model for simulating TDS concentrations in Walker Lake on the basis of flows and storages provided by GSFLOW. These modeling components along with software used to present and evaluate model results are collectively referred to herein as the DSS. Management scenarios that consider variations in climate and changes in agricultural practices in the Middle Walker River basin (MWRB) are simulated in a separate model and will be linked to the LWRB through a shared boundary (i.e., Carroll et al., 2010; Boyle et al., 2013). A baseline scenario is developed using historic simulation of climate, river diversions, and reservoir storages and releases, and the century-long degradation of Walker Lake and build-up of TDS. Management scenarios are evaluated in terms of the resulting projected lake storage and TDS concentrations, with the goal of meeting water quality standards for Walker Lake.

2. Walker River basin

2.1. Walker Lake

Evaporation from Walker Lake is greater than the total inflow during most years due to agricultural diversions. Consequently, there has been a fairly steady decline in stage of about 0.5 m/yr since 1918. Evaporative losses and diminished inflows from Walker River have increased TDS concentrations in the lake. TDS concentrations in Walker Lake were at such high levels in 1979 that only 3 of 17 fish species that lived in the lake were still present at this time (Koch et al., 1979). The threatened and endangered Lahontan cutthroat trout (LCT) was regularly stocked; however, stocking ended in 2008 due to a very low survival rate, and the last LCT capture was reported May 2009.

The ecologic health of Walker Lake is of great concern to local communities that rely on the fishery for economic and spiritual reasons. Additionally, Walker Lake is a stopover point on the Pacific route for migratory birds from within and outside the United States. There are international treaties in place that attempt to protect the integrity and success of the migratory flyways. This puts additional pressure on the users of Walker River to help maintain the lake as a viable fishery. Management options to increase inflow to the lake have been proposed that include agricultural sector adjustments and water-use efficiency measures. However, there are large uncertainties in how these management solutions will affect storage and TDS concentrations in the lake. Accordingly, separate DSSs of the MWRB and LWRB are being developed to help evaluate various management options to restore the lake. Here we present results for the LWRB while evaluating changes in water management in the MWRB through changes in river flows through a shared boundary. Flows entering the LWRB model boundary represent the combined effects of the change in river diversion and other effects upstream of the model boundary.

A Total Maximum Daily Load (TMDL) standard of 12,000 mg/L has been considered as a reference point for restoring the lake to a point that can support fish and other associated wildlife (NDEP, 2005). The TMDL standard is used herein as a reference point to evaluate the effectiveness of proposed water management scenarios.

2.2. Description of hydrologic system

The entire Walker River basin occupies a drainage area of about 10,230 km^2 in west-central Nevada and eastern California, and the study area consists of the lower 3,210 km^2 of the basin that is downstream of the Wabuska stream gage (LWRB; Fig. 1). Climate in the study area is typical of the semi-arid Great basin desert regime with ranges in precipitation from 115 mm on the valley floors to 420 mm in the mountains (Lopes and Medina, 2007). The study area boundary (and active model domain) generally follows the topographic divide that isolates surface drainage features of the LWRB. In most cases this boundary follows along the mountain crests adjacent to Walker Lake. The headwaters of the Walker River originate in the eastern Sierra Nevada in California as the West and East Walker Rivers (Fig. 1). The West and East Walker Rivers join to form the main stem Walker River that flows 110 km to its terminus at Walker Lake. The Walker River is the largest and most important tributary to Walker Lake. Additional to the Walker River, there are many intermittent and ephemeral streams that drain the mountains surrounding the lake. Walker Lake is a remnant of ancient Lake Lahontan, a large pluvial lake that occupied a large part of the Great basin most recently during the late Pleistocene (Russell, 1885; Benson, 1988).

Natural vegetation in the study area can be characterized by three main vegetation zones: (1) a riparian zone that extends along nearly the entire reach of the Lower Walker River and adjacent to the south side of Walker Lake in an area of groundwater discharge, and along small perennial reaches of local streams within the Wassuk Range; (2) a scrubbrush zone that dominates the valley floors of the study area outside of the riparian zone; and (3) a pinyon-juniper woodland zone that dominates areas at altitudes ranging from about 1676 m to 2743 m in the Wassuk and Gillis Ranges (Fig. 1).

Annual lake levels were reconstructed for the period 1909–1928 and routine monthly monitoring of Walker Lake has been done from 1928 to present (Everett and Rush, 1967; Fig. 2). Groundwater generally flows toward Walker Lake and leaves the lower basin as either outflow through basin boundaries, evapotranspiration, discharge to streams and lakes, or is pumped. The movement of groundwater in the LWRB is described in detail by Lopes and Allander (2009). Generally, as the lake levels have declined, groundwater levels have also declined in the vicinity of the lake and both groundwater levels and simulation results

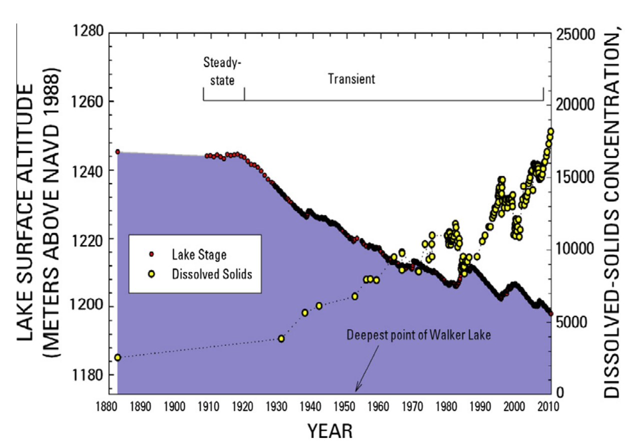

Fig. 2. Graph showing decline in Walker Lake stage, increase in Walker Lake total dissolved solid concentrations, and simulation periods.

indicate that in addition to loss of lake storage, an additional 16% of the lake storage was lost from surrounding groundwater.

The hydrogeology of the LWRB is fairly typical of perennial river basins within the basin and Range Physiographic Province (Maurer et al., 2004). Consolidated rocks form the mountains that separate basins where unconsolidated sediments are deposited. Maurer et al. (2004) further subclassified consolidated rock units into eight hydrogeologic units and unconsolidated sediments into four hydrogeologic units. The distribution of hydrogeologic units in the Lower Walker River basin is shown in Fig. 3. Carbonate rocks, basaltic flows, and highly fractured rocks are considered to have low permeability.

Maurer et al. (2004) identified four categories of unconsolidated sediment in the LWR, including fluvial deposits, valley floor sediments, alluvial slope sediments, and playas (Fig. 3). Fluvial deposits in the LWRB generally occur along the valley bottom adjacent to and beneath Walker River. Valley floor sediments are unconsolidated with a slope of less than 3%, except where intersected by fluvial deposits and playas. Valley floor sediments generally consist of interbedded layers of fine-grained and coarse-grained sediments (Lopes and Allander, 2009). Alluvial slope sediments are unconsolidated with a slope greater than 3% deposited along the base of mountain ranges. Sediment textures that form alluvial slopes transition from coarse deposits near the mountain front to finer deposits where fans give way to playas at the valley bottoms.

2.3. Water use in the Lower Walker River basin

The majority of water is diverted from the Walker River upstream of the model area represented in the LWRB DSS (Boyle et al., 2013). Management scenarios consisting of changes in water use in the MWRB are manifested as changes in flow where the Walker River enters the northern model boundary near the Wabuska stream gage (Fig. 1). Water use in the lower basin consists of agricultural irrigation by the Walker River Paiute Tribe. Water use for irrigation throughout the Walker basin is generally correlated to water supply because the system operates under persistent water supply deficit; only 64% of water needs were satisfied during the period 1981–2010 (Camp, 2013). Accordingly, seasonal water demand for irrigation was assumed to be constant; ET rates are chronically below PET (Huntington et al., 2012). Water use infrastructure consists of systems of canals, irrigation ditches, Weber Reservoir and related infrastructure that supports the agricultural operation of the Walker River Paiute Tribe, and is maintained and operated by the Bureau of Indian Affairs. Some of the perennial flows in the Wassuk Range are captured and diverted to supply water to the Hawthorne Army Ammunition Depot. This water is conveyed through pipes and is used for municipal, industrial, and recreational purposes. The community of Walker Lake relies on fresh groundwater supply from the Cottonwood Creek canyon alluvial fan aquifer.

Irrigation demand is the amount of water needed in an irrigation season to fully irrigate crops for the season, which includes irrigation delivery and application inefficiencies; inefficiencies become groundwater recharge or are lost to transpiration by natural vegetation. Irrigation demand was calculated as the area of crops irrigated with Walker River water, multiplied by the crop water use rate for a full irrigation year and divided by the mean irrigation project efficiency. There were no records of actual year to year area of irrigated acreage available so it was assumed that the decreed acreage was constant from year to year, and during water limited years water use was reduced accordingly. Allander et al. (2009) used Landsat data to estimate an irrigated area of about 8.5 km^2 during water year 2000.

