D. Yates[1*], J.K. Szinai[2,3,*], and A. D. Jones[2,3]

[1] National Center for Atmospheric Research, Boulder, CO, United States of America.

[2] Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, United States of America.

[3] Energy and Resources Group, University of California, Berkeley, CA, United States of America.

[*] These authors contributed equally

Corresponding author: David Yates (`yates@ucar.edu`)

Key Points:

- Interactions among hydro-climate, hydropower, and water's energy use are critical for evaluating Western US water-energy climate risks
- Under climate change, our Western US water model finds declining streamflows, growing agricultural demands, and increased groundwater use
- With warming and drying, water-related energy use grows while hydropower generation decreases under most climate scenarios by mid-century
- Higher energy use for water coincides with declining hydropower generation, suggesting the need for added grid capacity in the future

Abstract

Electricity and water systems in the Western US (WUS) are closely connected, with hydropower comprising up to 80% of generation, and electricity related to water comprising up to 20% of electricity use in certain states. Because of these interdependencies, the serious threat of climate change to WUS resources will likely have compounding electricity impacts, yet water system models rarely estimate energy implications, especially at the geographic scale of the expansive WUS water and electricity networks. This study, therefore, develops a WUS-wide water system model with a particular emphasis on estimating climate impacts on hydropower generation and water-related energy use, which can be linked with a grid expansion model to support climate-resilient electricity planning. The water system model combines climatically-driven physical hydrology and management of both water supply and demand allocation, and is applied to an ensemble of 15 climate scenarios out to 2050. Model results show decreasing streamflow in key basins of the WUS under most scenarios. Annual electricity use related to water increases up to 4%, driven by growing agricultural demand and shifts to energy-intensive groundwater to replace declining surface water. Total annual hydropower generation changes by +5% to -20% by mid-century, but declines in most scenarios. Energy use increases coincide with hydropower generation declines, suggesting additional energy capacity may be needed to achieve WUS grid reliability and decarbonization goals, and demonstrating the importance of concurrently evaluating the climate signal on both water-for-energy and energy-for-water.

Plain Language Summary

Electricity and water systems in the Western United States (WUS) are strongly interdependent. Water fuels hydropower generation and electricity is used to pump, transport, treat, heat, and dispose of water. Climate change poses a serious threat to water availability in the WUS, and is likely to also affect hydropower generation and electricity use related to water, adding to the challenges of keeping the electricity grid reliable going forward. This study develops a water system model to evaluate the impact of a set of climate change scenarios on water availability and demand in the WUS by 2050, and to test how hydropower and water-related electricity use changes as a result. We find that in many key basins, streamflow decreases under the climate scenarios. At the same time, reliance on groundwater increases to meet growing agricultural water demand. Hydropower generation shows decreases in most cases while energy use related to water increases. Because these hydropower generation declines tend to occur during periods when electricity demand for water grows, electricity grid planners will likely need to invest in added infrastructure to maintain grid reliability and decarbonization goals.

Introduction

Water systems are strongly tied to the electricity network, particularly in the Western United States (WUS), where electricity use for water includes water conveyance; municipal and agricultural groundwater pumping; potable water treatment, distribution, and heating; and wastewater treatment. It is estimated that about 6-7% of total electricity consumption across the WUS states is related to water, with some of the biggest single uses being inter-basin water transfers, such as those from the Sacramento-San Joaquin Delta of California and the Colorado River Basin to Arizona and Southern California (Tidwell et al., 2014). Simultaneously, hydropower is a key source of WUS electricity generation, comprising about 17% of WUS total electricity generation on average from 1990 – 2019, and making up as much as 77% of generation in Idaho (EIA, n.d.-b).

Both water and electricity systems are vulnerable to the impacts of climate variability and change, individually and often in reinforcing ways (McCabe & Wolock, 2007; Siirila-Woodburn et al., 2021; Dyreson et al., 2022). Across the WUS, higher temperatures and changes to the hydrologic cycle—including snowpack loss, earlier snowmelt, and more variable precipitation—are already occurring (Barnett et al., 2008; Dettinger et al., 2015; Hayhoe et al., 2004; Rhoades et al., 2018). Because of the inherently interconnected nature of the two systems, changing surface water availability affects hydropower generation, and in combination with increased water demand, raises associated energy use, such as for groundwater pumping (Madani et al., 2014; Moran et al., 2014). The electricity system further faces the compounding threat of higher demands for space cooling from higher temperatures (Vine, 2012; Turner et al., 2019; North America Electric Reliability Corporation, 2021).

