Integrated Hydrology and Operations Modeling to Evaluate Climate Change Impacts in an Agricultural Valley Irrigated With Snowmelt Runoff

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Abstract Applying models to developed agricultural regions remains a difficult problem because there are no existing modeling codes that represent both the complex physics of the hydrology and anthropogenic manipulations to water distribution and consumption. We apply an integrated groundwater – surface water and hydrologic river operations model to an irrigated river valley in northwestern Nevada/northern California, United States to evaluate the impacts of climate change on snow-fed agricultural systems that use surface water and groundwater conjunctively. We explicitly represent individual surface water rights within the hydrologic model and allow the integrated code to change river diversions in response to earlier snowmelt runoff and water availability. Historically under-used supplemental groundwater rights are dynamically activated within the model to offset diminished surface water deliveries. The model accounts for feedbacks between the natural hydrology and anthropogenic stresses, which is a first-of-its-kind assessment of the impacts of climate change on individual water rights, and more broadly on river basin operations. Earlier snowmelt decreases annual surface water deliveries to all water rights, not just the junior water rights, owing to a lack of surface water storage in the upper river basin capable of capturing earlier runoff. Conversely, downstream irrigators with access to reservoir storage benefit from earlier runoff flowing past upstream points of diversion prior to the start of the irrigation season. Despite regional shifts toward greater reliance on groundwater for irrigation, crop consumption (a common surrogate for crop yield) decreases due to spatiotemporal changes in water supply that preferentially impact a subset of growers in the region.

Plain Language Summary Warming temperatures associated with climate change will result in earlier snowmelt. This will impact agricultural systems that depend on snowmelt-derived surface water for irrigation. We present a model that dynamically links water use as dictated by prior appropriations law (i.e., priority based on first date of beneficial use) with groundwater use to augment surface water shortfall (i.e., “conjunctive groundwater use”). Simulations of water availability and water use patterns in a complex conjunctive-use agricultural basin fed by snowmelt are evaluated for a 35-year simulation period subjected to incremental atmospheric warming of 1°–5°C.

1. Introduction

Management of water resources in basins that conjunctively use surface water and groundwater requires an understanding of groundwater-surface water interactions and how those interactions are affected by water use and climate variability. Water use within a basin depends on the physical factors that control water availability throughout the system and the operational framework that governs water allocation. Interactions between the natural, physically based runoff-hydrology and the non-natural (i.e., anthropogenic) water operations can influence the spatial and temporal availability of water throughout a regional hydrologic system, resulting in complex nonlinear feedbacks between supply and demand (Sivapalan et al., 2014).

The greatest consumption of fresh water in the United States (US) is for irrigation, particularly in the arid western US (Maupin et al., 2010). Surface irrigation techniques (e.g., flood or furrow) are typically used on more than half of the irrigated land in the arid western US (Maupin et al., 2014). The spatial and temporal variability of irrigation return flow and groundwater recharge impacts water availability throughout an
agricultural region, and access to groundwater provides growers with a stable water supply during periods of drought (Allander et al., 2014; Hornbeck & Keskin, 2011; Howitt et al., 2014; Niswonger et al., 2014; Scanlon et al., 2016). However, increased reliance on groundwater for extended periods can result in unsustainable water use and lead to depletion of groundwater resources, deterioration of aquifers, and environmental degradation (Sophocleous, 2000). Groundwater depletion also can impact surface water resources, further exacerbating surface water shortages (Barlow & Leake, 2012).

Planning for future conditions requires a paradigm that represents the complex interactions between natural and human influences on hydrology. Anthropogenic modifications to hydrologic systems and climate change have called into question the underlying assumption of statistical stationarity on which many water management and water governance systems were designed (Milly et al., 2008, 2015). For example, recent and predicted climate trends show a tendency toward earlier snowmelt in the western US, resulting in a shift in the timing of streamflow and diminished spring snowpack (Barnett et al., 2005; Dudley et al., 2017; Stewart, 2009; Stewart et al., 2005; Sun et al., 2018). A wide range of water use sectors, in particular the agricultural sector, are dependent on the seasonality of surface water supply and mountain snowpack has historically served as a seasonal storage reservoir.

In addition to topographic considerations, agricultural systems have developed downstream of snow-covered mountains because meltwater is typically delivered during the irrigation season (Barnett et al., 2005). Thus, a shift toward earlier snowmelt runoff poses a significant challenge for growers where upstream reservoirs are not available because much of the meltwater will flow through the agricultural areas before it can be legally diverted for irrigation. Moreover, it is often challenging for growers to adapt their irrigation practices to earlier snowmelt due to limited sunlight and increased risk of flood and freeze events that are more common during winter. Hence, a non-stationary shift toward earlier snowmelt runoff presents a global challenge; approximately one-sixth of the world population is supported by a food supply reliant on meltwater (Easterling et al., 2007). Furthermore, the global demand for food is projected to double by 2050 (Barnett et al., 2005; Tilman et al., 2002).

Given the challenge to agriculture posed by earlier snowmelt, there is a strong need for evaluating future impacts of climate change and developing adaptive management strategies that can increase water resources sustainability. Simulation models are an important tool for developing and evaluating adaptive management strategies before committing capital investment into project implementation. Water stressed snow-fed systems have and will continue to increase their reliance on groundwater where possible to make up for surface water shortfalls during the growing season. This, in turn, exacerbates over drafting of available groundwater supplies. Therefore, models of conjunctive-use systems need to simulate not only runoff quantities, but also need to represent the relative timing of runoff to dynamically represent surface water diversions and groundwater extraction in support of water resources decision making.

One of the important challenges for adapting to climate change has been a lack of response by stakeholders to change their water use practices. This may be due, at least in part, to models that do not adequately portray future impacts of climate change across all water right priorities. In many basins historical experience may suggest that being in the upper reaches of a river basin and/or having high-priority water rights is a built-in safeguard against altered river flows in response to climate change. However, as peak runoff transitions to earlier in the year, it is likely that all growers will need to adapt to climate change to sustain agricultural production. Broad support for adaptation within agricultural communities that includes low and high-priority water users is required to collectively change current water use practices and incorporate innovative water management strategies. Future modeling studies need to adequately address system-wide impacts of changes to water management and require consideration of feedbacks between changing climate, water availability, and water governance.

As the timing of streamflow changes in response to warmer temperatures and earlier snowmelt, water availability throughout an agricultural system may change in unexpected ways due to the legal framework governing water allocations. This precludes using historical records of diversions or estimates of crop demands to simulate the impacts of changes in the timing of streamflow associated with climate change. Decisions to irrigate are typically based on soil moisture conditions, experience, peer behavior, and established practices (Foglia et al., 2018). Previous studies have relied on: (a) models to simulate physical hydrology and surface
water-groundwater interactions with water distribution based on historical records (e.g., Githui et al., 2016; Tian et al., 2015), net irrigation requirements (e.g., Brookfield et al., 2017), or soil moisture conditions (e.g., Condon and Maxwell, 2014a, 2014b; 2013; Winter et al., 2017), (b) surface water distribution based on legal priority without consideration of groundwater (Kennedy-Jenks Consultants, 1998; Triana & Labadie, 2012), (c) surface water distribution based on legal priority with externally determined response functions for stream-aquifer interactions (e.g., Briand et al., 2008; Fredericks et al., 1998), (d) surface water distribution based on legal priority with groundwater simulated by an external model (e.g., La Marche, 2001; Valerio et al., 2010), or (e) surface water distribution based on legal priority with a loosely coupled groundwater model that does not necessarily ensure water balance for each time step (e.g., Marques et al., 2006). However, tightly coupled integrated operation-hydrology models that iterate on feedbacks have not been used, despite the significant impacts that these feedbacks have on water use and availability (Morway et al., 2016).

In this study, we present a model with the ability to represent coupled feedbacks between surface water, groundwater, and water governance structures. This model simulates the distribution of water based on individual water right priority, the legal framework governing water distribution, and water availability within the system. Rather than using historical trends of water allocation and use to infer water availability (e.g., streamflow and groundwater levels), our model explicitly represents the legal framework governing water allocation within a tightly coupled (i.e., integrated) river operations-hydrologic model (hereafter referred to as “operations-hydrology model”). This flexibility allows us to simulate water distribution throughout the system under unprecedented hydrologic conditions while still adhering to the legal framework dictating water allocation.

We use an integrated operations-hydrology model (Morway et al., 2016) that couples the river operations model MODSIM (Labadie, 2010) with the coupled groundwater-surface water flow model GSFLOW (Markstrom et al., 2008) we refer to this coupled model as MSGSF. We use MSGSF to evaluate the impact of projected next century climate change by superimposing an increase in temperature from 1° to 5°C onto the historical climate (e.g., Hay et al., 2000). This increase in temperature results in earlier snowmelt and significantly reduces water availability during the irrigation season. The MSGSF model allows us to simulate deliveries to water rights by priority, dynamic increases in supplemental groundwater use due to surface water shortfalls, and the associated groundwater – surface water interactions while still adhering to the legal framework in place. The model is calibrated to streamflow, groundwater head, satellite thermal and spectral reflectance measurements for evapotranspiration (ET) and snow-covered area, and pumping records for individual wells using the Iterative Ensemble Smoother (IES) approach implemented in the model independent parameter estimation software PEST++ (PESTPP-IES; Doherty, 2015; Doherty & Hunt, 2010; White, 2018; White et al., 2019).

Models that can represent coupled feedbacks between surface water, groundwater, and water governance structures have rarely, if ever, been applied to regional systems using high resolution representation of water use. However, it is difficult to evaluate impacts of climate and other system changes to individual growers without representing these complex processes and their feedbacks. Previous studies have shown that specificity in model results is important for building consensus, and stakeholder engagement must be established for participation in sustainability projects (Liu et al., 2008). Furthermore, as growers are aware that return flows, priority-based delivery, supplementary pumping, groundwater discharge to streams and canals, and curtailment of delivery due to surface water shortfalls all cause feedback within the system, model realism is an important factor for stakeholder engagement. In this work, we rigorously represent high resolution water use structures and complex hydrologic feedbacks to demonstrate new modeling approaches, and how they can be applied to regional-scale real-world problems. Previous studies have greatly simplified model representation of developed basins. Here, we go to great lengths to represent important feedback processes between water supply and water use to satisfy stakeholder expectations about how these systems work, and to better understand threshold responses associated with nonlinear feedbacks between water supply and water use. Development and evaluation of these types of models will benefit the broader scientific community by providing examples from which simpler model representations can be compared.