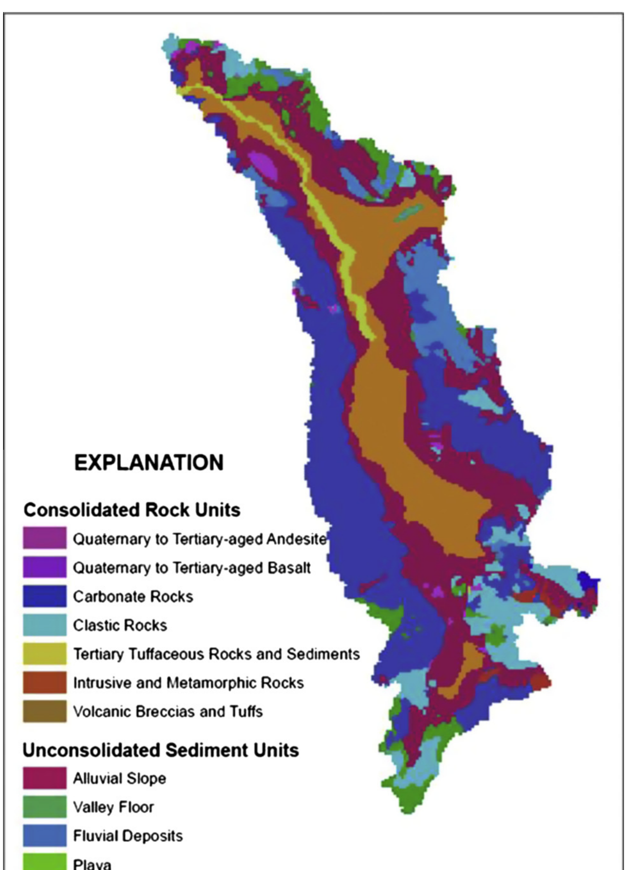

Fig. 3. Map of geologic units in the Walker River basin.

3. Decision support system

Analysis of management options in the Walker basin relied on a DSS to evaluate the system response to management options. An important goal of this work was to allow decision makers to develop scenarios and evaluate outcomes produced by the DSS for planning the course of action. The DSS used in this study consisted of (1) a management scenario generator, (2) a climate generator, (3) an integrated surface-water, groundwater, and water-management model, and (4) TDS transport and mixing calculations for Walker Lake. It was determined that TDS concentrations in the lake could be simulated through simple mixing calculations, and transport throughout the system was not simulated. The climate generator included modification of historical climate records for use as future climatic conditions.

GSFLOW was used to simulate hydrologic conditions, which provided an integrated representation of management, surface water, and groundwater systems, and their nonlinear feedbacks. GSFLOW simultaneously accounts for climatic conditions, runoff across the land surface, variably saturated subsurface flow and storage, and connections among terrestrial systems, streams, lakes, wetlands, and groundwater. GSFLOW includes the coupling of the distributed watershed-runoff model called PRMS (Leavesley et al., 1983) to MODFLOW-NWT, which is a Newton formulation of the 3D groundwater flow model called MODFLOW-2005 with capabilities to simulate unsaturated flow (Harbaugh, 2005; Niswonger et al., 2006, 2011). For details about GSFLOW, its capabilities, and applications refer to Niswonger and Prudic (2004); Hunt et al. (2008); Markstrom et al. (2008); Niswonger et al. (2008); Doherty and Hunt (2009); Huntington and Niswonger (2012);

Morway et al. (2012); Surfleet and Tullos (2013); Surfleet et al. (2012); Hunt et al., 2013).

Water rights in the LWRB are administered by the Nevada State Engineer and both surface water and groundwater rights are established according to the doctrine of prior appropriation (Sharpe et al., 2007). Water management in the LWRB system broadly includes operation of Weber reservoir, diversions from Walker River to canals, and irrigation applications. River water diversions to irrigation canals are made according to the decreed water right amount and the amount of water flowing in Walker River. Weber reservoir stores a maximum of 1320 hectare-meters of water. Water is released from Weber Reservoir back into the main channel of Walker River as needed to provide for irrigation demand when water levels are above minimum pool stage. When water levels are at or below minimum pool stage, flow releases from Weber Reservoir are at or below the rate of inflow to Weber Reservoir. When Walker River inflows to Weber Reservoir are greater than can be stored and are greater than irrigation demand, excess flow is released into the main channel and allowed to move downstream toward Walker Lake. These operating rules were simulated by using formulas that represent a spillway for releasing water in excess of the maximum reservoir storage, and a gated channel that releases a specified amount of water (according to the demand rate) while the reservoir stage remains above the intake elevation of the release gate.

Downstream of Weber Reservoir there are lateral canals that divert water from Walker River and deliver water to fields on both sides of the river. The amount of water diverted to a canal is determined by demand rates if there is enough water in the river to supply the demand. Diversions occur up to the total amount of water in the Walker River if river flow is less than demand. Diversions are managed by the Walker River Paiute Tribe and water priorities beyond diversion from Walker River are unknown. The DSS assumes that diverted water is equally distributed among fields. Within the DSS water flowing into alateral canal is subsequently distributed to fields according to the daily irrigation schedule. Irrigated water is evapo-transpired or percolates beneath fields and becomes groundwater recharge. As part of the management options evaluated herein, two different agricultural sector behaviors were considered, (1) representing farmers that allow water rights transfers intended for the lake to pass down the river to the lake and, (2) farmers that use water transfers to irrigate fields. These scenarios are referred to herein as "pass through" and "no pass through", respectively.

3.1. Hydrologic model setup

Gridded datasets of elevation, geology, vegetation, soils, and land use were used to discretize and parameterize GSFLOW. Climate (precipitation and temperature data sets) was distributed spatially across the model (1200–3426 m above Mean Sea Level AMSL) based on the Parameter-elevation Regression on Independent Slopes Model (PRISM) mean monthly precipitation patterns (Daly et al., 1994), and daily temperature and precipitation at three weather stations: Wabuska (1321 m), Hawthorne (1303 m) and Mina (1387 m). Each of the weather stations measured weather conditions near the valley bottom. There was no weather data available for higher altitude sites in or near the study area. Precipitation and temperature relations to elevation were estimated from the PRISM data sets by calculating precipitation and temperature correction factors that correct climate measured at the climate stations to each model grid cell according to cell altitude and location. Thirty-year average monthly PRISM precipitation and temperature data sets provided relationships to extrapolate high altitude climate from the low altitude climate stations on a daily basis.

The common period of available record used from these weather stations was a 32-yr period from 1976 to 2007, which corresponds to the period used for model calibration. A 40-meter digital elevation model (DEM) was used to delineate the watershed boundaries and streams. Other digital data include slope and aspect (derived from the 40-meter DEM), soils data from the 1:250,000 State Soil Geographic database (STATSGO; USDA, 1991), and land cover for computing vegetation type and canopy density. The 40-meter 2001 National Land Cover Data (NLCD) database (http://www.epa.gov/mrlc/nlcd-2001.html; accessed 2/1/2013) was used to determine the dominant vegetation type, percentage of impervious surface, and vegetation canopy density for each model cell. Vegetation and impermeable surfaces data reflect conditions from 1998 to 2000 and are assumed constant over the entire simulation period.

Basin fill thickness was inferred from well data and geophysical data provided by Schaefer (1980) and Lopes and Allander (2009), and Blair and McPherson (1994). Basin-fill thickness was assumed to range from 180 m to 610 m with an average of 360 m. Geologic units for the model were broadly divided into unconsolidated sediments and consolidated rocks (Fig. 4). Geologic heterogeneity within these units was defined as part of the automated parameter estimation procedure using the pilot point procedure in Pest (Doherty, 2003, 2008). Model cells were set to a 400 m $\times$ 400 m spatial resolution over the 3210 km^2 model domain; however, streams and canals were represented as sub-grid features and measured or interpolated geometries were used where available. The hydrogeologic framework model (HFM) was discretized vertically into 6 layers, and horizontally into approximately 20,000 active grid cells per layer, for a total of approximately 120,000 active cells. The HFM was divided into four basic geologic units, including: layer 1 as soil, 2–4 as shallow fluvium and alluvium, 5 as fluvium in mountain block channels and valley fill alluvium, and 6 as mountain block. Thicknesses for layers 1, 2–4, 5, and 6 ranged from 0–4 m, 1–20 m, 7–325 m, and 2000 m, respectively. Based on the steep topography near the watershed divides, no-flow boundary conditions were assigned along the edges of the model domain that coincide with watershed divides.