While grappling with such climate stressors, many of the WUS electricity systems are also simultaneously working to decarbonize their generation portfolio (Dyreson et al., 2022). For example, California, Washington, and Oregon have set targets for 100% carbon-free electric generation (De León, 2018, p. 100; Morehouse, 2019; Sara Cline, 2021). However, reaching such zero emissions targets and integrating renewables could be more difficult and more expensive if there is a decline in carbon-free, and flexible resources like hydropower (Tarroja et al., 2016, 2019; Wessel et al., 2022), alongside an increase in energy demand (Diffenbaugh et al., 2015; Christian-Smith et al., 2015; Gleick, 2017; Kern et al., 2020). Problematically, reduced hydropower capacity is expected to lower dispatchable electricity generation for balancing intermittent solar and wind resources, challenging grid reliability (EIA, U.S. Dept of Energy, 2022).

Literature in the emerging field of Multi-Sector Dynamics emphasizes the gap in understanding of the complexities of coupled human-Earth systems, multi-sector interactions, and compounding risks, particularly in the context of these concurrent energy transitions and increased future climate shocks (Reed et al., 2022; Simpson et al., 2021). Despite recognition of the importance of evaluating the reliability and resilience of water and electricity systems to climate change and their cross-sectoral linkages (Allen et al., 2018; California Natural Resources Agency, 2018; Craig et al., 2018; Harrison et al., 2016; Liu et al., 2017; Molyneaux et al., 2012; U.S. Department of Energy, 2014), most long-term planning studies in the WUS have not adequately incorporated the three-way interactions between climate, electricity, and water (Bartos & Chester, 2015; Cohen et al., 2022; Craig et al., 2022; Marsh, n.d.; Parkinson & Djilali, 2015; Wei et al., 2017; White et al., 2017). One likely reason for this, is a lack of modeling tools that can readily address this triad. For example, Siirila-Woodburn et al., 2021 provide a comprehensive assessment of the possible hydrological impacts of reduced snowpack in the WUS under climate warming, but note the need for "modelling strategies that represent key human and natural system processes in a self-consistent manner" to fully quantify water management and subsequent electric system implications, and provide decision support for adaptation planning.

There are no models that we are aware of which are comprehensive in their spatial and temporal representation of the integrated nature of the WUS's water and electric systems. Therefore, there is a need for scale-appropriate models, which 1) capture the regional interdependencies of the inter-basin water transfers and transmission networks of the WUS water and electrical systems, respectively, and simultaneously represent 2) the hydro-climate of the WUS and 3) "water-for-energy" (i.e. hydropower) as well as 4) "energy-for-water" (i.e. energy demand for groundwater pumping, conveyance, water treatment, etc.) (Kern et al., 2020;

Lofman et al., 2002; Mehta et al., 2013; Mo et al., 2014; Tarroja et al., 2019; Wada et al., 2015). Further, there is a need for such coupled water and energy systems models to evaluate the implications of climate change in the WUS and its sub-regions to quantify climate impacts and feedbacks on the water and electricity sectors while exploring zero-emission grid pathways (Cohen et al., 2022; Wessel et al., 2022).

To address these gaps we develop a novel, large-scale Western U.S. Water Systems Model (WWSM), within the Water Evaluation and Planning (WEAP) decision support system, which combines climatically-driven physical hydrology and water supply and demand management representation, with hydropower generation and water sector electricity demand (D. Yates et al., 2005). WWSM can evaluate when, where, and for whom there may be water supply shortages, and quantify the conservation or alternative supplies needed to maintain system balance. In addition to elucidating such WUS-wide changes to the water system, WWSM was developed for the hydropower and energy demand results to serve as inputs to electricity planning models to determine the effect of water-related climate impacts on the Western Electricity Coordinating Council (WECC) grid region, the major synchronized grid in western North America (Figure 1a). WWSM could be linked with any capacity expansion model, but in particular, the geographic scope and the highly disaggregated representation of hydropower generation of WWSM are determined by the spatial extent and detail of the electricity capacity expansion model SWITCH (Solar, Wind, Conventional and Hydroelectric generation and Transmission), and its application to the WECC region (Johnston et al., 2019; Mileva et al., 2016; Sánchez-Pérez et al., 2022).