Our work aims to understand the extent to which high-priority water rights can insulate growers from the impacts of global warming in a snow-fed river basin. High-priority water rights have the highest value and are often associated with the largest capital investment to maximize productivity. Inherent in these...
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investments is the perceived guarantee or high likelihood of getting a full allocation of water rights during times of water limitations (Sterle et al., 2019). However, geographic and hydrologic conditions, and built conveyance systems cause deviations in the delivery of water that can be discordant with priority. MSGSF provides a framework to represent these factors to better understand how high-priority water rights may safeguard against the impacts of global warming.

2. Study Area

2.1. Site Characteristics

Carson Valley is an important agricultural area located in western Nevada and eastern California, south of Carson City, Nevada, and is an extensional basin located near the western edge of the Basin and Range province (Figure 1). The western edge of the valley is defined by the Sierra Escarpment, a large normal fault separating the Sierra Nevada to the west from the Basin and Range to the east. The eastern edge of the valley consists of a complex network of normal faults forming horsts and grabens in Plio-Pleistocene volcanic rocks, Plio-Pleistocene sedimentary rocks mostly derived from the volcanic rocks, Quaternary alluvium,

Figure 1. Modeling domains for the Carson Valley system. Flow is generally from south to north. Carson City is located approximately 5 km (3 miles) north of the model boundary.
and older granitic and metavolcanics bedrock (Armin & John, 1983; dePolo et al., 2000; Ramelli et al., 2003). Most agricultural land in the Carson Valley is located on fluvial deposits in the low-lying areas of the valley, with a small portion of agricultural land located on alluvial deposits. Snowmelt runoff from the adjacent eastern Sierra Nevada is the main source of inflow, providing for both surface water irrigation (SWI) and recharge to replenish groundwater. Carson Valley is representative of many other snow-fed agricultural basins in the western US and other similar latitudes globally that face decreased spring and summer streamflow due to climate change.

As flows in the river rise and recede in response to snowmelt, water rights in the Carson Valley dictate how the available water is distributed. Individual water rights were established based on the date that some portion of river water was first diverted and put to beneficial use (e.g., irrigation), commonly referred to as the prior appropriation framework or “first in time, first in right.” Prior appropriation is a common river management system throughout much of the western US. However, river basins that do not employ the prior appropriation doctrine often use a set of complex if-then rules to guide river management. Regardless of the legal framework governing water distribution from a river, the integrated MSGSF software used here and applied to Carson Valley is able to represent the complex spatial distribution of water rights with assorted priorities (1850s–1900s; Figure 2a) and can be readily transferred to other basins, assuming information about water right locations and priorities are available in addition to model inputs required for characterizing a basin’s hydrogeologic properties.

### 2.2. Water Resources

Water entering the Carson Valley is primarily derived from snowmelt runoff draining the high-elevation watersheds of the East Forks and West Forks of the Carson River in the northeastern Sierra Nevada. With maximum elevations of 3,494 m (11,464 feet), most of the precipitation falls as snow during the winter months and peak flows occur during the spring snowmelt pulse. These upper watersheds have a combined

![Figure 2](image-url). The location of (a) major streams grouped by administrative stream segment, surface water rights by priority decade, stream inflows, and surface water storage locations, (b) permitted point of diversion and place of use for groundwater rights used for irrigation and (c) areas permitted for application of treated effluent. Surface water flow is generally from south to north.
drainage area of 1.095 km² (270,600 acres) and consist mainly of low permeability granitic bedrock. Runoff occurs as overland flow and shallow subsurface flow in soils and decomposed granite. Accordingly, water drains quickly to the river when precipitation falls as rain or during snowmelt periods, and only a small portion of the streamflow hydrograph derives from groundwater. The average annual surface water inflow to the Carson Valley is approximately 428 million cubic meters (Mm³; 348,000 acre-feet) and the average surface water outflow is 332 Mm³ (269,000 acre-feet); surface water inflow from the East Fork of the Carson River, West Fork of the Carson River, and tributaries along the west side of the valley are 305 Mm³ (247,000 acre-feet), 86.8 Mm³ (70,000 acre-feet), and 37.0 Mm³ (30,000 acre-feet), respectively (Maurer & Berger, 2007; Maurer et al., 2004a, 2004b). The Carson Valley receives approximately 16 Mm³ (12,700 acre-feet) of additional water as subsurface inflow from the Carson Range and Eagle Valley on its western and northern boundaries, respectively.

A complex network of sloughs and canals are used to distribute surface water to approximately 158 km² (39,000 acres) of flood irrigated alfalfa and native pasture grasses (Figure 2a). Flood irrigation is the dominant method of irrigation in the Carson Valley and results in substantial groundwater recharge and surface water return flows that benefit water rights further downstream in the system. Annual ET from the basin fill sediments has been estimated to be approximately 180 Mm³ (146,000 acre-feet), with 144 Mm³ (117,000 acre-feet) from irrigated pasture grasses and alfalfa, 12 Mm³ (10,000 acre-feet) from native phreatophytes, 10 Mm³ (8,500 acre-feet) from open water (Maurer & Berger, 2007; Yager et al., 2012). The agricultural areas of Carson Valley receive approximately 230 mm (9 inches) of rain annually with nearly 80% falling during the non-irrigation season between October 1 and April 1.

Agricultural irrigation is the dominant use of groundwater in the Carson Valley, accounting for an average of 38% of the total groundwater withdrawals in the Carson Valley between 1980 and 2015. Historical records of annual groundwater withdrawals for agricultural irrigation range from approximately 7.0 Mm³ (5,700 acre-feet) in 1985 (53% of total annual pumpage) to approximately 3.8 Mm³ (500 acre-feet) in 1995 (19% of total annual pumpage; Clark, 2005; King, 2015; Maurer & Berger, 2007; Yager et al., 2012). This withdrawal is well below the 63.6 Mm³ (71,600 acre-feet) committed to irrigation by the Nevada Department of Water Resources (NVDWR; State of Nevada Division of Water Resources, 2017). The point of diversion (POD) for irrigation wells and the associated place of use (POU) are shown in Figure 2b.

Treated wastewater effluent is the second largest source of water (after Carson River streamflow) used for irrigation in the Carson Valley, accounting for approximately 12.4 Mm³ (10,000 acre-feet) per year between 1990 and 2015. To reduce nutrient loads and protect the clarity of Lake Tahoe, approximately 8.0 Mm³ (7,300 acre-feet) of treated effluent from the Lake Tahoe Basin is exported to the Carson Valley. The remaining 4.1 Mm³ (2,500 acre-feet) of treated effluent originates from communities in or around Carson Valley. The effluent is stored during the winter months and used to irrigate approximately 50 km² (12,350 acres) of land in portions of the Carson Valley during the irrigation season (Figure 2c.)

### 2.3. Operations

The Alpine Decree, the legally binding framework for river operations (i.e., water allocation), defines eight segments of the Carson River which are regulated autonomously and over 900 individual water rights within the Carson Watershed (United States v. Alpine Land and Reservoir Co., 1980). Our model covers the first six segments and includes 546 individual water rights. The Alpine Decree dictates that the Water Master, a federally appointed official in charge of distributing water for irrigation, will direct the distribution of surface water within a segment (Figure 2) based on the relative priorities of water rights specific to each segment. When there is not enough water to satisfy all water rights within a segment, the river goes on regulation and the junior water rights stop receiving water to continue providing water to the senior water rights. Furthermore, the Alpine Decree does not compel upstream segments to deliver a minimum amount of water to downstream segments. Together, these facets of the Alpine Decree essentially establish a nested priority system, where junior priority water rights along an upstream segment may be satisfied before more senior water rights in a downstream segment. As an example, junior priority water rights in an upstream segment (e.g., East Fork) can continue to take water and are not required to curtail their diversion to release water to a senior priority water right in a downstream segment (e.g., Main Carson River below the confluence of the East and West Forks for the Carson River).
Two other important stipulations to water distribution are included in the Alpine Decree: (a) When flow at the Gardnerville gage (U.S. Geological Survey [USGS] gage 10309000, Figure 2a) along the East Fork is less than 5.66 cubic meters per second (m$^3$s$^{-1}$; 200 cubic feet per second [ft$^3$s$^{-1}$]) irrigation is said to be “regulated” and one-third of the flow is diverted to the Allerman Canal and the remaining two-thirds stays in the East Fork for use further downstream (referred to as the “Allerman Split”) and (b) on the West Fork, the available water supply is rotated on a weekly basis between the California and Nevada segments and junior priorities in Nevada that do not receive direct diversions the previous week will be allowed to use return flows during the weeks when the California segment is being irrigated (referred to as the “West Fork Rotation”). As river flows diminish and there is not enough water to satisfy the most junior priority water rights, typically around the time flows at the Gardnerville gage fall below 5.66 m$^3$s$^{-1}$ (200 ft$^3$s$^{-1}$), flow in the river becomes regulated. When the river is operated under regulation the Federal Water Master adjusts irrigation deliveries based on water availability throughout the system and has been directed to “exercise discretion in distributing the water to meet the demands of the various land types...insofar as it is practical to do so” (United States v. Alpine Land and Reservoir Co., 1980). This flexibility ensures water is allocated based on priority during times of shortage but precludes the use of historical irrigation rates for future scenarios under different climatic conditions and resulting river flows.

There are five small freshwater reservoirs within the Carson Valley that are used for irrigation during the period considered in this study (1980–2015). The Alpine Decree states that all freshwater reservoirs in the Carson Valley can be filled from October to May, and the full capacity is distributed to the reservoir account holders by the end of the irrigation season. However, the storage rights have been transferred to a single reservoir (Mud Lake) or other uses. As such, Mud Lake is the only reservoir currently in use and the only reservoir represented in the model.