Boundary conditions were simplified as much as possible by locating the model boundary along natural physical boundaries of the system. In steep topography surface water divides likely correspond to groundwater divides. However, in valley areas that connect adjacent basins, groundwater flow across the model boundary and specified-head boundaries developed from groundwater levels are required to simulate flow through these boundaries (inter-basin groundwater flow). Additionally, because only the lower portion of the Walker River basin is included in the model, a river inflow boundary condition was used where the Walker River enters the model domain. This boundary was strategically located where a USGS stream gage (Wabuska streamgage) has collected continuous streamflow data for the period 1903 to present, with some discontinuities that were reconstructed using proxy data. Because GSFLOW simulates most hydrologic processes as internal fluxes through coupling of process equations, very few external boundary conditions are required. Other than specified-head and river inflow boundary conditions, precipitation and temperature data sets are the only other boundary condition data required to force the model. Short wave solar radiation, which can be specified as a boundary condition, was derived from slope, aspect, season, and temperature internally by the model.

Total dissolved solid concentrations were simulated using a water and mass balance approach. River, runoff, groundwater, and precipitation inflows to Walker Lake were simulated by the flow model component of the DSS and associated TDS concentrations were calculated assuming conservative and complete mixing within the lake. TDS concentrations in lake inflows are very dilute,

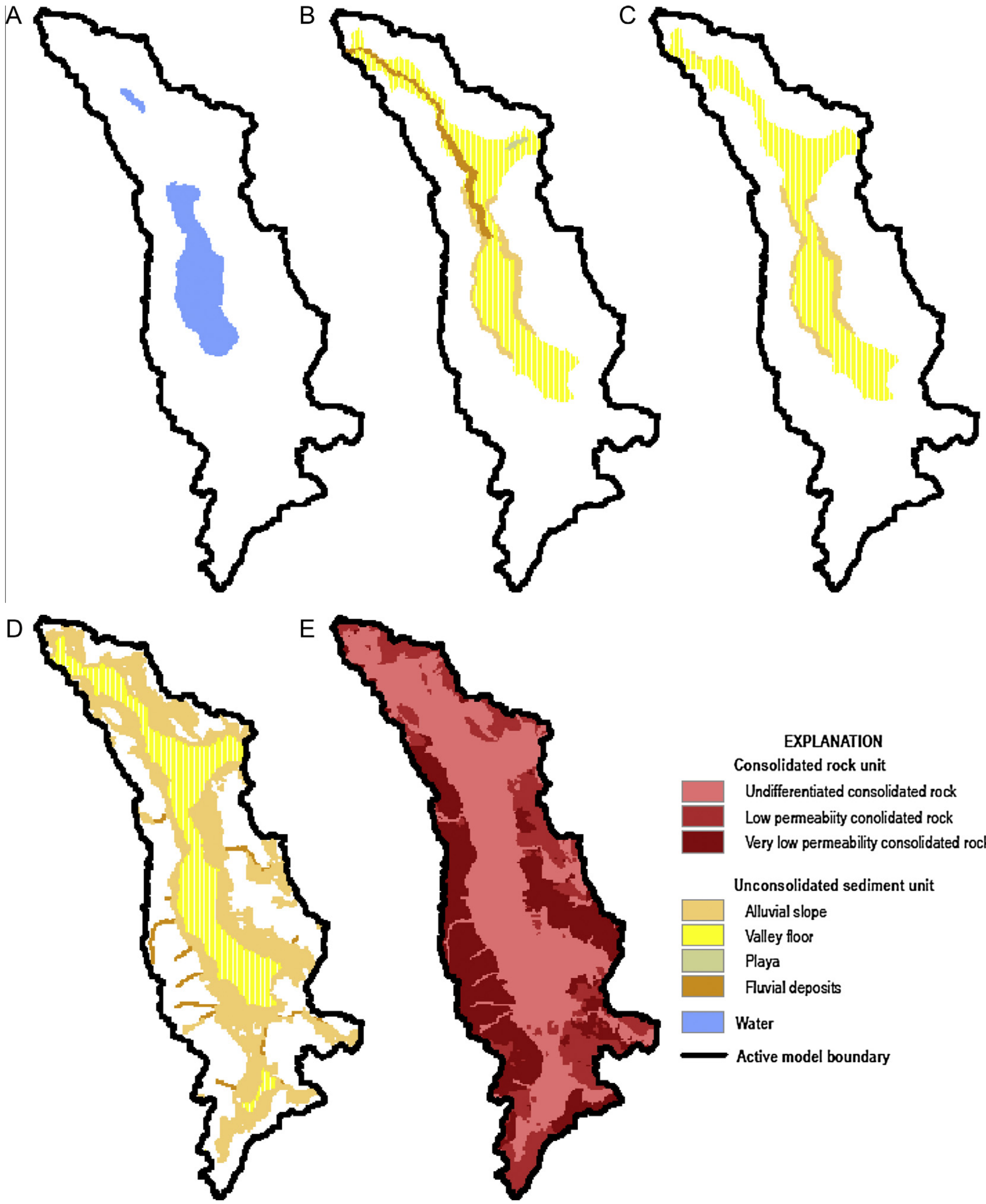

Fig. 4. Map of hydrogeologic framework for the Lower Walker River basin.

and only had the effect of diluting the TDS concentrations in the lake. Thus, increasing inflows to the lake lower TDS concentrations in the lake. Lake outflows consist of evaporation and lake seepage to groundwater. Lake evaporation increases the TDS concentrations in the lake by decreasing the amount of water in the lake and not changing the mass of TDS. Dissolution of salts on the dry lakebed is not included in the model.

3.2. Calibration

For calibration purposes, the hydrologic model was forced with historical temperature and precipitation observations during a 37-yr historical period (1976–2007). The model was calibrated using a 3-step process (Markstrom et al., 2008). For the first step of the calibration process, the surface water component of the model (i.e., PRMS) was calibrated independent of the groundwater system for the 37-yr period by matching externally estimated regional water balances and observed streamflows. PRMS was calibrated by adjusting parameters that affect the distribution of solar radiation and potential ET in order to match the average flow of water through the watershed and observed annual water balance. Spatial distributions of PRMS parameters that represent physical and hydrologic properties of soils were estimated from maps provided by the STATSGO database and maps of surficial geology (USDA, 1991; Maurer et al., 2004). These spatially distributed properties were then adjusted during the calibration procedure by scaling the magnitude of each soil parameter distribution. Time steps used in the model ranged between 1 day and 7 days.

The groundwater component of GSFLOW (i.e., MODFLOW-NWT) was calibrated using monthly averaged rates of deep percolation and net ET demands provided by PRMS. MODFLOW-NWT was calibrated to streamflow measured in the Walker River and mountain tributaries, groundwater level measurements, lake stage levels, and externally estimated regional water balances.

Additionally, the model was calibrated such that simulated water use matched measured water use amounts, including natural and agricultural ET (Allander et al., 2009; Huntington and Allen, 2010). Aquifer property parameters for horizontal hydraulic conductivity, vertical hydraulic conductivity of the alluvial aquifer, Walker Lake lakebed hydraulic conductivity, and maximum potential evapotranspiration of groundwater were calibrated using automated calibration with pilot points and Tikhonov regularization provided by PEST (Doherty, 2003, 2008; Hunt and Doherty, 2006). Tikhonov regularization was used to impose prior information about hydraulic conductivity on the basis of geology and other qualitative and quantitative estimates of hydraulic conductivity. Pilot points provided a means of modifying hydraulic conductivity within geologic units if these changes improve correspondence between measured and simulated values.

A total of 129 parameters were estimated through calibration of the hydrologic model, including parameters that control the magnitude of potential lake evaporation, Walker River inflow during steady-state period, maximum potential evapotranspiration of groundwater, vertical hydraulic conductivity of alluvial aquifer, lakebed conductance for Walker Lake, lakebed conductance for Weber Reservoir, streambed conductance for Walker River upstream of Weber Dam, and streambed conductance for Walker River downstream of Weber Dam. Horizontal hydraulic conductivity was distributed using a total of 194 pilot points in five layers at 66 mapped locations and were represented by a total of 121 parameters (Fig. 5). Observation data used to estimate model parameters included lake stages, streamflow, groundwater levels, and measured lake evaporation (Fig. 5).

3.3. Management scenarios

Management scenarios are being developed in consultation with water managers and stakeholders. These scenarios are being evaluated using 60-yr simulations, representing the period 2011–2070. Management scenarios represent feasible modifications to historical water allocations. In order to evaluate improvements to Walker Lake due to changes in water management, management scenarios are compared to a baseline scenario. The baseline scenario model is essentially the calibrated model extended 5 yrs using measured observation data and an additional 60-yr projection period. The Baseline Scenario model begins October 1918 and simulates the hydrologic system through the end of September 2010 based on historic conditions, and projects hydrologic conditions starting water year 2011 through end of September 2070. The first set of management scenarios consider improvements in project irrigation efficiencies that represent the effects of lining water delivery canals, and more efficient irrigation practices, including conversion from flood to sprinkler-based irrigation. The second set of management scenarios are additional streamflows at Wabuska stream gage that represent water right transfers. Flows were increased at the Wabuska stream gage by 308, 925, 1850, 3084, 4934, 6167, and 9251 hectare-meters/yr for two different approaches of management of Weber Reservoir (i.e., pass through and no pass through).