In this study WWSM quantifies changes in streamflow and water deliveries, and subsequent changes in hydropower generation (water-for-energy) and energy demand (energy-for-water), under an ensemble of mid-century climate change projections for the entire WUS. Under these climate scenarios, WWSM results show decreasing streamflow in key WUS basins, especially the Colorado. In most cases, electricity use for water also increases, driven by higher agricultural water demand and shifts to more energy-intensive groundwater, while hydropower generation declines. We find that energy use increases coincide with and exacerbate hydropower decreases, confirming the need for future WWSM application in conjunction with a grid planning model, to evaluate the risks and trade-offs among alternative climate adaptation strategies and decarbonization pathways in the WUS and the WECC. Further, the results suggest that WWSM can provide a promising Multisector Dynamics testbed for exploring the relative influences of various human and environmental processes on decision-relevant outcomes and the relative influences of various uncertainties arising from the climate system, hydrologic processes, infrastructure configuration, and management regimes (Reed et al., 2022).

The remainder of the paper is organized as follows: Section 2 provides details of WWSM, including a description of the WUS physical hydrology, WUS water management, and energy data used. Section 3 describes the calibration and validation process of WWSM, while Section 4 describes climate scenarios which were applied to WWSM in Section 5 to explore the impacts of climate change on water supply and demand, and the subsequent changes in energy-relevant metrics.

The western U.S. water systems model (WWSM)

The WWSM's study area includes the major basins and tributaries within the WECC region of the Columbia River, Snake River, Missouri River, Colorado River, Platte River, Salt River, Sacramento River, Feather River, San Joaquin River, among many others, and infrastructure such as the major conveyance projects for inter-basin water transfers, reservoirs, and hydropower generators. WWSM models irrigated agriculture throughout the WUS, and also divides the region into 47 (three more in Canada and Mexico) unique urban demand nodes that approximately correspond to electric utility boundaries with SWITCH-WECC (Figure 1b). WWSM uses a monthly time step, with the period 1980 through 2010 first used to evaluate the model's ability to represent historic water supply and use and associated energy generation and use attributes before running future climate scenarios.