Expert testimony cited in the Alpine Decree suggests the net annual irrigation water requirement for flood irrigation in the Carson Valley is between 1.37 and 2.74 cubic meters per square meter (4.5 and 9.0 acre-feet per acre) depending on slope, soils, conveyance efficiency, and depth to groundwater. The subsequent opinion by Judge Thompson eliminated any specific duty from the Alpine Decree, ensuring water rights in priority receive adequate water for irrigation if it is available (United States v. Alpine Land and Reservoir Co., 1980). The irrigation system in the Carson Valley relies heavily on surface water and groundwater return flows (Unger & Tracy, 2006). Return flows from flood irrigation have been estimated to account for 20%–30% of the applied water during the period considered in the current study (Yager et al., 2012) and is consistent with efficiency estimates for flood irrigation used in other studies (Brookfield et al., 2017; Canessa et al., 2011; Gates et al., 2012; Githui et al., 2016). The model presented herein attempts to capture the dynamic nature of these irrigation practices.

3. Methods

In this study we use GSFLOW (Markstrom et al., 2008) and the MODSIM-GSFLOW modeling platform of Morway et al. (2016) and Niswonger et al., (2017) to explore the potential effects of climate change on water availability and water distribution in the Carson Valley, Nevada and California. The reader is referred to Figure 4 in Morway et al. (2016) and Figure 1 in Niswonger et al. (2017) for previously published schematics of the integrated model framework (also see the supporting information). The most consistent feature of future climate among global circulation model (GCM) results for the Sierra Nevada is an increase in temperature ranging from 0.0° to 5.0°C over the next century (e.g., He et al., 2018). Increased temperatures have already affected runoff to Carson Valley and are likely to substantially impact snowpack and snowmelt-derived streamflow in the future (Barnett et al., 2005; Berg & Hall, 2017; Schwartz et al., 2017; Stewart, 2009; Stewart et al., 2005; Young et al., 2009). This study simulates the impacts of increased temperature on snow accumulation and snowmelt in the upper watersheds, the associated change in the timing of streamflow entering the Carson Valley, and the impacts these changes have on water availability and distribution in a conjunctive-use basin governed by prior appropriations doctrine, where groundwater is often used to supplement surface water shortfalls. All models are discretized into 168 m (550 feet) square grid cells, approximately 1/10th the average area of water rights in the Carson Valley.
3.1. Upper Watershed Models

GSFLOW models of the upper watershed were run using the Precipitation Runoff Modeling System (PRMS; Markstrom et al., 2015) components of GSFLOW (Markstrom et al., 2008) using a daily time step. The “PRMS-only” mode simulates lateral surface and shallow subsurface flow, including distributed water and energy balance calculations of precipitation, ET, snowpack, and overland flow. Separate models are used for the watersheds of the East Fork and West Fork of the Carson River. These models were constructed using the GSFLOW-Arcpy toolbox (Gardner et al., 2018). Models were constructed using several geospatial data sets describing elevation, vegetation cover, soils, surficial geology, and climate within the watersheds. These ancillary data were used to derive input data requirements for the GSFLOW models and are distributed to constant area 168 m rectangular grid cells draped over the watersheds upstream of the East Fork near Gardnerville gage (USGS site 10309000; “East Fork GSFLOW model area” in Figure 1) and West Fork at Woodfords gage (USGS site 10310000; “West Fork GSFLOW area” in Figure 1) gages (Figure 2a). Climate was distributed spatially across the model cells that ranged in elevation from 1,425 to 3,143 m and from 1,425 to 2,562 m above Mean Sea Level for the East Fork and West Forks of the Carson River, respectively. Spatial variability in climate is represented by the Parameter-elevation Regression on Independent Slopes Model (PRISM) mean monthly precipitation patterns (Daly et al., 1994). PRISM monthly precipitation is adjusted to represent daily variability using precipitation data recorded at the Blue Lakes and Spratt Creek Snow Telemetry (SNOTEL) sites. For additional details regarding development of the GSFLOW models using the GSFLOW-Arcpy scripts, refer to Gardner et al. (2018).

Additional to the watersheds that drain to the East Fork and West Fork of the Carson River, the Carson Valley receives inflow from 16 perennial streams along the Carson Range. GSFLOW models were not constructed for the Carson Range because of the relatively small amount of inflow generated from these watersheds. Linear regression models were used to estimate streamflow entering the valley from the Carson Range. Regression models were generated using the available intermittent records for these streams as dependent variables and flows from the East Fork (USGS site 10309000) and West Fork (USGS site 10310000) as independent variables (Maurer et al., 2004b).

3.2. Carson Valley Operations Model

MODSIM is a river operations and decision support system network-flow model that uses a minimum-cost optimization algorithm to deliver water through complex networks based on water availability, demands, priorities, and operational rules subject to operational constraints (e.g., maximum canal conveyance capacities). Streamflow entering the Carson Valley from the East Fork, West Fork, and 16 perennial streams along the Carson Range are specified as inputs into the MODSIM network (Figure 3b). Measurements of diversions to major irrigation canals provided by the Federal Water Master are used to restrict the capacity of the canals in MODSIM, as well as calibration targets. When flows at the Gardnerville gage on the East Fork of the Carson River (USGS 10309000) drop below 5.66 m$^3$s$^{-1}$ (200 ft$^3$s$^{-1}$) the capacity of the Allerman canal is set to one-third of the flow at the Gardnerville gage, effectively enforcing the regulations specified in the Alpine Decree (United States v. Alpine Land and Reservoir Co., 1980).

In MODSIM, the priority of each water right and operational rules determine the relative cost incurred along the delivery route. MODSIM requires a unique cost structure to determine a unique solution to the network-flow problem. The relative costs for the 546 water rights in our model are based on the administrative segments and priority year specified in the Alpine Decree (United States v. Alpine Land and Reservoir Co., 1980). Many water rights in the same administrative segment have the same priority year. As such, we rank water rights in each administrative segment by priority year and location, giving higher priority to older water rights further upstream. The existence of multiple routes for water delivery can also lead to a non-unique cost structure and model failure. To address this, the cost of all canal diversions was reduced based on the POD from the river, with upstream canal diversions having lower costs (higher priority). The lowest cost assigned to any canal is used as the water right cost increment and is subsequently added to the cost of all water rights served by that canal, thereby maintaining the relative cost structure defined by the priority year and administrative segment regardless of the delivery route.
MODSIM attempts to satisfy the surface water demand (SWD) based on water availability and priority throughout the system. It should be noted that in this work SWD is the desired amount of water available for irrigation, which includes gains and losses associated with conveyance, distribution, and field application of irrigation water, and thus is equivalent to the gross irrigation water requirement (GIWR; Savva & Frenken, 2002). This differs from the crop demand but is consistent with the MODSIM parlance. Available data suggest that episodic irrigation rates of over 0.3 m per day (1.0 foot per day) are applied to fields with permeable soils and a deep water table. However, during periods of low flow when irrigation is regulated the Federal Water Master may restrict the amount of surface water to meet the needs of other water rights in priority. As a result, these same fields may get substantially less water during periods of low flow, depending on their priority and water availability at their POD. A distinction was made between SWD\textsubscript{u} and SWD\textsubscript{r}, model parameters representing the SWD during periods when the river is unregulated and regulated, respectively. The large uncertainty in SWD throughout the Carson Valley warrants the inclusion of these parameters in the calibration process for each of the 546 water rights.

3.3. Carson Valley Hydrologic Model

The groundwater system, including groundwater-surface water interactions, is modeled using the Newton-Raphson solver in the MODFLOW component of GSFLOW (Niswonger et al., 2011). GSFLOW is the integration of the PRMS and the groundwater flow model called MODFLOW-NWT (Markstrom et al., 2008; Niswonger et al., 2011). MODFLOW simulates three-dimensional groundwater flow and surface water-groundwater interactions in channels and reservoirs. We simulate stream-groundwater interactions using the MODFLOW Streamflow Routing Package (SFR2; Niswonger & Prudic, 2005). One-week stress periods were used in the model; boundary conditions vary on a weekly basis.

Groundwater recharge from irrigation, ET from shallow groundwater, and rejected infiltration are simulated using the MODFLOW Unsaturated-Zone Flow Package (UZF1; Niswonger et al., 2006). However, to maintain computational efficiency suitable for calibrating the highly parameterized model, unsaturated
zone storage was neglected. Rather, efficiency factors estimated during calibration were used to partition irrigation water between ET and groundwater recharge using the Agricultural Water Use Package for MODFLOW (AG; Niswonger, 2020). These efficiency factors represent the partitioning of irrigation water into ET, groundwater recharge, and return flows as determined through calibration to observed ET rates, groundwater levels, and surface water observations over the calibration period. As such, these efficiency factors represent “business as usual” irrigation practices and do not consider improvements in irrigation efficiency that may occur during times of water shortage.

The timing and amount of groundwater pumping for irrigation also vary throughout the Carson Valley, depending on the timing and amount of available surface water for each water right. This dynamic pumping is also simulated using the AG Package. Non-irrigation groundwater pumping and subsurface inflows are simulated using the MODFLOW Well Package (WEL). All groundwater pumping rates are automatically reduced by the model when the water table drops below the cell bottom that contains the well screen (Niswonger et al., 2011).

The active model domain for the GSFLOW groundwater model covers approximately 930 km\(^2\) (230,000 acres). Mountain front recharge is simulated as injection wells along the southern and western boundaries of the Carson Valley model (Figure 1), with rates determined through calibration; initial rates are based on areas of similar recharge rate reported in Maurer and Berger (2007). Precipitation as a function of elevation is calculated using daily records from the Minden, Nevada, climate station (Menne et al., 2012) and linear regression using 14 weather stations in or near Carson Valley (Maurer & Halford, 2004). A single parameter representing diffuse groundwater recharge as a fraction of precipitation (UZF; FINF) is estimated during calibration.

The hydrogeology of the study area is characterized by six units: Fluvial deposits, alluvial deposits, sedimentary rock, volcanic rock, granitic bedrock, and metamorphic bedrock. The depth to bedrock is interpolated from gravity surveys (Maurer, 1984) and/or inferred from published geologic maps (Armin & John, 1983; dePolo et al., 2000; Ramelli et al., 2003). The location of the Hot Springs Fault, a normal fault forming the east side of the Carson Valley graben, is used to define a transition from shallow (less than 100 m) alluvial deposits to the east and deeper (100–800 m) alluvial deposits and basin fill deposits to the west, as suggested by the gravity surveys and available driller’s logs.