Collaborative modeling is iterative in order to disseminate knowledge gained from the DSS for future scenario development, adaptive modification of scenarios, and implementation of management options. As depicted in Fig. 6, collaborative modeling with stakeholders and water policy institutions provides management change options in the form of water use scenarios. In addition, climate scenarios that are of interest for evaluating management change options also are constructed through interaction with stakeholders. Water use and climate scenarios are incorporated into the DSS to produce outcomes that are then evaluated by stakeholders to refine management change options.

4. Results

4.1. Calibration

Fig. 7 shows comparisons of simulated Walker Lake stage with observed stage data. Generally, the hydrologic model is able to simulate lake stage, rate of decline, and responses of lake levels to streamflow variability over time. Simulated lake stages are biased low by about −0.08 m, and have a standard deviation of residuals of about 0.6 m. The model's ability to simulate groundwater conditions is shown by comparing simulated and observed groundwater hydrographs at selected locations (Fig. 8). All water level observations are from within the basin fill aquifer. Hydraulic properties of the consolidated rock units were calibrated by synthetically deriving observed groundwater heads equal to land surface where streams were known to be perennial and where springs existed in the mountains (Huntington and Niswonger, 2012). Fig. 9 shows all the simulated and observed groundwater levels as compared to the 1 to 1 line (perfect fit) for reference. The overall standard deviation of residuals is 11.8 m with an overall bias of the model to under simulate water levels in the basin fill aquifer by −2.7 m.

There is generally a good agreement between simulated and observed streamflows during both high flow and low flow conditions at all three streamflow gages on the Lower Walker River. Simulation bias in streamflow is 1%, 7%, and 1% at Walker River at Little Dam, Schurz, and Lateral 2a, respectively (Fig. 10). There also are two stream gages in the Wassuk Range that were used for model calibration and to evaluate hydrologic simulation in the mountains. These gages indicate that the mountain streams produce relatively small amounts of runoff to the lake for intermittent periods; the model simulated the timing and magnitude of these small streamflow events generally well.

4.2. Baseline simulation of water management

The LWRB model was modified to predict a baseline projection 60-yrs into the future based on a set flow criteria (Baseline Scenario). The baseline scenario model (LWR-BAS) was used to simulate the historical period with an additional 60-yr projection (i.e., water years 1918–2070). Streamflow at Wabuska is observed streamflow through September 2010, and then beginning in October 2010 (beginning of water year 2011) repeats 30-yr streamflow record observed at Wabuska for water years 1981 through 2010 twice. This period of historical conditions was used as it provides a representative mix of drought and wet period cycles that are statistically consistent with historical conditions. Additionally, repeating historical climate conditions for projected conditions received the greatest support by stakeholders. Although climate models project warming conditions into the future, these trends were not represented in the projected simulations in accordance with stakeholder agreements. However, this 30-yr period was slightly modified to normalize the bias of the period with respect to the long term mean annual flow by substituting the extreme runoff year of 1983, which is unlikely to reoccur in any given 30-yr period, with the large but more average streamflow of water year 1995. For the 60-yr projection period, Weber Reservoir is operated at maximum operating stage of 1283 m, and all agricultural diversions are made in accordance with the irrigation demand of 22.7×10^6 m^3/yr. Uncertainties in future climate conditions, irrigation practices, and the relatively consistent historical relationship between water availability and water use supports the use of a constant demand rate, rather than calculating irrigation demand according to atmospheric variables and soil moisture states, as typically is done using GSFLOW (Morway et al., 2012; Huntington and Niswonger, 2012; Woolfenden et al., 2014).

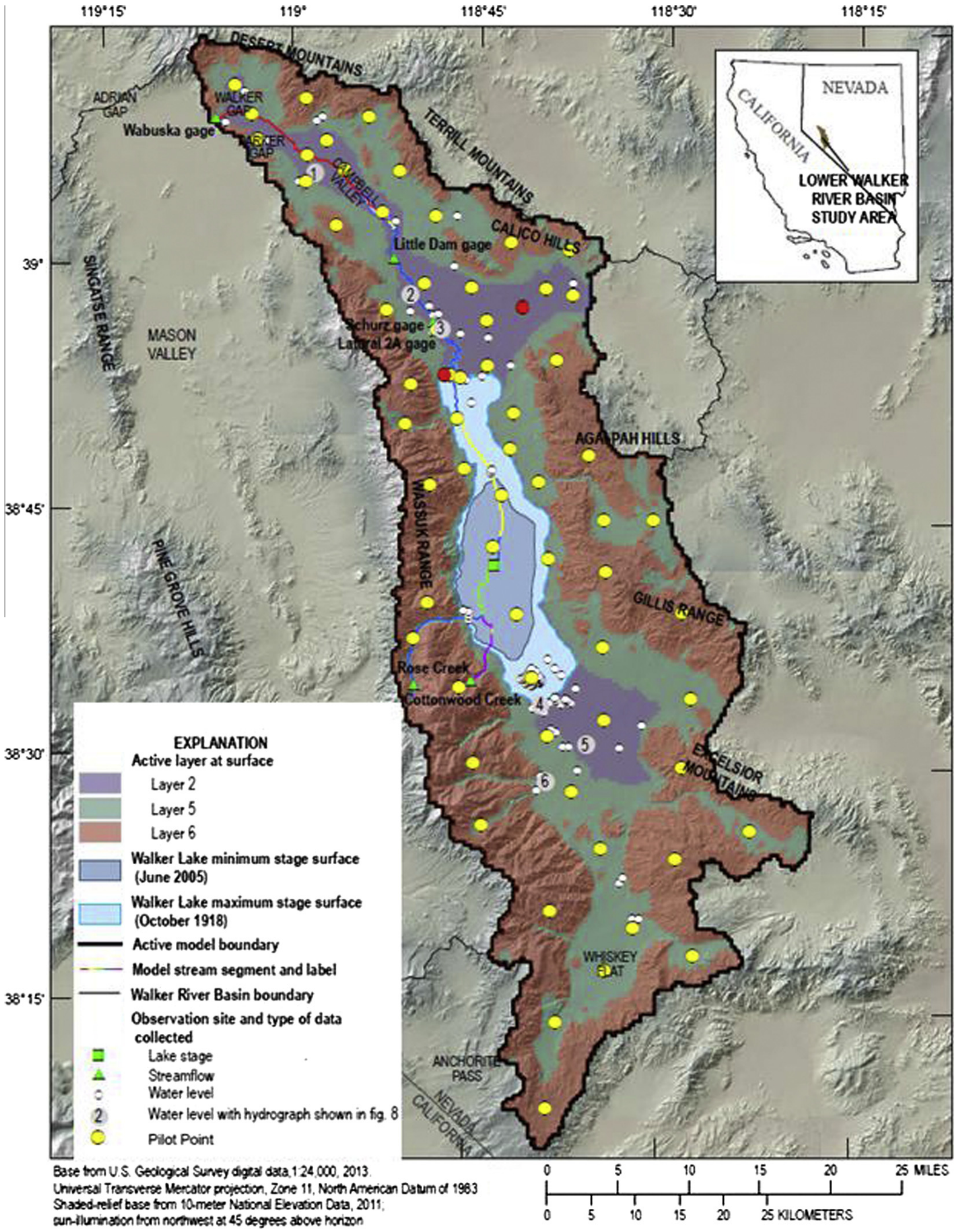

Fig. 5. Map of hydrogeologic units used for groundwater model of the Lower Walker River basin, including distribution of pilot points used for calibration, and change in lake surface area during simulation period. Locations are also shown for selected groundwater hydrographs shown in Fig. 8.

The 60-yr projected baseline scenario indicates that due to continued inflow deficit to Walker Lake, lake stage and volume will continue to decline and TDS concentrations will continue to increase (Fig. 7). Most notable for this scenario is the general behavior of TDS concentrations in Walker Lake. Lake volume fluctuations for the projected period are similar to those that occurred in the past (1981–2010); however, the resulting changes in TDS are much greater. This is due to the continual decrease in lake volume following 1981 that leads to a lower mixing volume in the lake, and therefore, greater variability in TDS. Accordingly, there is higher inter-annual variability of TDS concentrations as compared to the past when lake storage was greater. Of particular interest is the increase in TDS concentrations simulated between 2047 and 2054, which is synonymous with the drought period of 1987–1994. During this time, there was no inflow to Walker Lake from Walker River. TDS concentrations during this 8-yr period more than double from about 23,000 mg/L to about 58,000 mg/L (Fig. 7). This demonstrates that for a potentially smaller future Walker Lake, during droughts the rate of increase of TDS concentrations will be much greater than observed in the past. Similarly, reduced evaporation will enhance the benefits of above average years of precipitation that will dilute TDS concentrations.