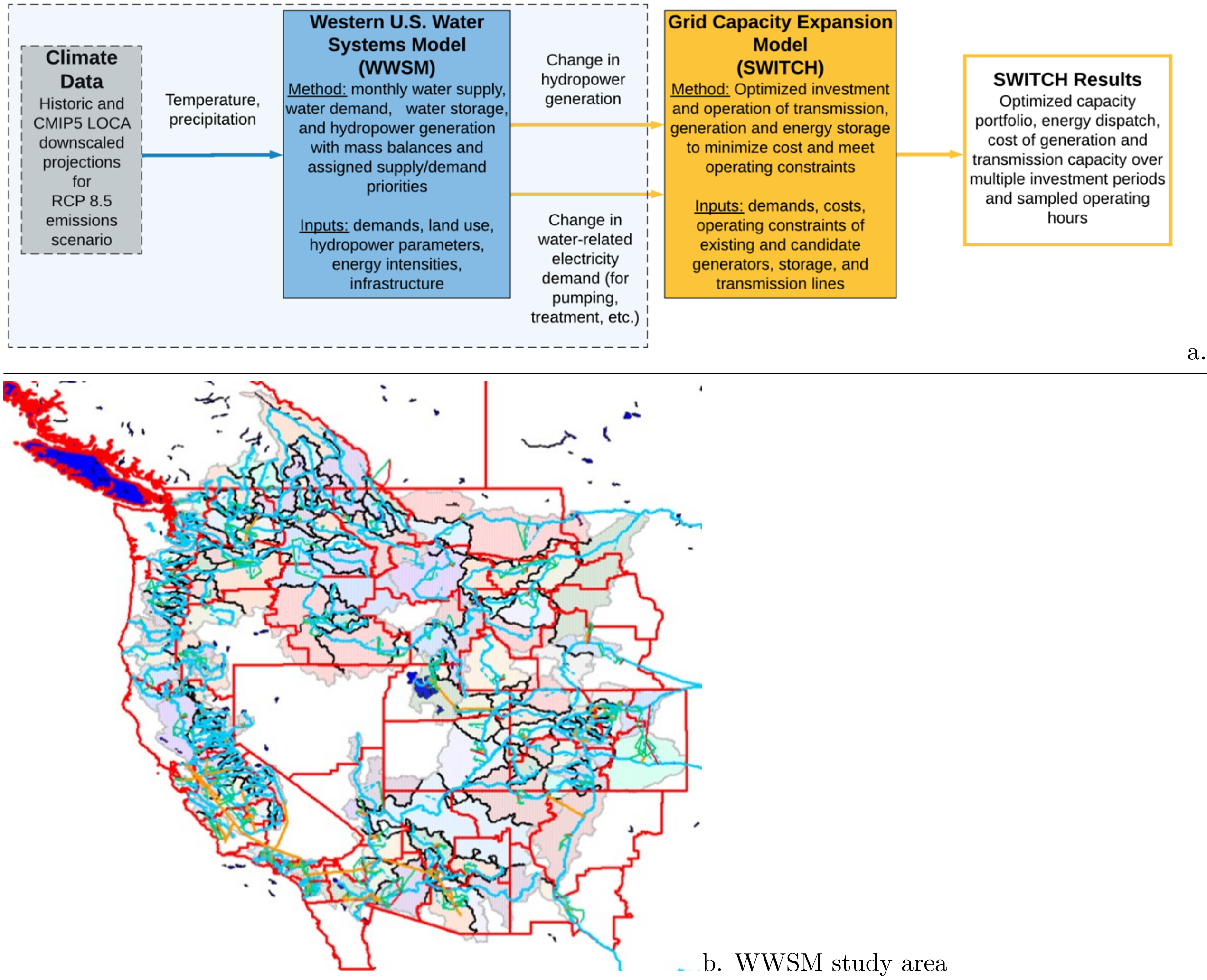


Figure 1. Climate-Water-Energy integrated modeling schematic and WWSM study area. a. This paper focuses on the methodology and results within the outlined box of the overall integrated Climate-Water-Energy modeling framework. Changes in hydropower generation and water-related electricity demand from WWSM are inputs into the SWITCH-WECC model, which are the subject of forthcoming studies. b. The map shows the WWSM study area the representation of the water system. Blue lines are rivers, orange lines are conveyance, green lines are transmission links between demands and supply sources, and the color-shaded areas are the various catchments. Red boundaries indicate the SWITCH-WECC load zone areas which are the boundaries of the urban water demand nodes.

The western U.S. water systems model (WWSM) and data

WWSM is developed within the WEAP platform, which is a hybrid water resources management and watershed hydrology tool that can evaluate different climate scenarios, land uses, demands, and policies (D. Yates et al., 2005). WEAP has been used to assess climate impacts on water management for numerous studies, including on energy-water linkages (Albrecht et al., 2018; Howells et al., 2013; Sattler et al., 2012; D. Yates et al., 2013; David Yates et al., 2013), and the details of the WEAP model algorithm are well documented (D. Yates et al., 2005). Therefore, here we describe the WEAP model at a high level and focus on the particular WWSM configuration and data used in this study.

Rivers, catchments, and groundwater basins

WWSM divides the WUS into the river basins identified through a collection of catchment objects disaggregated by 1000-meter elevation bands and categorized by land use-land cover (Agriculture, Forest, Grass and Shrub, Other, Urban, or Water) ("ESA CCI Land cover website," n.d.). Because a large focus of this analysis is on hydropower, catchments are primarily delineated according to the location of generators and important management points that correspond to gage locations, with major reservoirs as the outlet points of many associated rivers. This catchment delineation process results in 147 rivers and 311 catchments, comprising 2,170,000 km^2 (840,000 mi^2). These catchments characterize the hydrology of the land area to calculate runoff, agricultural irrigation demand, and urban outdoor irrigation demand. Groundwater aquifers are defined for the primary alluvial systems associated with irrigated groundwater pumping, with 50 unique groundwater basins identified, including those of Sacramento (CA), San Joaquin (CA), Phoenix Active Management Area (AZ), Denver Basin (CO), Salt River Basin (ID), Columbia Basin Groundwater Management Area (WA), and Willamette (OR). Groundwater parameters include horizontal distance from the river centerline, transmissivity and initial storage (D. Yates et al., 2005; Zimmerman, 1998). Groundwater storage levels were initialized for each basin, based on the steady-state, storage levels established through a 40-year simulation of WWSM that assumed no water use.

Water use and water infrastructure

Urban water demand in WWSM is disaggregated into a separate indoor and outdoor node for each of the 47 corresponding WUS SWITCH-WECC electric load zones (the 3 non-US zones are not modeled in WWSM). For each urban indoor node, water demand is modeled for the domestic and commercial and industrial (C&I) sectors as the product of a water use rate per-capita by sector * regional population ("USGS Water Data for the Nation," n.d.). WWSM indoor domestic per-capita water use is based on a US average value (60 gallons per capita per day, gpcd/220 liters per capita per day, lpcd) or city-level or state average data where data was found (ranging from 41 gpcd/160 lpcd for San Francisco to 68 gpcd/260 lpcd for Sacramento). For C&I water, because we lack data on production, square footage, etc. we assume demand also changes with population, and is only for indoor use from the commercial, industrial, mining, livestock, aquaculture, and thermoelectric sectors as categorized by USGS ("USGS Water Data for the Nation," n.d.). For all scenarios we assume per-capita domestic and C&I water use stays constant, and population grows annually in each region by 1% from 2015 levels ("USGS Water Data for the Nation," n.d.).