The finite difference grid consists of four subsurface layers. The upper layer (layer 1) represents the shallow groundwater system in areas mapped as fluvial or alluvial deposits and has a constant thickness of 9 m. The second and third layers represent the intermediate groundwater system and are defined by the depth to bedrock and the mapped surface geology, excluding granitic and metamorphic bedrock. In areas mapped as sedimentary rock or volcanic rock the thickness of layers 2 and 3 are each half the depth to bedrock and represent the surficial geology. The bottom layer (layer 4) represents buried sedimentary rock in the deepest part of the basin (greater than 500 m below ground surface) and granitic or metamorphic bedrock throughout the rest of the model domain. In areas mapped as alluvial or fluvial deposits, the thickness of layers 2 and 3 depend on the depth to bedrock and location. To the east of the Hot Springs Fault, if the depth to bedrock is less than 200 m, the thickness of layers 2 and 3 are each half the depth to bedrock, with layer 2 representing the surficial geology and layer 3 representing sedimentary rock; if the depth to bedrock is greater than 200 m, the upper 100 m represents alluvial deposits and the rest represents sedimentary rock. To the west of the Hot Springs Fault, if the depth to bedrock is less than 500 m, the thickness of layers 2 and 3 are each half the depth to bedrock and represent the surface geology; if the depth to bedrock is greater than 500 m, the upper 250 m represent the surface geology in layer 2 and the rest represents fluvial deposits in layer 3. The model domain contains 103,676 active cells, and each cell is 168 m on a side, approximately 1/10th the average area of water rights in the Carson Valley.

The GSFLOW model simulates groundwater pumping from over 7,000 wells, 438 of which are used for irrigation. Well locations and well screen depths are based on available POU and POD maps (State of Nevada Division of Water Resources, 2019), estimated based on geology, and/or estimated based on well screen depths of wells used for the same purpose. Changes in the depth of well screens due to drilling deeper wells to meet future demands are not considered in this study. If the POU of irrigation wells (State of Nevada Division of Water Resources, 2017) overlaps land with surface water rights (Yager et al., 2012) these wells are...
modeled as supplemental wells. Groundwater withdrawals for each water right with access to supplemental groundwater (within the POU) are calculated by the AG Package based on surface water shortfalls as:

$$\text{SUPPMP} = \max \left( 0, \text{SWD}_n \times \text{FRACSUP}_n - \text{SWI} \right)$$

where \( \text{SWD}_n \) is the SWD and the subscript \( n \) denotes periods of regulated (\( \text{SWD}_r \)) or unregulated (\( \text{SWD}_u \)) flows, \( \text{FRACSUP} \) is the fraction of SWD below which supplemental groundwater irrigation is triggered, and \( \text{SWI} \) is the simulated surface water delivered to the water right for irrigation. This provides a dynamic link between agricultural demand and supply that is necessary for evaluating the response of a conjunctive-use system to changes in both surface water and groundwater availability throughout the system. In addition, the location of approximately 3,000 domestic wells (extraction) and septic leach fields (injection) were inferred from parcel maps and included as wells in the appropriate model cells. Pumping rates for all non-agricultural groundwater withdrawals in the model are based on historical records and do not include estimates of future pumping rates.

ET for each water right is simulated as the sum of ET from SWI, ET from well water irrigation, ET from precipitation during the irrigation season, and ET from shallow groundwater. The component of ET from SWI is calculated by the AG Package as:

$$\text{ET}_{\text{sw}} = \text{SWD}_{\text{deliv}} \times \text{SWEF}_n$$

where \( \text{SWEF}_n \) is the surface water efficiency factor and the subscript \( n \) denotes regulated (\( r \)) or unregulated (\( u \)) flows. Similarly, the ET from well water irrigation is calculated by the AG Package as:

$$\text{ET}_{\text{well}} = \text{SUPPMP} \times \text{WELLEF}$$

where \( \text{WELLEF} \) is the well water efficiency factor. ET from precipitation during the irrigation season and shallow groundwater ET are both calculated by the UZF package. The values of SWD, SWEF, WELLEF, and FRACSUP for each water right are determined through calibration (discussed in the Model Calibration section). Model-wide values of extinction depth and potential ET used to simulate shallow groundwater ET are also determined through calibration. Values of potential ET were adjusted for each scenario to reflect the increase in temperature (see Section 3.5).

### 3.4. Integrated Model

MODSIM is coupled to GSFLOW using a fully implicit scheme to account for nonlinear feedbacks between MODSIM and GSFLOW (Morway et al., 2016). Each stream segment in the GSFLOW model corresponds to a network link in MODSIM. The flows in each link determined by MODSIM are passed to GSFLOW which calculates groundwater-surface water exchanges throughout the model using the SFR2 package. The gains and losses to each stream segment determined by GSFLOW are used to update the flows in each segment of the MODSIM model. MODSIM then calculates water deliveries using the updated flows. This process is repeated until there is agreement between the two models during the weekly stress period. Details of this approach can be found in Morway et al., (2016).

### 3.5. Model Calibration

Hydrologic models used to forecast future water availability, explore adaptive strategies, and support potential management decisions likely benefit from calibration to diverse data sets that reflect the relevant behavior of the system and potential future conditions of interest. The upper watershed GSFLOW models are calibrated in a three-part, step-wise, manual approach (Hay et al., 2000): (a) Adjusting parameters controlling the solar radiation, temperature, and ET in the watersheds, (b) adjusting parameters controlling the form of precipitation, snow accumulation, and snowmelt processes, and (c) adjusting parameters controlling overland runoff and subsurface storm flow. In contrast, the operations-hydrology model (MSGSF) is calibrated using a highly parameterized approach (e.g., Doherty & Hunt, 2010; Doherty, Fienen, & Hunt, 2010; Hunt et al., 2007) to estimate hydrogeologic properties, water use parameters, boundary conditions, initial conditions, and vertical discretization that best reproduce observations of ET, streamflow, groundwater heads, and supplemental pumping rates in a sum-of-squared residual (L-2 norm) sense. The computationally efficient iterative ensemble smoother method recently implemented in the PEST++ modeling package
(PESTPP-IES) is used to calibrate the model (Doherty, Hunt, & Tonkin, 2010; Welter et al., 2015; White et al., 2019; White, 2018).

3.5.1. Upper Watershed Model Calibration

The first step in calibrating the upper watershed GSFLOW model involves adjusting parameters controlling the solar radiation, temperature, and ET in the watersheds to match the annual water balance. This part of the calibration relies upon local measurements of solar radiation and annual water balances to reproduce externally calculated ratios of precipitation and runoff. After calibration of the annual water balance, simulated snow processes are evaluated by comparison to remotely sensed snow cover data to represent relationships between temperature, the form of precipitation, and snowmelt over the highly variable climate conditions during the 1980–2015 calibration period. We developed a continuous daily time series of fractional snow-covered area (fSCA) for the East Fork and West Fork of the Carson River watershed using daily imagery acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor to calibrate snowmelt parameters. Cloud-covered pixels were flagged and filled using a weighted average of the nearest values at the same pixel position within the time series and weights were assigned based on temporal proximity to the pixel needing to be filled. We then resampled the MODIS data set to the spatial resolution and extent of the data set used to build the upper watershed models to facilitate comparison between the two. Additional calibration of parameters controlling overland runoff and subsurface storm flow were adjusted to best match the daily streamflow measurements at the USGS stream gages (sites 10309000 and 10310000 in Figure 2). Streamflow from the calibrated upper watershed models of the East Fork and West Fork of the Carson River watersheds are applied as inflows to the MSGSF model.

3.5.2. Carson Valley MSGSF Calibration Parameters

A total of 12,979 parameters are estimated during the calibration of the Carson Valley MSGSF model (Table 1). Parameters are grouped into the following categories: SWI demands for each water right during unregulated (565) and regulated (565) flows, effluent irrigation demands (9), SWI efficiency for each water right during unregulated (565) and regulated (565) flows, surface water efficiency for effluent irrigation (9), fraction of surface water deliveries that trigger supplemental well water irrigation (368), well water irrigation efficiency for supplemental irrigation (368) and well only irrigation (89), zonal hydraulic properties (6 zones in 4 layers), hydraulic property multipliers at pilot points (4 property multipliers at 1,484 pilot points), boundary conditions (85), initial heads at pilot points (1,484), and elevation of the bottom of each model layer at pilot points (1,484). In addition, a multiplier to calculate seepage loss from streams (LOSSFACTOR; Niswonger & Prudic, 2005), six parameters controlling weighting factors and convergence criteria in the Newton solver (Niswonger et al., 2011), and the starting and ending date of supplemental groundwater irrigation are also included as calibration parameters.

A total of 1,484 pilot points are used to model the spatial variability of hydrologic parameters, initial conditions, and vertical discretization. Evenly spaced pilot points for each layer were generated using utilities in pyemu (White et al., 2016); layer 1 contains 628, layer 2 contains 432, layer 3 contains 278, and layer 4 contains 146. A two-dimensional exponential variogram is used to interpolate between pilot points in each layer. The range of the variogram depends on the pilot point spacing within each layer and ranges between 2,500 m in layer 1 and 7,500 m in layer 4. Zonal values for horizontal hydraulic conductivity, vertical anisotropy, specific yield, and specific storage represent the mean values for each of the hydrogeologic zones (Figure 3) and are multiplied by the respective interpolated array. Initial values and parameter bounds for these properties were determined from Domenico and Schwartz (1998), Ramelli et al. (2003), and Yager et al. (2012). The interpolated arrays for initial head and the bottom of each layer are added to the arrays representing the best estimates of those values.