The 60-yr projected baseline scenario indicates a groundwater budget that is not substantially different compared with the 30-yr period of 1981–2010 but does have greater fluctuations in groundwater storage due to a thicker unsaturated zone around the lake and adjacent to the river resulting in greater seasonal banks storage. Seepage from streams and lakes decreases relative

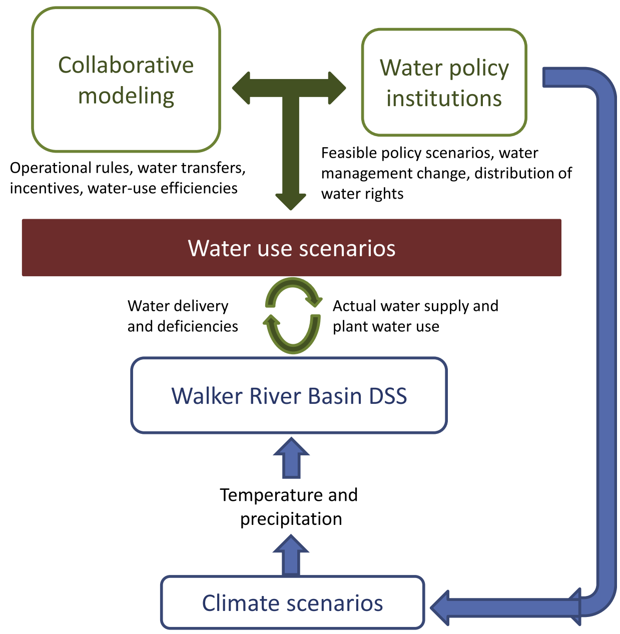

Fig. 6. Illustration showing management change development process.

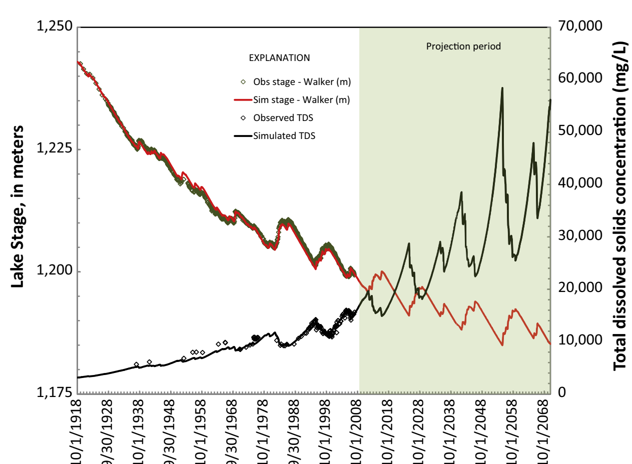

Fig. 7. Simulated versus measured Walker Lake stage and total dissolved solid concentrations for historical period and base case projection period simulation.

to the historical period due to the extremely wet year in 1983 that did not occur during the projected period. Additionally, lower lake levels result in lower groundwater levels surrounding the lake and an overall decrease in groundwater seepage to the lake. These decreasing inflow components are mostly offset by recharge from agricultural inefficiencies. Infiltration from irrigation is increased over the 2011–2070 period as compared with the 1981–2010 period because fallowing of fields that has occurred in the past was assumed not to occur during the projected period. These effects of surface water groundwater interactions on the response of Walker Lake to management change scenarios underscore the need for an integrated DSS.

4.3. Water use scenarios

4.3.1. Improved irrigation efficiencies

Water management scenarios were developed envisioning improved irrigation efficiencies manifested through changes in irrigation methods, such as conversion from flood irrigation to center pivot or drip irrigation methods and lining of irrigation canals. The efficiency scenario models (LWR-E%) start simulations beginning October 1918 and simulate the hydrologic system through the end of September 2010 relying on historical conditions (as with the LWB-BAS scenario). Improved irrigation efficiencies are superimposed on the baseline simulation starting water year 2011 through end of September 2070. The scenarios tested here are for irrigation project efficiency improvements of 5%, 10%, 15%, 20%, and 25% as compared to the historic efficiency of 40%. Improvements in irrigation efficiencies in these amounts were determined to be feasible on the basis of current agricultural practices and efficiencies, and presently available technologies that have been applied in other regions (Oweis et al., 1999; Pereira et al., 2002). Changes in irrigation efficiencies were simulated by reducing the water application rates to fields to represent a transition from flood irrigation to sprinkler systems. Similarly, improved efficiencies were simulated by setting hydraulic conductivity values to zero for canals to represent concrete lined canals. In each of these scenarios, a crop demand of 9 m^3/yr remains the same; however, improved efficiencies result in less evaporation from ponded water on fields, and less deep percolation of water beneath fields and canals. Thus, improved irrigation efficiency reduces recharge associated with agriculture and further exacerbates groundwater overdraft in the basin. The total irrigation demand amount is diverted whenever storage in Weber Reservoir is adequate for providing the demand – otherwise the model uses only available water to partly satisfy the irrigation demand (i.e., a reduced irrigated area). These practices are typical for growing alfalfa because alfalfa produces reasonable yields during deficit irrigation.

The 60-yr projected efficiency scenarios indicate that improvements in irrigation efficiencies will result in increases in volume and stage of Walker Lake and decreases in TDS concentrations, and increased crop consumptive use (Fig. 11). Fig. 11 shows the results in terms of relative increases in Walker Lake volume and crop consumptive use and relative decrease in Walker Lake TDS concentrations as compared with the baseline scenario at the end of the 60-yr simulation period. Table 1 shows the percent increase in lake volume, percent decrease in lake TDS concentrations, and percent increase in crop consumptive use for the 5 levels of irrigation efficiency improvements. Each of the efficiency simulations still result in declining levels for Walker Lake and increasing TDS concentrations over time indicating that improvements in irrigation efficiency in the LWRB is not sufficient to stabilize Walker Lake levels and TDS concentrations (Fig. 12). Additionally, results indicate that there is a diminishing benefit as irrigation efficiencies increase due to decreases in groundwater recharge that would otherwise provide recharge for groundwater extraction and reduce seepage losses from the river and lake, a result that would not have been evident without an integrated DSS.

As would be expected, the efficiency scenarios indicate that with improvement in irrigation efficiency, the frequency of recurrence of full irrigation seasons increase. For this analysis, a full irrigation season occurs when 90% or greater of seasonal irrigation demand is met. The baseline scenario resulted in 34 out of 60 yrs, or 57% recurrence of full irrigation seasons. Table 1 lists the increases in the percent of years during which the full irrigation is met. Accordingly, improved irrigation efficiency provides additional water that increases production for the current agricultural areas. However, because of severe water deficit for agriculture in the LWRB, improved irrigation efficiencies do not improve conditions in Walker Lake relative to present conditions. Rather, improved irrigation efficiencies reduce the worsening trends in Walker Lake storage and TDS concentrations (Fig. 12).

4.3.2. Increased streamflows from upstream water right transfers

Water rights transfers provide another management tool for delivering additional streamflow to Walker Lake. Although the