For urban outdoor water demands, we make a simplifying assumption that a certain fraction of the urban identified land-cover areas is irrigated (David Yates et al., 2021), and estimate water use for that area based on mass-balance equation similar to the methodology for irrigated agriculture. We extrapolate irrigation fractions from an estimate by the Los Angeles Department of Water and Power (LADWP), which reports there is about 85,000 acres (340 km^2) of greenspace in its service territory or about 25% of its total area assumed irrigated (Los Angeles Department of Water and Power, 2015). We use the LADWP value for less dense urban areas in the Southwest and lower fractions for wetter and/or more dense urban areas.

Water demand for irrigated agriculture is modeled for the agricultural land area multiplied by the fraction irrigated within each catchment (Pervez & Brown, 2010); (Homer, 2020). For this irrigated area, the water use is calculated as part of the mass-balance equation using a Penman-Monteith formulation of evapotranspiration (ET) an average representative crop coefficient, and seasonal soil moisture thresholds. Monthly irrigation thresholds are used to trigger an irrigation application for each agricultural catchment (Purkey et al., 2008). Additional details are in the SI.

Reservoirs, diversions, desalination, and reuse

133 of the major reservoirs of the WUS are included in WWSM, which together provide about 280 Billion m^3 (BCM) of available storage capacity. These reservoirs include those providing hydropower generation in the SWITCH model and the larger reservoirs in the WUS identified by the National Inventory of Dams (NID) with a primary purpose of water supply or hydroelectric generation ("National Inventory of Dams," n.d.). For reference, the NID lists more than 5,000 dams (215 BCM capacity) in the WUS with a primary purpose of water supply and hydropower, out of a total 11,000+ dams (400 BCM capacity). Parameters to characterize reservoir storage capacity and volume-area relationship are from NID data and state and local water resource databases, and each reservoir's surface evaporation is included in the mass balance based on the temperature data of the catchment where each reservoir is situated.

The WWSM's major conveyance projects include: California: the State Water Project (SWP; the California Aqueduct and Coastal, East, and West Branches), Central Valley Project (CVP), Friant Kern Canal, Los Angeles Aqueduct, Colorado River Aqueduct (CRA), and the All-American Canal (AAC); Arizona; the Central Arizona Project (CAP); Utah: the Central Utah Project; Colorado:

the Roberts Tunnel, Moffat Tunnel, Frying Pan-Arkansas and the Colorado-Big Thompson Projects; and Washington: the Columbia Basin Project. To mimic current operations, for the SWP and CVP, releases are constrained based on available volumes determined by a water year categorization, calculated based on a river index of the Pit and Feather Rivers' streamflow. Water deliveries are driven by monthly demand, but a monthly pattern of maximum releases is imposed based on historical allocations, along with an annual maximum constraint based on contracted annual volumes (California Department of Water Resources, n.d.).

One desalination plant in Carlsbad, California ("Carlsbad Desal Plant," n.d.), providing water to San Diego, is included as it is the largest desalination plant in the US (producing 50 million gallons per day). Other, much smaller, plants in California are excluded (California State Water Resources Control Board, n.d.). WWSM also includes non-potable reuse to supply urban outdoor demand up to 5% of the urban indoor return flows in the drier Southwest states (California, Arizona, and Nevada).

Hydropower generators

There are 192 individual hydropower generators in WWSM, which together provide about 48 GW of installed capacity. In the US portion of the WECC, these are all the generators greater than 30 MW, the threshold used by California to denote large hydropower (Commission, current-date). Only one generator is included in Canada, because of limited data available for calibration. Hydropower generators are either modeled as run-of-river or with reservoir storage. Power is generated as WWSM releases water from the reservoir, or as water flows through the run-of-river turbines, and generators are parameterized based on head, tailwater elevation, and max turbine flow. WWSM generation is further calibrated to match as closely as possible the historical monthly and annual generation patterns. Data is from Energy Information Administration (EIA) , NID, and US Bureau of Reclamation (USBR) data, and filled in as much as possible from other publicly available documentation such as Federal Energy Regulatory Commission (FERC) filings and utility websites. ("Bureau of Reclamation," n.d.; "Form EIA-923 detailed data with previous form data (EIA-906/920)," n.d.; "National Inventory of Dams," n.d.; EIA, n.d.-a). Additional detail is in the SI.