3.5.3. Carson Valley MSGSF Calibration Observations

The MSGSF integrated model was calibrated to 8,367 hydrologic observations in the Carson for water years 2001–2005 (Table 2). Annual (106) and monthly (985) total streamflow volumes at three USGS gages (USGS, 2016) and 14 gaging stations operated by the Federal Water Master (Federal Water Master, 2015) provide constraints on the distribution of surface water throughout the system (Figure 2), including diversions to main irrigation canals, return flows, and groundwater-surface water interactions. Annual pumpage
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Table 1
Parameter Groups Used for Model Calibration, Sources for Initial Parameter Values and Bounds, and Manual Adjustments Made Before Calibration

| Parameter           | Description                                                                 | Basis for initial values and parameter bounds                      | Manual adjustments                          |
|---------------------|------------------------------------------------------------------------------|---------------------------------------------------------------------|---------------------------------------------|
| SWD unregulated     | MODSIM demand when deliveries are unregulated                                | Alpine Decree and local irrigation practices                        | Reduced for areas with high simulated ET    |
| SWD regulated       | MODSIM demand when deliveries are regulated                                  | Alpine Decree and local irrigation practices                        | Reduced for areas with high simulated ET    |
| SWD effluent        | MODSIM demand for effluent irrigation                                        | Average annual effluent volumes and irrigated area                  | Adjusted to match ET rates from areas of effluent application |
| Well demand         | Demand for land with only well irrigation                                     | Average annual crop consumption                                     | Reduced for areas with high simulated ET    |
| SWEF                | Fraction of surface water irrigation consumed by crops (GSFLOW AG package)   | Brookfield et al., 2017; Gates et al., 2012, Githui et al., 2016    | Reduced for areas with high simulated ET    |
| WELLEF              | Fraction of well water irrigation consumed by crops (GSFLOW AG package)       | 10% higher than SWEF to approximate increased application efficiency| Reduced for areas with high simulated ET    |
| FRACSUP             | Surface water irrigation threshold below which supplemental pumping is triggered | Unregulated SWD divided by average crop consumption                  | Reduced for wells with high simulated pumping |
| Hydraulic conductivity (zonal mean) | Mean hydraulic conductivity for each zone                                       | Yager et al., 2012; Domenico & Schwartz, 1998                        | -                                           |
| Anisotropy ration (zonal mean) | Mean ratio of vertical to horizontal hydraulic conductivity for each zone | Yager et al., 2012; Domenico & Schwartz, 1998                        | -                                           |
| Specific yield (zonal mean) | Mean specific yield for each zone                                             | Yager et al., 2012; Domenico & Schwartz, 1998                        | -                                           |
| Specific storage (zonal mean) | Mean specific storage for each zone                                            | Yager et al., 2012; Domenico & Schwartz, 1998                        | -                                           |
| Pilotpoint multipliers | Pilotpoint values used for interpolation of multiplier arrays for each hydraulic property | Initial value of 1.0, homogeneous mean value for all hydraulic parameters | -                                           |
| Pilotpoint addition | Pilot point values used for interpolation of additive arrays for initial head and vertical discretization | Initial value of 0.0                                               | -                                           |
| Subsurface inflow   | Mountain front recharge rates                                                 | Maurer & Berger, 2007                                               | Adjusted to match groundwater head measurements along the Carson Range |
| Loss factor for stream seepage | Multiplication factor to calculate stream seepage                            | Inferred from Ou et al., 2013                                       | -                                           |
| Newton solver parameters | Parameters controlling Newton solver weighting factors and convergence criteria | Trial and error for initial runs providing good convergence        | -                                           |
| Supplemental pumping period | Day of year supplemental pumping due to SW shortfalls can start and stop      | Oral communication with local irrigators                            | -                                           |

Abbreviations: AG, Agricultural Water-Use Package; ET, evapotranspiration; SWD, surface water demand; SWI, surface water irrigation.
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Table 2
Observations and Calibration Criteria for the Carson Valley MSGSF model

| Observations                           | Source                                      | Relative contribution |
|----------------------------------------|---------------------------------------------|-----------------------|
| Annual crop ET                         | Huntington et al., 2018                     | Strong                |
| Annual pumpage for irrigation (basin-wide) | NDWR, 2016                                 | Moderate              |
| Annual streamflow                      | USGS, 2016; Federal Water Master, 2015     | Moderate              |
| Annual pumpage for irrigation (individual wells) | NDWR, 2016                                 | Moderate              |
| Monthly streamflow                     | USGS, 2016; Federal Water Master, 2015     | Weak                  |
| Groundwater heads                      | USGS, 2016; Federal Water Master, 2015     | Weak                  |
| NWT iterations                         | Niswonger et al., 2011                     | Moderate              |
| NWT convergence criteria               | <1% mass balance error each stress period   | Strong                |

Initial observation weights are based on estimates of measurement uncertainty or required model performance. Minor adjustments to the weights of the observation groups were made such that the relative contribution to the objective function reflects the relative importance of the observation group to predictions of interest.

(Allen et al., 2007; Huntington et al., 2018) help constrain irrigation rates, efficiency factors, and parameters controlling ET from groundwater and direct precipitation.

Simulation metrics pertaining to the number of inner (261) and outer (261) Newton iterations and the percent discrepancy for mass balance (261) were assigned as inequality constraints within the PESTPP-IES solution (e.g., White et al., 2019) to ensure adequate model convergence for each weekly stress period. The “preferred value” for these groups were 1,000, 100, and 1.0, resulting in an objective function penalty when the inner iterations exceeded 1,000, the outer iterations exceeded 100, and the percent discrepancy exceeded 1.0%, respectively. An additional set of inequality constraints was used to incur an objective function penalty when ET rates from irrigated parcels exceeded 1.2 m per year (4 feet per year), the upper limit suggested by the remotely sensed data.

3.5.4. Application of PESTPP-IES

The IES implemented in the PEST++ suite (PESTPP-IES) is a numerical algorithm that assimilates data (i.e., observations) in a batch sense through the adjustment of a stochastically generated parameter ensemble (Chen & Oliver, 2013; White, 2018; White et al., 2019). The ensemble consists of numerous realizations of parameter vectors, corresponding simulated equivalent to observations, and the original observation vector (i.e., calibration targets) plus or minus “noise” drawn from a probability distribution defined by observation uncertainty. Each parameter value in a realization is drawn from a multivariate Gaussian probability distribution. The probability distributions for parameters are defined using expert knowledge, and covariances between parameters are defined using reasonable parameter limits along with geostatistical relationships defined by variograms. The number of realizations in the ensemble should reflect the dimensionality of the inverse problem solution space, which in practice is difficult to estimate and can change during the parameter estimation process. Previous studies used between 50 and 100 realizations; in the current study we use 150 realizations to address a potentially larger solution space associated with more diverse observation data set.

Parameter vectors are updated with each calibration iteration using the Gauss-Levenberg-Marquardt algorithm to minimize the misfit between the observations and the simulated equivalent of the observations. These updates use an approximation to the Jacobian matrix calculated using the ensemble-based empirical cross-covariances between the parameter ensemble and the corresponding outputs. This greatly reduces the computation burden of estimating the Jacobian matrix as compared to using finite difference methods (White et al., 2019). Parameter updates are constrained by the upper and lower limits of each parameter. Since PESTPP-IES uses an approximate form of Bayes equation, the final parameter and observation ensembles represent a stochastic sample of the posterior covariance of the parameters and the simulated equivalent of the observations, respectively, that does not rely on assumptions of model linearity (White et al., 2019). The mean parameter vector resulting from the IES process is used to evaluate the calibration results and simulations of future climate scenarios.
Spurious cross-correlations can be generated when the number of realizations in the ensemble is low and the number of parameters and observations are high. Localization is a technique that specifies which simulation results can inform which parameters, thus ignoring relationships between parameters and simulation results that are not expected to be significant or that are non-physical. We use a correlation-based adaptive localization method based on Luo et al. (2018). The correlation-based adaptive localization algorithm (AUTOADALOC; White et al., 2019) calculates Pearson correlation coefficients between each pair of observations and parameters. Each observation vector is then shifted, aligning it with the parameter vector from a different realization and the correlation coefficients are recalculated. This essentially shuffles the realizations and allows the estimation of background or “error” correlations that arise from having a relatively small ensemble size compared to the large number of parameters and observations. AUTOADALOC imposes restrictions on the observations informing parameter updates based on the statistical distance between the correlation coefficient and the background correlation coefficient estimates, ignoring pairs of observations and parameters with correlation coefficients that are not statistically different than the background correlations. In this study, correlation coefficients more than two standard deviations from the background value are considered significant.

3.6. Scenarios

Some climate models predict annual near surface atmospheric temperatures to warm by as much as 5°C in the Sierra Nevada region by the end of the 21st century (e.g., He et al., 2018). However, there is little or no discernible change in mean precipitation predicted for most of the Sierra Nevada (Berg & Hall, 2015; He et al., 2018; Huang & Ulrich, 2017). We isolate the impacts of the dominant prediction of warming air temperature by superimposing temperature increase increments of 1°C up to a maximum of 5°C on climate data from 1980 to 2015 (e.g., Young et al., 2009) and keep all other climate factors constant and equal to the historical records. GCMs provide an alternative approach for evaluating the impacts of future climate conditions and the established future warming trends (e.g., He et al., 2018). GCMs have the benefit of representing covarying precipitation and temperature conditions that are physically realistic, while superimposing increasing temperatures onto historical climate records provides a more straightforward approach for isolating the effects of warming on agricultural water use.

The influence of higher temperatures on snowpack dynamics and the associated streamflow are simulated in the upper watershed models. The resulting hydrographs are used as inputs into the MSGSF model. In addition to the streamflow response, the annual groundwater ET rates in the Carson Valley are increased by 4 mm per degree Celsius to account for the predicted changes in atmospheric conditions in the Carson Valley (Huntington et al., 2016). However, irrigation efficiencies are held constant at the calibrated value. An analysis of the calibration results and NVDWR pumping records suggests a FRACSUP value of 0.81 represents water rights with a history of using supplemental groundwater. As such, this value is used for all water rights with access to supplemental groundwater in all future simulations. Non-agricultural groundwater use (i.e., municipal, industrial, domestic, etc.) and effluent imports are assumed to remain constant at 2015 values. The results of the increased temperature simulations are discussed in terms of the difference from the baseline (i.e., 0°C increase) simulation over the 35-year simulation period. All temperature simulations have the same irrigation parameters (SWD, SWEF, WELLEF, and FRACSUP), precipitation, number of wells, and non-irrigation well pumping amounts. However, due to decreased streamflow during the irrigation season in the temperature change scenarios the river goes on regulation earlier. This results in SWDr being used during these times, rather than SWDu. As such, the annual basin-wide demand decreases slightly with increasing temperature.