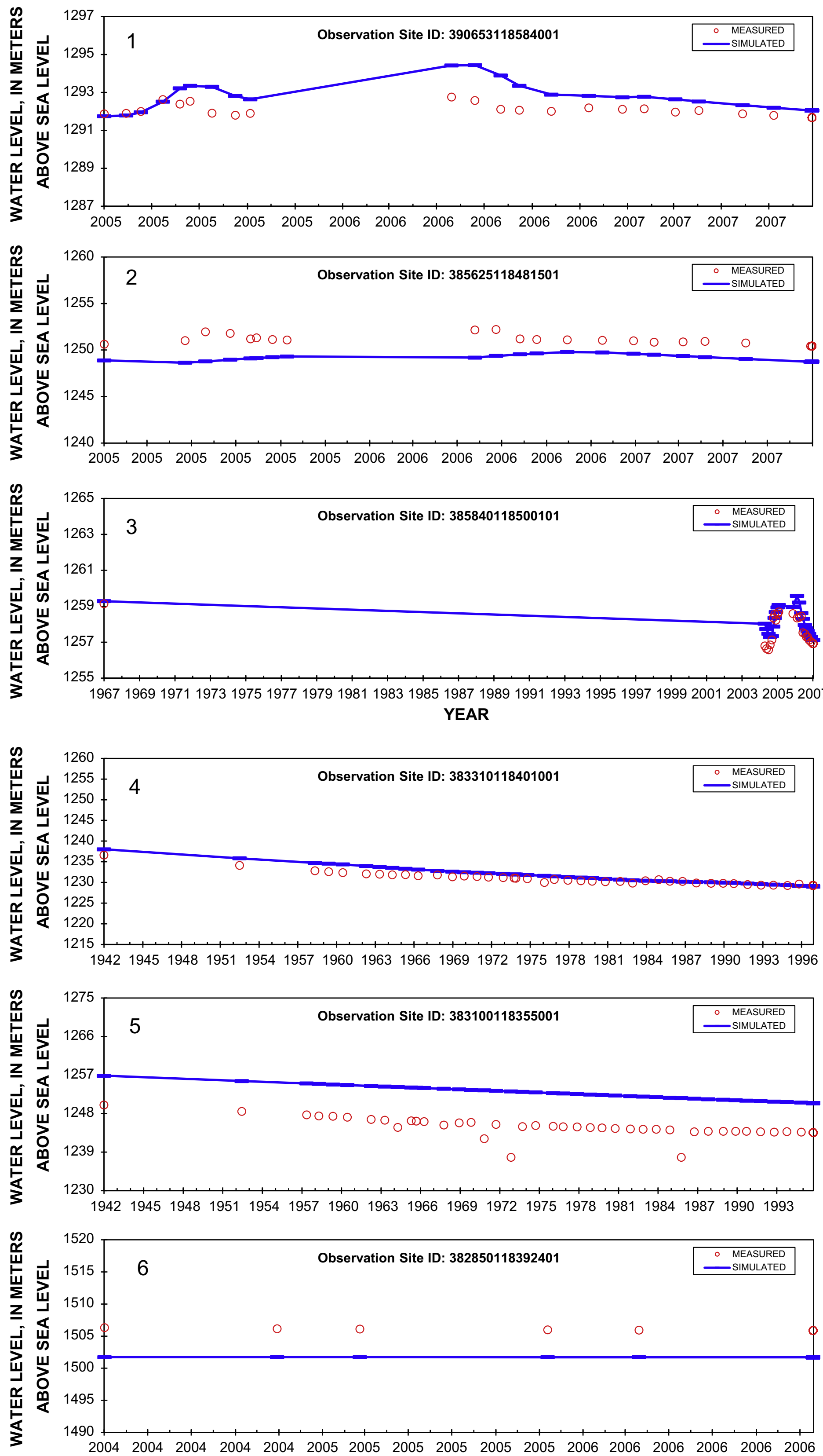

Fig. 8. Measured verses simulated groundwater hydrographs for selected wells in the Lower Walker River basin.

water right transfers simulated herein are hypothetical at this point in the Walker Lake management plan, the legal framework for water right transfers has been established for the Walker River basin (http://images.water.nv.gov/images/rulings/6271r.pdf). A water right is transferred from an existing water right holder in the Middle Walker River (MWR) basin by allowing water normally

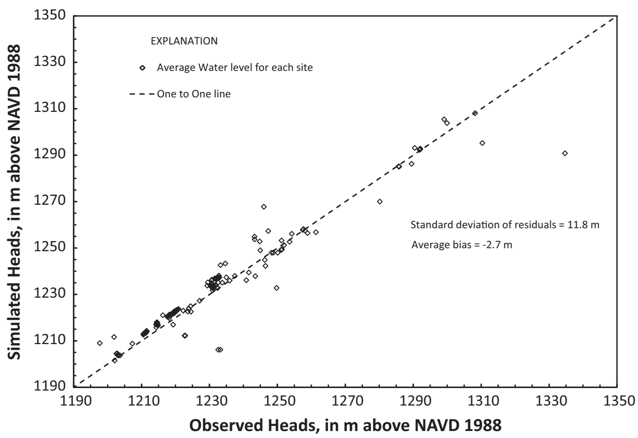

Fig. 9. Graph of measured and simulated groundwater levels for all wells in the Lower Walker River basin that were used for model calibration.

diverted to remain in the river. To simulate this change in water use, the LWR-BAS model again was modified such that the water right amount was allowed to pass the point of diversion and flow downstream toward Walker Lake. As with the LWR-BAS (baseline) scenarios, the water right transfer scenarios (MWR-Q) simulate the period 1918–2070, with the management change implemented for the period 2011–2070. Other than the water rights transfers and the implementation of a pass-through option at Weber Reservoir, all other aspects of the simulations are identical to the baseline simulation (LWR-BAS). In these simulations, inflow through the model boundary at the Wubuska stream gage due to water rights transfers was increased to evaluate the benefits to Walker Lake (Table 2).

Each of the MWR-Q scenarios is run using both non-pass-through and pass-through options for Weber Reservoir management, referred to as MWR-QNP and MWR-QP, respectively. The MWR-QNP option assumes that management of Weber Reservoir continues as it has been managed in the past, where all available flow is stored in the reservoir with flows only allowed to pass downstream when maximum operating stage in the reservoir is exceeded. MWR-QNP assumes water rights transferred from diversions in the MWRB are available to satisfy water rights in the LWRB. MWR-QP assumes that the water rights transferred from the MWRB are allowed to pass through the Weber Reservoir and move downstream toward Walker Lake. For MWR-QP, additional streamflow entering at Wabuska streamgage is not available for agricultural use, and agricultural diversions remain the same as in LWR-BAS. The main purpose for evaluating these two different management approaches is to demonstrate and compare how management of Weber Reservoir and associated agriculture in the LWRB influences the amount of water that reaches Walker Lake for a range of water rights transfers.

The MWR-Q scenarios indicate that increases in streamflow deliveries to Wabuska stream gage will result in increases in volume of Walker Lake and decreases in TDS concentrations. These scenarios also indicate that the management of Weber Reservoir plays an important role in how much water flows into Walker Lake. Fig. 13 shows the results of the MWR-Q scenarios as percent increase in crop consumptive use, and percent decrease in Walker Lake TDS concentrations at the end of the 60-yr projected period relative to the LWR-BAS scenario. Additionally, MWR-QNP scenario results indicate that increased flows at Wabuska stream gage increase lake stage at the end of 60-yrs by 183% relative to the baseline scenario (Table 2). Although these relative increases seem large, because the baseline conditions of the lake are so poor the TMDL standard is met only for the greatest inflow amount. MWR-QP scenarios resulted in modest increases in lake stage relative to MWR-QNP. Crop consumptive use in MWR-QNP scenarios increases with water rights transfer amounts up to 12%, indicating that a portion of the water transfer is used to help satisfy agricultural demands in the LWRB (Table 2). Although water rights transfers reduce the worsening trends in lake stage and TDS, all but the

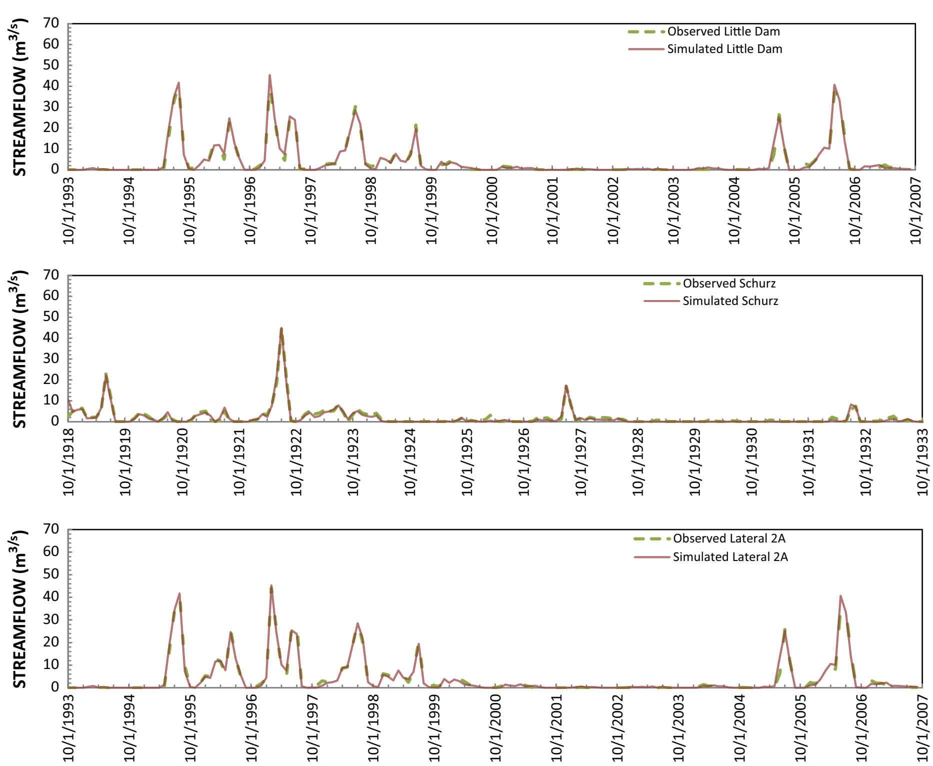

Fig. 10. Graph of measured and simulated monthly average Walker River flows for the Little Dam, Schurz, and lateral 2A stream gages.

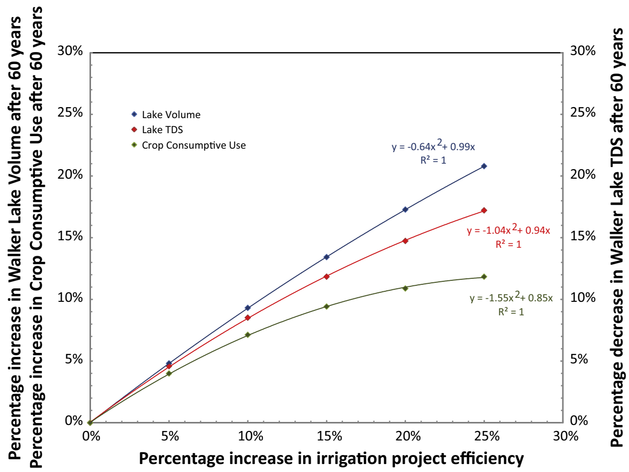

Fig. 11. Graph of simulated Walker Lake percent changes in volume, total dissolved solid concentrations, and Lower Walker River basin crop consumptive use at the end of the 60-yr projection period for improved irrigation efficiency management change scenarios.