Energy demand for water

Electricity powers all stages of the managed water cycle (Table 1) including groundwater pumping, long-distance conveyance, treatment, use, wastewater treatment, reuse, and desalination. In WWSM, we track this embedded energy by multiplying energy intensity values (energy use per unit of water, kWh/m^3) with the monthly water volumes calculated in WWSM throughout the stages of this managed water cycle. Energy intensity values are either derived from endogenous model data (i.e. groundwater pumping based on water depth), exogenous calculations (distribution energy, water heating energy, agricultural energy), or averages across literature (desalination, treatment, wastewater treatment, reuse) as described below and the SI.

Table 1. Energy intensity of managed water cycle in WWSM. The first column shows the stages of the water cycle with embedded energy starting from supply extraction/generation, for groundwater pumping, desalination, or conveyance of surface water. Urban water is treated to potable quality (agricultural water is assumed untreated). Water is distributed to end-users, for irrigation or heating. Urban wastewater is treated and then returned to the environment or treated for reuse. Energy intensities in WWSM are explained in subsequent columns and values averaged from the literature are from the following sources, unless otherwise noted: (Cooley & Wilkinson, 2012; GEI Consultants/Navigant Consulting, 2010, p. 1; GEI Consultants/Navigant Consulting & GEI Consultants/Navigant Consulting, 2010, p. 2; Klein et al., 2005; Liu et al., 2017; Stokes-Draut et al., 2017; Tarroja et al., 2014; Tidwell et al., 2014).

@ >p(- 6) * >p(- 6) * >p(- 6) * >p(- 6) * @ Stages of managed water cycle with embedded energy & Energy use category & Energy Intensity & Description & Groundwater Pumping & 0.005 kWh/m^3 per meter of lift & Calculated as $E = \frac{q\rho \text{gh}}{n}$, where: q is the simulated monthly volumetric flow rate;

h is the differential height of the lift from the aquifer's simulated depth-to-water-table;

ρ is water density; and

n is an average pump efficiency which we assume to be 0.49 averaged from (Burt et al., 2003; Green & Allen, n.d.).
& Conveyance & 0.005 kWh/m^3 per meter of lift & Calculated as $E = \frac{q\rho \text{gh}}{n}$, where:

q is the simulated monthly volumetric flow rate;

h is the lift height for specific projects (listed in SI);

ρ is water density; and

n is an average pump efficiency which we assume to be 0.57 from (Burt et al., 2003).
& Desalination & 3.8 kWh/m^3 & Seawater desalination electricity averaged from literature.
& Potable Water Treatment (Urban) & 0.3 kWh/m^3 & Conventional drinking water treatment electricity applied for all urban (not agricultural) deliveries, averaged from literature.
& Water distribution & Varies by urban demand node, see SI & Pumping and distribution electricity to bring water from treatment plant to end-user applied to all urban water deliveries. Urban demand nodes are assigned "hilly", "moderate", or "flat" energy intensities (0.26, 0.13, 0.01 kWh/m^3 respectively

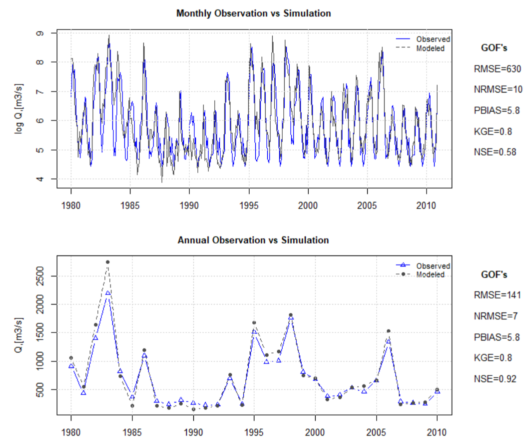
(McDonald et al., 2014)) based on a ranking of their average calculated slope-length values (Homer, 2020; "HydroSHEDS," n.d.).
& Agricultural water use & 0.125 kWh/m^3 & Agricultural water use electricity includes local surface water deliveries (averaged from literature, applied for non-groundwater deliveries) + irrigation (weighted average based on applied water by crop in CA ("Agricultural Land & Water Use Estimates," n.d.), typical irrigation technology by crop ("Statewide Irrigation Systems Methods Surveys," n.d.), and energy intensity by irrigation technology (Burt et al., 2003)).
& Domestic water heating & Varies by urban demand node, see SI & Water heating electricity for domestic water only (not C&I) is calculated as product of the average electric water heater saturation by state ("Residential Energy Consumption Survey (RECS) Table HC8.8 Water heating in homes in the South and West regions, 2015," n.d., p. 8), the average hot water share in typical US residential homes (33.2%) (William B. DeOreo et al., 2016), and the specific heat of water based on typical water heater characteristics (90% efficiency, about 44°C of warming based on average 10°C inlet and 54°C outlet temperatures).
& Wastewater Treatment & 0.5 kWh/m^3 & Secondary wastewater treatment electricity applied to return flows from all urban indoor water averaged from literature.
& Non-Potable Reuse Treatment & 0.3 kWh/m^3 & For non-potable reuse, an energy intensity is applied for the incremental treatment above secondary wastewater treatment from literature.