4. Results

4.1. Calibration Results

Predicted outflows from the calibrated upper watershed models were evaluated using three common model evaluation statistics: Volumetric efficiencies (VE; Criss & Winston, 2008), the Nash-Sutcliffe Efficiency (NSE; Krause et al., 2005), and the Kling-Gupta Efficiency (KGE; Gupta et al., 2009). All three statistics were computed at the outlets of the three models presented herein and are summarized in Table 3. Because the
MSGSF model uses weekly stress periods, a comparison to observed mean daily streamflow was not possible. Using a suggested ranking table offered in Woolfenden and Nishikawa (2014) (Table 10), simulated daily flows for the East and West Forks of the Carson River rate from less than fair to good, depending on the statistic. However, the monthly goodness-of-fit statistics, which rate from fair to good depending on the statistic, are a more pertinent statistic for the present analysis.

Including snow-covered area and streamflow observations in the calibration improved flow statistics for both watersheds (e.g., Woodruff & Qualls, 2019). The ISSCA from the GSFLOW models tends to be higher than the MODIS-derived fSCA. However, forest canopy cover is positively correlated with mean error ($R = 0.48$) across the entire range of canopy cover values (0%–62%) and it has been shown that MODIS underestimates snow cover beneath forest canopies (e.g., Raleigh et al., 2013), potentially introducing bias in these observations. The agreement between the simulated and measured streamflow over the range of climate conditions represented by the calibration period (1980–2015) suggests the models are adequately simulating the release of water over a range of climatic conditions in the Carson Valley, including periods that are warmer than the average. Years of above average winter temperature conditions occur periodically during the last 35 years of recorded climate and streamflow conditions, and these years are characterized by a higher frequency of rain and rain on snow events.

The calibration results for ET for irrigated land within the Carson Valley are discussed in terms of cubic meters per square meter covered by the water right (i.e., meters) during the irrigation season and averaged over the calibration period. Most of the irrigated land (69%) has simulated ET values within 0.1 m (0.3 foot) of the METRIC estimates of ET (Figure 4a). Irrigated parcels with simulated ET values greater than 0.1 m (0.3 foot) above the METRIC estimate are typically located near the river. Irrigated parcels with simulated ET values less than 0.1 m below the METRIC estimate are typically located on coarser alluvium along the sides of the valley. Parcels with low and high ET residuals also occur adjacent to each other in these areas. The basin-wide average ET residual for all irrigated land is only $-6$ thousand cubic meters (Tm$^3$; $-4.9$ acre-feet), indicating a satisfactory representation of basin-wide processes related to agricultural ET.

The calibration results for groundwater pumping rates for agriculture are discussed in terms of annual volumes averaged over the calibration period. Most of the annual pumping rates are within 50 Tm$^3$ (40.5 acre-feet) of the values reported by NVDWR. The model tends to over simulate pumping rates in the southeastern part of the model and under simulate pumping rates in the southwestern and western parts (Figure 4b). Most of the discrepancy between simulated and reported pumping rates is likely due to the difficulty in estimating pumping rates for individual wells that serve multiple water rights, as well as individual water rights that have access to multiple wells. Also, a single pumping threshold parameter may be unable to capture the complexity of groundwater irrigation decisions. However, most of the land (71%) with groundwater irrigation rights have average pumping rate residuals within ±0.1 cubic meter per square meter (±0.3 acre-feet per acre). The basin-wide average residuals for all irrigation wells is $-11$ Tm$^3$ (8.9 acre-feet), indicating an adequate representation of basin-wide groundwater pumping for irrigation.

The simulated heads for most (70%) of the observation wells used for calibration are within 5.0 m of the reported value. Wells with very high (>10.0 m) or very low (<−10.0 m) residuals are located near complex geologic structures: (a) Along the northwestern model boundary where the contact between bedrock and fluvial sediments shift to the east, and (b) east of Gardnerville where thin sedimentary deposits overlie heavy

| Model Outlet                  | VE Daily | VE Monthly | VE Annual | NSE Daily | NSE Monthly | NSE Annual | KGE Daily | KGE Monthly | KGE Annual |
|-------------------------------|----------|------------|-----------|-----------|-------------|------------|-----------|------------|------------|
| Upper Watershed – East Fork (PRMS) | 0.58     | 0.66       | 0.86      | 0.55      | 0.76        | 0.91       | 0.77      | 0.79        | 0.83       |
| Upper Watershed – West Fork (PRMS) | 0.65     | 0.72       | 0.90      | 0.71      | 0.85        | 0.95       | 0.82      | 0.92        | 0.97       |
| Carson Valley (MSGSF) | NA       | 0.60       | 0.81      | NA        | 0.77        | 0.89       | NA        | 0.80        | 0.85       |

Abbreviations: KGE, Kling-Gupta Efficiency; MSGSF, MODSIM-GSFLOW; NSE, Nash-Sutcliffe Efficiency; PRMS, Precipitation Runoff Modeling System; VE, Volumetric efficiencies.

Table 3
Fit Statistics for Calibration of the Three Models to Streamflow
ily faulted bedrock associated with a tectonic accommodation zone (Cashman et al., 2009). The basin-wide average residuals for all observation wells is −2.1 m, indicating a satisfactory representation of the groundwater system.

4.2. Validation

The MSGSF model was validated using 7,549 groundwater head measurements from 228 wells throughout the Carson Valley and streamflow measurements from USGS gage 13011000 (Figure 2a). The validation period is for water years 1980–2015 (October 1 through September 30), excluding the calibration period (water years 2001 through 2005). The validation period tends to underpredict groundwater heads by an average of 6.1 m. The root mean squared error (RMSE) for all groundwater head measurements during the validation period is 9.9 m. The validation period shows high head residuals near the edges of the valley where groundwater is influenced by complex faulting, similar to the calibration period. Removing these outliers (+/−2 standard deviations) results in a RMSE of 6.2 m.

Using the same three model evaluation statistics for monthly streamflow presented in Table 3, the VE, NSE, and KGE values for the validation period are 0.58, 0.71, and 0.79, respectively. Although all three statistics decrease slightly relative to the calibration period, they are within 0.02, 0.06, and 0.01 of their original values, respectively. The model tends to underpredict streamflow out of the Carson Valley with an average bias over the 35-year period of −46.2 Mm$^3$ per year (−37,400 acre-feet per year), or approximately −13% of the average measured outflow (Table 4). The bias is greatest in January and February, with values of −14.0 Mm$^3$ (11,300 acre-feet). The bias during the irrigation season ranges from −0.5 Mm$^3$ (−420 acre-feet) in September to 5.9 Mm$^3$ (4,800 acre-feet) in April, with an average during the irrigation season of 2.0 Mm$^3$ (1,620 acre-feet) per month, approximately 0.9% of the average measured outflow during the irrigation season (Table 5).
4.3. Simulation Results

Model results show the impacts of increased temperature associated with climate change in a snow-fed agricultural system governed by the prior appropriations doctrine. We evaluate the impacts to streamflow, agricultural surface water and groundwater use during the irrigation season, crop consumption (irrigation season ET), and groundwater heads by comparing the 35-year average of the scenario to that of the baseline. Increased temperatures cause an increase in rain events and earlier snowmelt in the upper watershed causing a greater proportion of the annual streamflow to occur prior to the irrigation season (April 1 to September 30; Figure 5). Earlier streamflow into the Carson Valley results in less surface water available during the irrigation season, causing irrigation to be regulated earlier in the season. Since SWD is always less than SWDu, the overall SWD in the model decreases as surface water inflow during the irrigation season decreases. Despite the decrease in SWD the system experiences a decrease in surface water deliveries (Figures 6–8), an increase in supplemental groundwater use (Figure 9), a decrease in ET – a commonly used surrogate for crop yield (Figure 10), and a decrease in groundwater levels (Figure 11) as a result of earlier

Table 4
Annual Average Water Budget Components for the Carson Valley MSGSF Model

| Scenario | Surface water inflow | Effluent imports | Groundwater inflow | Precipitation | Surface water outflow | Total ET | Groundwater storage |
|----------|----------------------|------------------|--------------------|---------------|----------------------|----------|---------------------|
| Historical | 440.3 | 12.2 | 15.7 | 210.9 | -342.0 | -331.7 | NA |
| Validation | 443.0 | 12.2 | 16.3 | 210.9 | -295.8 | -352.8 | -5.6 |
| 0°C | 443.0 | 12.4 | 16.3 | 210.9 | -301.3 | -330.1 | -9.7 |
| 1°C | 439.8 | 12.4 | 16.3 | 210.9 | -301.5 | -327.5 | -10.0 |
| 2°C | 437.8 | 12.4 | 16.3 | 210.9 | -303.4 | -324.6 | -10.3 |
| 3°C | 436.9 | 12.4 | 16.3 | 210.9 | -306.7 | -321.6 | -10.7 |
| 4°C | 436.9 | 12.4 | 16.3 | 210.9 | -311.0 | -318.3 | -11.0 |
| 5°C | 437.5 | 12.4 | 16.3 | 210.9 | -316.1 | -314.9 | -11.4 |

Values for each scenario are averaged over the 35-year simulation period. Historical surface water outflow was compiled using USGS gage 10311000. All other values were determined from Maurer and Berger (2007). All temperature simulations include irrigation wells and effluent imports that existed in 2015, resulting in higher irrigation well withdrawals and effluent irrigation compared to the historical data and validation model. Values are in millions of cubic meters. ET, evapotranspiration.