Table 1
Increase in lake stage, percent change in lake TDS concentration, and percent change in crop consumptive use at the end of the 60-yr projection period with changes in irrigation efficiency.

% Increase in irrigation efficiency	0	5	10	15	20	25
Increase in lake stage (m)	0	1.1	2.1	3	3.8	4.5
% Decrease in TDS concentration	0	5	9	12	15	17
% Increase in crop consumptive use	0	4	7	9	11	12
% Recurrence of full irrigation season	57	68	82	85	90	95

two largest water rights transfers (6167 and 9251 hectare-meters/yr) result in no change or continued lake storage decline and increased TDS during the 60-yr projection period (Fig. 14). The MWR-QP scenario for the water rights transfers of 6167 and 9,251 hectare-meters/yr resulted in modest increases in storage and decreases in TDS concentration for the 60-yr simulation period as compared with the volume and TDS levels at the beginning of the forecasted simulation period in 2011. Only the greatest water right transfer (i.e., 35% of total agricultural consumptive use) resulted in average TDS concentrations less than the TMDL standard at the end of the 60 period (Fig. 15). These results are

Table 2
Increases in crop consumptive use and Walker Lake stage due to water rights transfers to Walker Lake.

Increased flow at Wubuska gage, hectare-meters per year	308	925	1850	3084	4934	6167	9251
% Increase in crop consumptive use	2	6	9	12	12	12	12
% Increase in Walker Lake stage	5	19	39	65	102	125	183

significant because of their influence on stakeholders to participate and adopt particular management changes.

5. Discussion

Walker Lake is a terminal lake that has undergone severe degradation due to river diversions for agriculture over the last century. Because there is broad support by stakeholders and institutions to restore the lake, there is an opportunity to change water management and improve in-stream flow and provide additional inflow to the lake to increase storage and decrease TDS concentrations. However, due to complex water allocation practices, distributed river water diversion points, conjunctive use of surface water and groundwater, and competition among water users with varying water priorities, system response to management change is not straightforward. As illustrated herein, water rights transfers intended to restore conditions in Walker Lake may not benefit the lake unless anthropogenic and hydrologic processes that occur downstream of water rights transfers are considered, such as streamflow capture by wells, reservoir evaporation, riparian transpiration, surface water groundwater interaction, and diversions. Thus, it is necessary to evaluate the resulting amount of water that reaches the lake that is associated with the proposal of a particular water right transfer or improved water use efficiency. This analysis is greatly benefited by a DSS with integrated hydrologic simulation capabilities.

An important implication of the water rights transfer scenarios is the role that water use in the LWRB plays on improving conditions in Walker Lake. Because agriculture in the LWRB has historically been water limited, additional water passing to the lower basin helps satisfy irrigation demands and lessens the benefit to

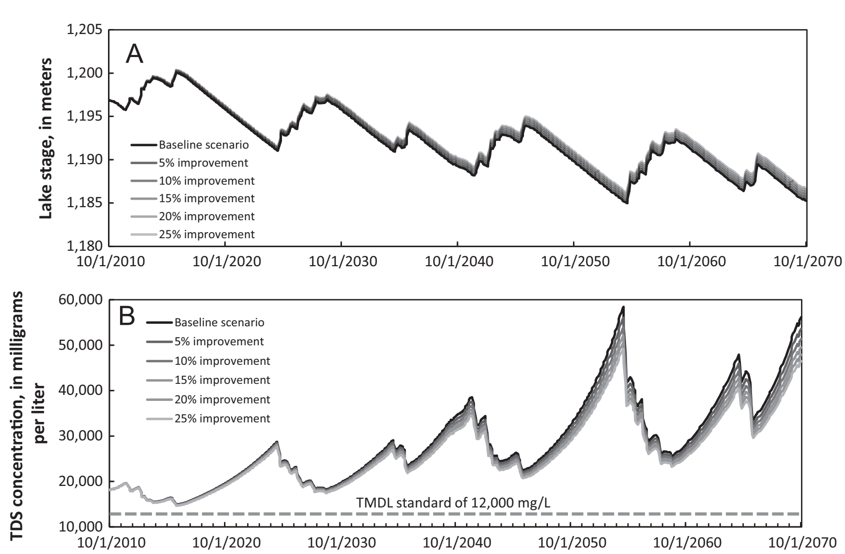

Fig. 12. Graphs of percent (A) changes in stage, and (B) total dissolved solids concentrations in Walker Lake for irrigation efficiency scenarios.

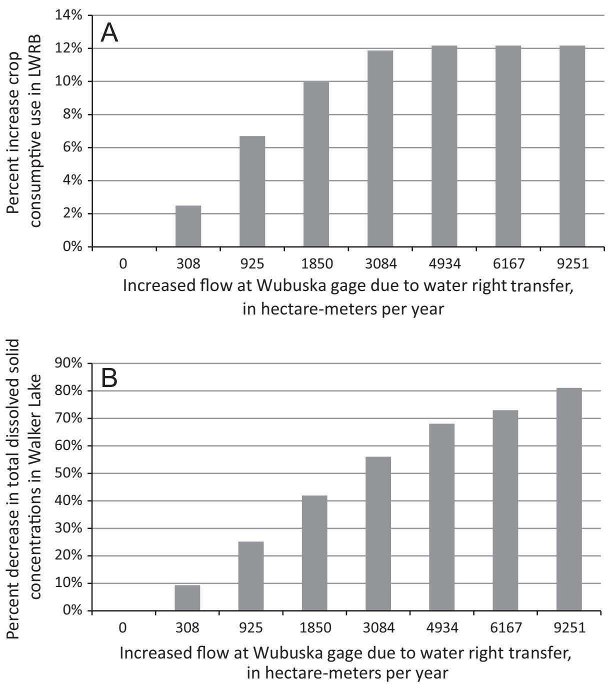

Fig. 13. Graphs of percent (A) increase in crop consumptive use in the Lower Walker River basin, and (B) decrease in total dissolved solid concentrations in Walker Lake for water right transfer management change scenarios.

Walker Lake (Fig. 13a). Agriculture in the LWRB is owned by the Paiute Tribe that has been heavily affected by development in the MWRB. Competing water needs create political and social tensions that deter efforts to make management changes. As illustrated by the results presented herein, the DSS helps to inform stakeholders of likely outcomes to maintain appropriate expectations for the implementation phase of management changes to restore Walker Lake. Our results suggest that only the largest water rights transfers (i.e., increased flows at the Wabuska stream gage) considered herein in the MWRB are sufficient to improve the lake relative to present day conditions, and water rights transfers must be accompanied by participation from the agriculture sector in the MWRB and LWRB to maintain instream flow and provide these transfers to the lake. The largest water right transfer is effective in restoring TDS concentrations to below the TMDL standard for ecological functioning; however, this transfer represents 35% of the total agricultural water use. Management changes of this magnitude represent significant challenges for water resources managers tasked to improve Walker Lake.

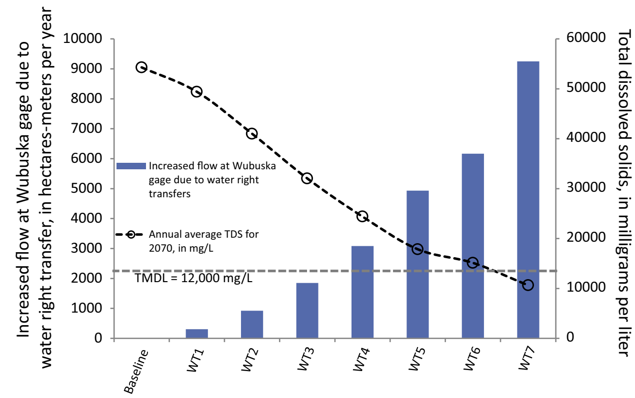

Fig. 15. Graph of annual average total dissolved solid concentrations at the end of the 60-yr projection period for increased flows at Wubuska gage due to simulated water right transfers (WT1–WT7).