Demand priorities and supply preferences

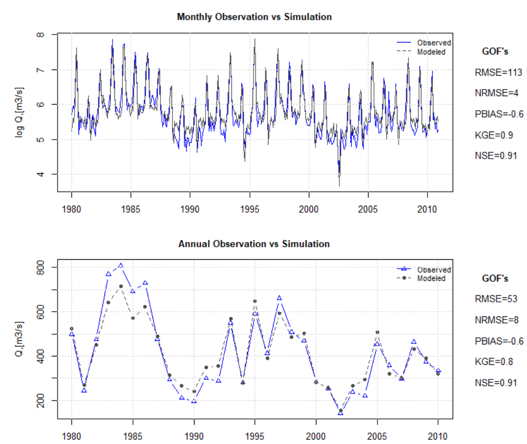
WWSM determines the monthly water allocation order from supply sources to demand sites, and for instream environmental flow requirements, reservoir storage, and hydropower generation based on a user-defined priority system (D. Yates et al., 2005). Priorities represent water rights, and are also important during a water shortage, in which case higher priorities for critical demands (i.e., urban water supply) are satisfied as fully as possible before lower priorities are considered. Consistent with the way water is generally managed in the WUS, we assign demand priorities as follows (with 1 being the highest priority): 1) environmental flows, 2) urban (both indoor and outdoor), 3) agriculture, 4) reservoir storage, and 5) hydropower. We have attempted to systematically identify water supply sources for both agricultural and urban demands, including their preferences and capacities. We therefore assign water supply preferences as follows: 1) reuse (when available, for urban outdoor only), 2) surface water, 3) groundwater. These priorities are used as a baseline for this analysis; future work will test scenarios with different priorities, for example, to evaluate the impact of conservation efforts by lowering the priority for urban outdoor water.

Calibration and Validation

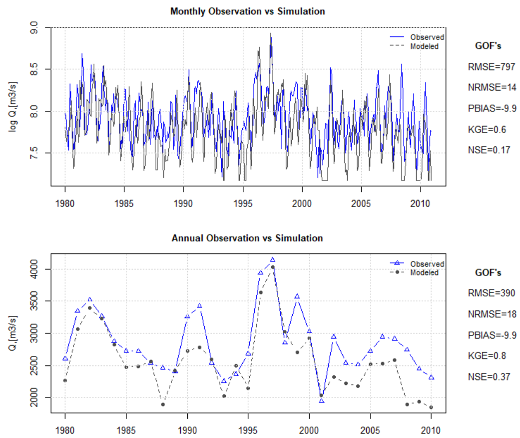
Using 1980 – 2010 climate data (Livneh et al., 2013), WWSM is calibrated against historical observations for its modeled streamflow. Catchment hydrological parameters, including soil water capacities and hydraulic conductivities, are first estimated from the soil database STATSGO (U.S. Department of Agriculture, n.d.) and two parameters, leaf area index and an evaporative or "crop" coefficient, are applied to the specific land use categories within each sub-catchment (David Yates et al., 2021). Then a manual calibration is undertaken, including consideration of reservoir operations, where modeled streamflow and diversions are compared to observations ("USGS Water Data for the Nation," n.d.) using goodness-of-fit statistics. After calibration, WWSM is generally skillful at reproducing large-scale WUS hydrologic characteristics for both monthly and inter-annual variability. For key WUS locations WWSM captures seasonality and volume of flows well, with positive NSE values and biases below 10% (Figure 2). Although biases are generally low, the managed flows do show lower skill (poorer correlations as measured by NSE and KGE) because WWSM is driven by monthly water demands and not individual delivery contracts.