Table 5
Irrigation Season Water Budget Components for the Carson Valley MSGSF model

| Scenario | Surface water inflow | Surface water outflow | Water right ET | Irrigation well withdrawals (GWI) | Surface water demand (SWD) | Surface water irrigation (SWI) |
|----------|----------------------|----------------------|----------------|-------------------------------|-----------------------------|--------------------------------|
| Historical | 334.2 | -212.9 | -144.4 | -11.2 | NA | NA |
| Validation | 356.8 | -253.0 | -131.4 | -18.6 | 158.5 | 118.3 |
| 0°C | 356.8 | -255.3 | -104.2 | -38.3 | 158.5 | 116.4 |
| 1°C | 341.1 | -241.9 | -102.0 | -39.3 | 157.9 | 112.8 |
| 2°C | 324.1 | -227.5 | -99.5 | -40.5 | 157.2 | 108.7 |
| 3°C | 305.8 | -212.1 | -96.8 | -41.7 | 156.4 | 104.4 |
| 4°C | 286.4 | -195.5 | -93.9 | -42.9 | 155.5 | 100.1 |
| 5°C | 265.9 | -178.0 | -91.0 | -44.1 | 154.8 | 95.6 |

Values for each scenario are the sum of over the irrigation season (April–September) averaged over the 35-year simulation period. Historical data represents the period from 1980 to 2015. Historical surface water outflow was compiled using USGS gage 10311000. Surface inflow is not readily available due to intermittent records. All other values were determined from Maurer and Berger (2007). All temperature simulations include irrigation wells that existed in 2015, resulting in higher irrigation well withdrawals. Values are in millions of cubic meters. ET, evapotranspiration; GWI, groundwater irrigation.
streamflow. The extent and magnitude of these changes scale with increasing temperature, driven primarily by seasonal shifts in the snowmelt pulse and the resulting streamflow hydrograph entering the Carson Valley. The combination of surface water right priority, location within the system, and proximity to senior water rights influences the simulated irrigation amounts.

4.3.1. Streamflow into Carson Valley

Simulated streamflow from the baseline scenario averaged across the 35-year simulation period show that the time of year when the center of mass (COM; defined as half the total annual runoff) occurs is approximately mid-May where the East Fork (Figure 5a) and West Fork (Figure 5b) enter the Carson Valley. The COM of runoff for the East Fork and West Fork arrive approximately 1.2 and 0.8 weeks earlier with each 1°C increase in temperature, respectively. Under the 5°C temperature increase scenario, approximately 33% of the annual East Fork flows and 47% of the annual West Fork flows enter the Carson Valley before the irrigation season starts (Figure 5).

There is a considerable decrease in simulated East Fork and West Fork streamflow into the Carson Valley during the 6-month irrigation season with increasing temperature (Table 5). This decrease is responsible for most of the impacts simulated in the Carson Valley. Increasing temperature results in a minor reduction of annual streamflow into the Carson Valley of approximately 5.1 Mm$^3$ (4,100 acre-feet), approximately 1% of the mean annual flow. However, there is not a consistent trend in total annual streamflow into the Carson Valley, suggesting that earlier snowmelt and drainage may offset the impacts of increased temperatures on ET in the upper watershed models. The largest decrease in annual streamflow into the Carson Valley occurs in the 3°C scenario (Table 4), suggesting a temperature threshold where ET in the upper watershed may be maximized.

4.3.2. Agricultural Surface Water Use

The simulated basin-wide SWI decreases by approximately 4.2 Mm$^3$ per degree Celsius (3,400 acre-feet per degree Celsius; Table 5). Basin-wide SWI decreases from 3.6 to 20.8 Mm$^3$ (2,900 to 16,900 acre-feet) compared to the baseline for the 1° and 5°C, respectively. This represents a 3%–18% decrease in basin-wide SWI compared to the baseline simulation. The decrease in SWI depths and the percent decrease in SWI scale...
with water right priority decade and increasing temperature (Figures 6a and 6b). The decrease in average annual SWI depth for water rights with priority dates of 1890 and later exceed 0.2 m (0.66 foot) for the 5°C scenario, roughly a 25% decrease from the baseline simulation. In contrast, the SWI depth for the most senior water right decade (1850s) decreases by less than 0.09 m (0.29 foot) in the 5°C scenario, approximately a 10% decrease from the baseline simulation. The SWI volume for water rights with priorities in the 1850s, 1860s, and 1890s decades decrease by approximately 5.5 Mm³ (4,400 acre-feet) in the 5°C scenario (Figure 6c). The decrease in SWI volume for the senior priority water rights (1850s and 1860s) is explained by insufficient water available in the West Fork to supply the large area covered by these water rights. The decrease in SWI volume for the junior priority water rights (1890s) is explained by their relatively low priority,
the large area covered by these water rights, and their location along the higher elevation benches within the East Fork segment where high infiltration rates and the lack of opportunity for return flows exacerbate surface water shortages.

The model’s ability to distribute the available surface water based on water right priority is most apparent near the confluence of the East Fork and West Fork (Figure 7, black outline). For senior water rights (1859 and prior) near the confluence, the 5°C scenario shows a decrease in SWI of over 25% along the Carson River, 20%–30% along the West Fork, and less than 5% along the East Fork, reflecting the relative priority of the administrative segments. The model routes the available water to meet the demands of senior priority water rights at the end of a segment (e.g., East Fork) despite significant surface water shortfalls for senior priority water rights along the West Fork and multiple irrigation canals connecting the East Fork to the West Fork.

The integrated model has the unique ability to simulate surface water-groundwater interactions (GSFLOW) while simultaneously allocating surface water based on both priority and water availability within the system (MODSIM). This can result in varying impacts depending on the location of water rights in relation to
the location of return flows. To illustrate this effect, the mean percent change in SWI for each priority year within a given administrative segment is subtracted from the percent change in SWI for each water right with that priority year within that segment (Figure 8). For example, the mean percent change in SWI for all water rights with an 1864 priority year within the West Fork administrative segment is subtracted from the percent change in SWI for each individual water right with an 1864 priority year along the West Fork. Irrigation return flows from the East Fork augment streamflow in the West Fork and result, for this example, in less of an impact to downstream 1864 water rights along the West Fork relative to the mean (Figure 8e, green outline). Similarly, return flows from effluent irrigation (see Figure 2) augment flows along irrigation ditches in the northern portion of the model, resulting in less of an impact to adjacent water rights relative to the mean impacts experienced by water rights of the same priority year along the East Fork (Figure 8e, yellow outline). The “Allerman Split” rule (see Section 2.3) results in less of an impact to 1870s and 1880s water rights near the head of the Allerman Canal relative to the mean impacts experienced by water rights of the same priority year along the East Fork (Figure 8e, pink outline). The difference in impacts relative to the mean increase with increased temperature.

Figure 9. Change in supplemental groundwater pumping (i.e., groundwater irrigation) from baseline (0°C temperature increase) for: (a) 1°C, (b) 2°C, (c) 3°C, (d) 4°C, and (e) 5°C temperature increase. The red outline indicates junior water rights (>1890 priority) most impacted by surface water irrigation shortfalls. Units are in thousands of cubic meters (Tm³).

Figure 10. Change in evapotranspiration during the irrigation season (ET) from baseline (0°C temperature increase): (a) 1°C, (b) 2°C, (c) 3°C, (d) 4°C, and (e) 5°C temperature increase.
4.3.3. Agricultural Groundwater Use

The simulated basin-wide average groundwater irrigation (GWI) over the irrigation season increases by approximately 1.2 Mm$^3$ per degree Celsius (970 acre-feet per degree Celsius). The average basin-wide GWI reaches 44.1 Mm$^3$ in the 5°C scenario, still below the 63.6 Mm$^3$ of groundwater rights committed by the state. The difference from the baseline for the 1°C and 5°C climate scenarios ranges from 1.0 to 5.8 Mm$^3$ (810–4,700 acre-feet), respectively (Table 5). This represents a 3%–16% increase in GWI compared to the baseline simulation. The increase in GWI depth mostly scales with the associated surface water right priority and increasing temperature; the exception being 1890s decade water rights which show a larger than expected increase (Figure 6a). The majority of 1890s water rights are located on higher elevation benches near the end of the East Fork system, where coarse sediments contribute to significant conveyance losses and exacerbate surface water shortfalls. The larger than expected increase in GWI helps offset the larger than expected decrease in SWI depth, resulting in a decrease of total irrigation depth that is more in line with the other water right priority decades (Figure 6a, hatched lines).

Reduced surface water deliveries for more junior water rights (Figure 7) results in increased GWI (Figure 9, red outline), illustrating the dynamic link between the spatial distribution of surface water shortfalls experienced by low-priority water rights and the resulting increase in supplemental groundwater irrigation. Simulated average GWI for most wells show an increase of less than 50 Tm$^3$ (40 acre-feet) compared to baseline for the 1°C scenario (Figures 9a and 9b), with the highest increase being 60 Tm. The average increase in GWI per well is 8.0 Tm$^3$ per degree Celsius (6 acre-feet per degree Celsius). Wells associated with large junior water rights show increases in GWI with temperature of 30–100 Tm$^3$/°C (24–81 acre-feet per degree Celsius).

4.3.4. Evapotranspiration From Irrigated Lands

In arid regions a decrease in water availability during the irrigation season will result in a decrease in crop ET, and likely lower crop yields. The simulated basin-wide average ET for irrigated lands during the irrigation season (ET$_I$) decreases by approximately 2.7 Mm$^3$ per degree Celsius (2,200 acre-feet per degree Celsius). The difference in ET$_I$ from the baseline ranges from 2.2 to 13.3 Mm$^3$ (1,800 to 10,800 acre-feet) for the 1°C and 5°C climate scenarios, respectively (Table 5). This represents a 2%–13% decrease in basin-wide ET, compared to the baseline simulation. In the 1°C scenario, 80% of the irrigated land experiences less than a 5% reduction in ET$_I$ compared to the baseline scenario, with less than 1% of the irrigated land experiencing reductions of more than 10% (Figure 10). In the 5°C scenario, 21% of the irrigated land experiences less than a 5% reduction in ET$_I$, with over 30% of the irrigated land experiencing reductions of more than 20%. Irrigated lands with junior surface water rights and no supplemental groundwater rights show decreases in ET$_I$ of up to 44%.
4.3.5. Changes in Groundwater

Simulated groundwater heads decline broadly across Carson Valley. The decline in groundwater heads scales with increasing temperature. The decrease in mean annual groundwater storage compared to the baseline is $-9.7$ to $-11.4$ Mm$^3$ ($7,900$ to $9,200$ acre-feet) for the $1^\circ$ and $5^\circ$C scenarios, respectively (Table 4). Areas in the eastern part of the valley show declines of more than $1.5$ m ($5$ feet) over more than $50$ km$^2$ ($12,000$ acres) by the end of the 35-year simulation for the $5^\circ$C scenarios (Figure 11). Declines in head of up to $8$ m ($28$ feet) occur near large irrigation wells with large simulated supplemental pumping responses to surface water delivery shortfalls.