In addition to water rights transfers, other changes in water management are being evaluated in order to increase the amount of water flowing to Walker Lake. Increased water use efficiency is being considered; however, in order to increase efficiencies significant investments are required to line canals and update to newer irrigation technologies. Stakeholders and associated institutions are challenged to make these investments while at the time stabilizing their water use and agricultural productivity. Scenario testing and the resulting simulated outcomes provide detailed information about the benefits to the lake resulting from improved irrigation efficiencies. Stakeholders are using this information to weigh the costs and benefits and reach a consensus on the best steps forward, while reducing surprising outcomes that jeopardize future participation in management changes to improve Walker Lake. As is typically the case for restoring natural resources,

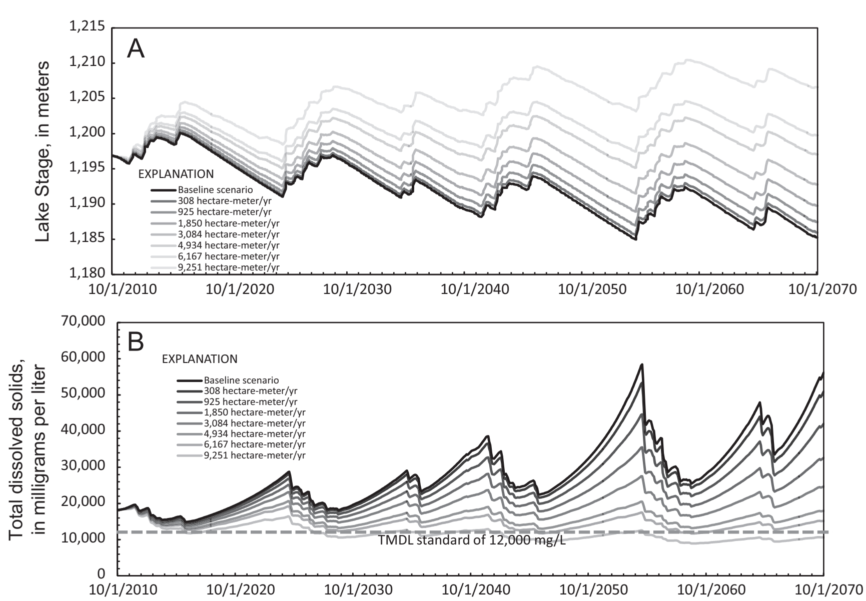

Fig. 14. Graphs of (A) lake stage, and (B) total dissolved solid concentrations for increased amounts of flow at the Wubuska gage due to simulated water right transfers.

multi-faceted management changes are required to realize significant benefits to Walker Lake. Improved water use efficiency is an important option for consideration, and the results presented herein provide important information for setting expectations in terms of benefits to the lake. Furthermore, the results indicate that there are other indirect factors to consider, including losses in groundwater recharge caused by improved irrigation efficiencies and changes in surface evaporation from Weber reservoir caused by changes in the amount of water stored in the reservoir. For example, greater irrigation efficiencies in the MWRB will result in losses in groundwater recharge and further exacerbate groundwater overdraft if pumping is not reduced.

In the Walker basin, tightly coupled interactions among climate, water management, surface water and groundwater require DSSs that can consider these interactions for accurately simulating outcomes related to changes in water management. Upstream water diversions have resulted in drastic storage decline and large increases in TDS in Walker Lake. Without integrated systems simulations provided by a DSS, outcomes of management solutions are very uncertain. For example, multiple jurisdictions can create conditions where efforts to restore the lake upstream may be hampered by increased water use lower in the basin. Knowledge about water use by stakeholders throughout the basin is necessary to develop management changes that result in the intended benefits. Because agricultural production in the basin has historically been water limited, there is a potential for water rights transfers intended to support the lake to be diverted for agricultural purposes. Participation in management changes by stakeholders in the lower basin is necessary to realize benefits to Walker Lake.

The results from this first set of water management change scenarios indicates that there is a potential to improve conditions in Walker Lake using management strategies that are feasible and agreeable by stakeholders and institutions within the Walker River basin. However, improvements to the lake are modest, required management changes are large in magnitude, and results have done much to calibrate expectations among stakeholders. Additionally, knowledge has been gained about the system; however, because of ongoing support to help restore Walker Lake, additional management change options will be explored with the aid of the DSS described herein. Based on the results of this first scenario analysis, information transfer will lead to new scenarios and modifications to those presented herein to further develop consensus to restore Walker Lake.

Feedbacks between water supply, management change, and water demand were not anticipated before the DSS was developed. For example, by explicitly simulating reservoir operations, water savings (or losses) were elucidated due to changes in reservoir evaporation associated with changes in reservoir management. Similarly, feedbacks between improved irrigation efficiency and groundwater recharge simulated by the model provide important information about how these management changes might affect other stakeholders that rely on groundwater. Decreases in recharge associated with increases in irrigation efficiency lower water table levels beneath Walker River, which increase seepage losses from the river (or reduce groundwater seepage to the river) and thus, reduce the amount of water flowing to Walker Lake. Groundwater surface water interactions are especially important during low flow periods when fish are trapped between impassible river reaches. Integrated simulation of surface water and groundwater provides important information about the amount of water required to achieve increases in lake storage (and therefore reductions in TDS) due to the large amount of aquifer storage around the lake that must be filled to restore lake levels. Surface water groundwater exchanges are important for simulating low river flows and the response of Walker Lake to changes in climate and water management. All of these feedback processes evolve in the model due to coupling of governing equations; simpler non-integrated modeling approaches neglect these feedback processes and thus require the scientist to try and anticipate important feedback processes independent of the DSS.

Significant resources are required to develop a DSS as presented herein to evaluate changes in management and provide simulated outcomes to stakeholders in large terminal lake basins. However, these resources are small relative to the value of implementing successful changes in the management of water resources that have the intended benefits to stakeholders and society. DSSs that are used for management scenario testing may also avoid missed opportunities that are caused by poorly designed changes in management. Detailed knowledge is important when changing water management because failed outcomes discourage future stakeholder participation and create conflict. Advancement in integrated systems simulations for water resources provides a means for improving stakeholder involvement, management strategies, and maximizing societal benefits. An integrated systems approach that incorporates the latest technological advancements in integrated hydrologic simulation offers new benefits for evaluating proposed changes in water management in order to increase the likelihood that benefits are realized. There is some tradeoff between using a more sophisticated integrated modeling based DSS relative to using a simpler conceptual or decoupled DSS modeling components.

Ensemble simulations are useful for evaluating uncertainty and a broad spectrum of system response to various decision variables and ensemble analysis are easily done using simpler and thus more efficient DSS. Fully integrated hydrologic models require additional computations; however, the design of GSFLOW maintains relatively efficient simulations and thus can be used for ensemble analysis for a reasonable computational expense. Simulations presented herein were run on a standard desktop computer (Intel Xeon processer with 6 2.8 GHz processors) and required about 3 h to run the 152 year simulations.

Coupled nonlinear hydrologic processes make estimating the benefits of management change to Walker Lake challenging. Rigorous representation of surface water groundwater interactions, landscape transformation, conjunctive use, and agricultural sector management create complicated feedbacks that require integrated management and hydrologic simulation system analysis. Use of the integrated hydrologic model GSFLOW demonstrates the benefits of rigorous coupling of system components to accurately evaluate outcomes associated with management change. As integrated hydrologic models become standard tools for water resources analysis, improvements in water management will likely be realized in water stressed regions around the world. Here we demonstrate that large changes in management are required to restore Walker Lake (i.e., a 35% reduction in agricultural water use). However, with these proposed management changes, Walker Lake could be restored to its original beneficial uses.

6. Conclusions

The Walker Lake basin exists in a persistent state of water supply limitation. Competition for water has led to a loss of over 100 km^2 of lake area and a deterioration of lake water quality over the last century. Associated impacts include loss of recreation, fisheries, and migratory bird habitat. Innovative management changes have been proposed and stakeholder involvement has been broad, despite competition for limited water supplies. Goals for restoring the lake are being developed on the basis of Total Maximum Daily Load standard of 12,000 mg/L (NDEP, 2005). Such a target is needed for restoration activities in the Walker Lake basin because resources put toward restoring Walker Lake need to be met with measures of success to encourage maintenance and continued support of management changes that result in improvements to the basin.

Tightly coupled system components of a decision support system, including climate, management, hydrologic, and water quality components provide a means of evaluating system response to management change in this developed terminal lake system. Nonlinear feedbacks between climate, hydrology, water and land use, and landscape change require integrated simulation approach. Recent advancements in hydrologic simulation capabilities provide new tools for improving collaborative modeling. Here we have stressed the importance of integrated hydrologic modeling. Previous approaches for collaborative modeling have neglected feedbacks because they have relied upon uncoupled water policy, hydrologic, and climatic DSS components. In the present example of the Walker basin, realistic representation of coupled processes has led to confidence building among stakeholders and agreement regarding the need for management change for restoring the lake. Simulated management change options evaluated thus far have resulted in only modest improvements in the lake relative to present conditions, and these management changes are large in magnitude (i.e., 35% decrease in water use by the agricultural sector). However, projected worsening of lake conditions under a business-as-usual scenario indicates that management changes produce significant improvements. Stakeholder expectations have been calibrated through the collaborative modeling process and DSS, and future restoration efforts are better defined. Most significantly, the DSS indicates that Walker Lake could be restored to support recreation, fisheries, and other ecological functions if management changes are implemented as described herein.

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