4.3.6. Outflow From Carson Valley

The mean annual streamflow out of the Carson Valley increases by approximately $2.9$ Mm$^3$ per degree Celsius ($2,300$ acre-feet per degree Celsius). Mean annual streamflow out of the Carson Valley increases from $0.2$ to $5.1$ Mm$^3$ ($162$–$4,100$ acre-feet) compared to the baseline simulation for the $1^\circ$ and $5^\circ$C scenarios, respectively (Table 4). The increase in cumulative outflow at the end of the 35-year simulation ranges from $10.6$ to $592$ Mm$^3$ ($8,600$ to $479,900$ acre-feet) for the $1^\circ$ and $5^\circ$C scenarios, respectively (Figure 12). Relatively large increases in winter outflow in water years $1980$, $1982$, and $1983$ are a result of annual inflows greater than $200\%$ of the 35-year average, as most of the runoff entered Carson Valley during the non-irrigation season during rain and/or rain on snow events, and therefore passes through to areas located downstream. Figure 12 shows that earlier snowmelt causes a large portion of the snowmelt to flow past Carson Valley before it can be used by growers, which significantly decreases irrigation water supply in Carson Valley and increases water supplies in Lahontan Reservoir downstream of the valley.

Mean monthly outflow from the Carson Valley increases for December through April for all scenarios (Figure 13). The increase in mean monthly outflow is greatest in March for all scenarios and ranges from $7.1$ to $42.1$ Mm$^3$ ($5,700$ to $34,100$ acre-feet), respectively. The greatest decrease in mean monthly outflow occurs in June for all scenarios and ranges from $9.9$ to $45.8$ Mm$^3$ ($8,000$ to $37,100$ acre-feet) for the $1^\circ$ and $5^\circ$C scenarios, respectively.

5. Discussion

Agricultural communities that rely on snowmelt for irrigation, as is the case for the region explored herein, have already acknowledged shifts in the timing of seasonal snowmelt runoff and associated reductions in surface water for irrigation (Barnett et al., 2005; Vicuña et al., 2012). This modeling study was continually updated and informed through frequent interaction with stakeholders and water managers (Singleton &
These meetings helped address stakeholder concerns and identified potential issues with the model throughout its development. Because irrigation source water includes surface water and groundwater, a realistic representation of groundwater flow and storage as well as surface water-groundwater interaction is important for assessing climate change impacts to groundwater sustainability and capture of streamflow by wells. Furthermore, as relative water right priorities dictate SWI for farms during years of below-average precipitation, an integrated operations and hydrology model is required to adequately represent SWI shortages during dry years. These simulation capabilities, including representation of climate and snowpack processes led to the application of a sophisticated water resource decision support tool. Calibration also is an important component of the model development as stakeholders reviewing model results expect the model to reproduce historical hydrologic conditions to a high degree of accuracy. Although development of this model required significant resources with model runtimes of around 12 h, it provides results that illustrate impacts of climate change on individual water rights holders, demonstrates broader impacts to the sustainability of agriculture in the region, and facilitated stakeholder “buy in” through detailed representation of individual water rights. Without the relatively high level of model sophistication, stakeholders’ lack confidence in model results and tend not to acknowledge model-predicted impacts or simulated management options for mitigation.

This study presents the impacts of global warming on agriculture if adaptation is not employed to help create awareness of likely impacts and to encourage growers to respond to this difficult challenge. One aspect not addressed in this work are the changes in land use practices that may occur as growers try and adapt to the earlier snowmelt runoff entering the basin. Other studies have presented adaptation strategies to earlier snowmelt runoff using reservoir reoperation (Sterle et al., 2020). Carson Valley has limited options for mitigating losses in irrigation supplies caused by earlier snowmelt runoff because there is no upstream reservoir, and because of a higher chance of freeze events and limited solar radiation in the early spring. Managed aquifer recharge is likely a good strategy to improve future water supplies in the Carson Valley, and shifts to more resilient crops and changes in cropping patterns are other possible options (Niswonger et al., 2017; Sterle & Singletary, 2017). Future work may include an evaluation of how irrigation efficiency (SWEF and WELLEF), managed aquifer recharge, and changes in crop ET affect the distribution of available water resources. Optimization of water management strategies under uncertainty (e.g., White et al., 2018) using this modeling framework could provide more efficient water allocation. For example, increased irrigation efficiency would likely reduce groundwater recharge associated with flood irrigation but increase water availability to downstream users during the irrigation season. Managed aquifer recharge during the non-irrigation season, especially during peak flows when flooding is a concern, may help replenish groundwater resources. Optimizing the location, timing, amount, and efficiency of surface water and

![Figure 13. Difference in mean monthly outflow volumes for all 5 temperature increase scenarios relative to the baseline scenario.](image-url)
groundwater irrigation under this framework could increase drought resilience while still adhering to the existing legal framework.

Another challenge in assessing impacts of climate change on irrigation water supply is the uncertainty in future climate conditions and how irrigation practices may change. Global climate models’ representation of future climate consistently predicts increases in atmospheric temperatures, with less consensus on the amount of increase (e.g., He et al., 2018). We address this uncertainty by presenting results for a range of temperature increases that are representative of likely conditions for the period ranging from present day to the end of this century. As with many other studies, we found greatest consensus and support from stakeholders for the delta approach that superimposes an increase in atmospheric temperatures onto the historical climate (1980–2015); no significant consistent trend in precipitation amount could be supported by the climate models analyzed for this work (Berg & Hall, 2015; He et al., 2018; Huang & Ulrich, 2017). However, evaluating the sensitivity of the model to changes in precipitation inputs may be warranted if GCM results suggest changes in precipitation in the Carson Valley (or other study areas) are to be expected (Vano & Lettenmaier, 2014; Vano et al., 2012). Providing simulation results over a range of future temperature increases allowed the stakeholder community to evaluate impacts for modest to extreme climate change conditions that recognizes uncertainty rather than a focus on a single outcome. Other important sources of uncertainty include precipitation amounts and partitioning into snow and rain, and the timing of snowmelt runoff that impact the amount of streamflow reaching the irrigation diversion points. Hydrogeologic uncertainty results in inaccurate delineation of aquifers and the hydrogeologic parameters that are used to simulate flow and storage in aquifers. There also is uncertainty in irrigation scheduling applied in the model that impacts the simulated crop consumption and return flow.

Increased SWI shortfalls with increased temperature result in a significant increase in groundwater use for irrigation. The spatial distribution of surface water shortfalls in addition to supplemental groundwater use for irrigation results in a complex pattern of overdraft. This threatens the sustainability of the aquifer as well as the water supply and water quality for other water use sectors. The process of sharing model results with a diverse group of stakeholders and incorporating their input throughout the development of the model aided in creating consensus that climate change will have broad negative impacts throughout the Carson Valley. Modeling codes that were integrated for this study to represent surface water–groundwater interactions and allocate water according to priority are all in the public domain and are freely available for other studies and regions. Additionally, these codes are flexibly and generally applicable to any developed hydrologic system, especially regions in the western United States and other systems in the world with appropriated water resources that are allocated according to governance structures. As illustrated in this study, water allocation can be difficult to represent and simulate accurately, and this condition has been an ongoing challenge for water managers that require models to better understand important factors affecting water supply and sustainability. The integrated software developed for this study is unique in its capabilities and represents a new tool that will likely be valuable for other investigators needing to assess climate change impacts to water resources in other basins with appropriated water resources.

6. Conclusions

The integrated MODSIM-GSFLOW allocates and routes water available throughout the system, including return flows, to satisfy demands based on priority. This model provides an important tool for evaluating water use in basins governed by prior appropriations. In addition, the dynamic link between surface water shortfalls and supplemental pumping provide an important tool for evaluating impacts of climate change to groundwater resources that result from surface water shortfalls in a conjunctive-use basin. The reduction of groundwater recharge associated with the decrease in surface water deliveries and an increase in supplemental groundwater use results in a decrease in aquifer storage throughout the valley. Understanding the complex relationships between water availability, water distribution, and water use throughout the system can help managers make informed decisions about future conditions and planning.

Earlier streamflow into the Carson Valley associated with increasing temperatures and earlier snowmelt results in surface water shortages during the irrigation season. Outflow from the Carson Valley increases due to more water entering the valley during the winter months before it can be diverted and consumed.
during the irrigation season. As a result, surface water deliveries within the Carson Valley decline and supplemental groundwater pumping increases while deliveries to Lahontan Reservoir (located downstream) increase. This in turn results in lower ET rates for irrigated lands and a decline in groundwater levels. Lower water deliveries and lower ET rates have been linked to lower crop yields (e.g., Donovan & Meek, 1983; Wright, 1988).

Management decisions further downstream, including diversions from the adjacent Truckee River Basin, are currently based on historical monthly flows in the Carson River and monthly storage objectives (Bureau of Reclamation, 1997). This study shows that the timing and amount of water availability throughout the system change substantially with increasing temperature, resulting in impacts to agricultural production and groundwater resources. Sterle and Singletary (2017) found that “rigid constraints to adaptation posed by existing water allocation institutions” is seen as a significant challenge facing water managers in the area. Models with the ability to simulate the legal framework that govern surface water allocation and the response of groundwater users to surface water shortfalls can provide managers with valuable information needed to plan for future conditions.

Data Availability Statement

Data sets used for this research study are available in these in-text data citation references: Streamflow (USGS, 2016), water rights (State of Nevada Division of Water Resources, 2016; United States v. Alpine Land and Reservoir Co., 1980), annual pumping rates and well logs (Clark, 2005; King, 2015; State of Nevada Division of Water Resources, 2019), and evapotranspiration (Huntington et al., 2018). Data for well locations, individual parcel locations, and the irrigation network are not publicly available due to privacy concerns but may be requested from the State of Nevada Division of Water Resources and Douglas County, Nevada Recorder’s office, respectively. The model software, input, output, and supporting files are available in the model archive (Kitlasten, 2021).

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