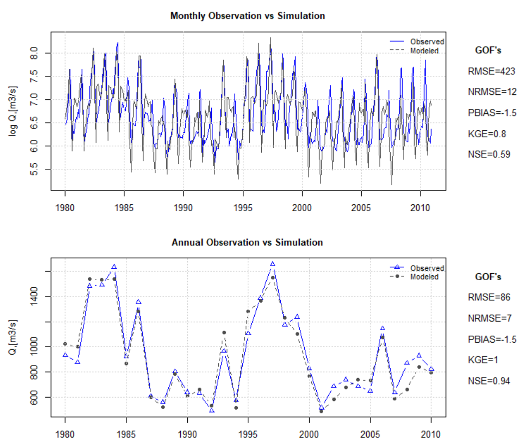
@ >p(- 2) * >p(- 2) * @ a. Sacramento Delta Outflow



& b. Colorado River Inflows into Lake Powell
c. Columbia River below Grand Coulee Dam, WA



& d. Snake River near Anatone, ID



e. SWP and CVP, CA & f. Total Lower Colorado River Deliveries

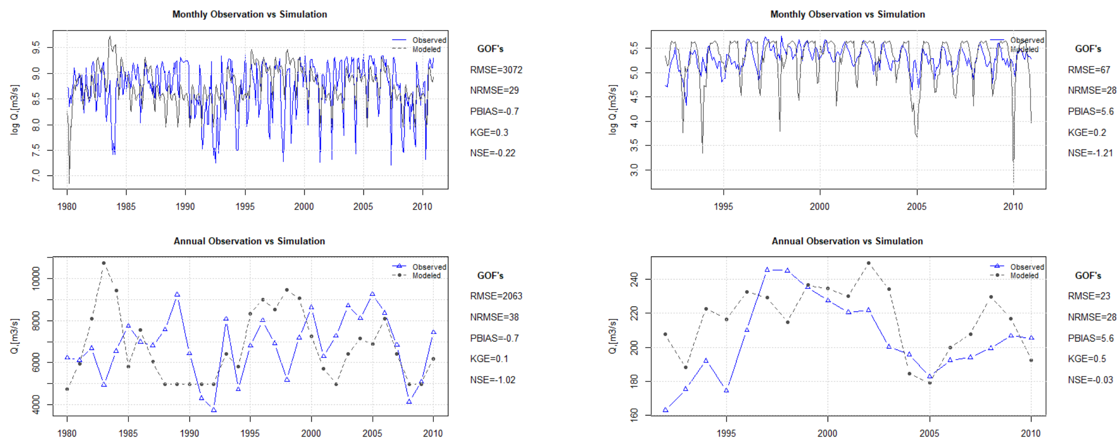


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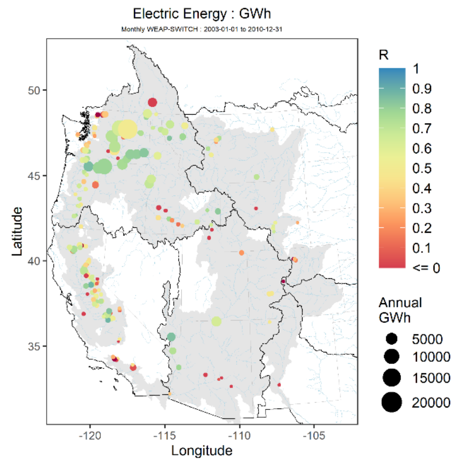
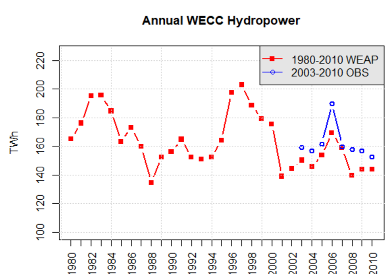
Figure 2. Annual and monthly observations compared to WWSM simulation results for historical period for key streamflow locations. Monthly (top) and annual (bottom) a. outflows of the Sacramento-San Joaquin Delta of California, b. Colorado River inflows into Lake Powell, c. Columbia River flows below Grand Coulee Dam, WA, d. Snake River inflows near Anatone, ID, e. Total diversions of the California SWP and CVP from the Sacramento-San Joaquin Delta, and f. Total Lower Colorado River diversions, including from the Central Arizona Project (CAP), All American Canal (AAC) to California, and the Colorado Aqueduct (CRA) to California. Note that the annual simulation results are higher than observed for the Colorado deliveries because we have included CAP as fully online from the start of the simulation, although CAP only became fully operational around 1997. Each figure has several goodness-of-fit (GOF) statistics including Root Mean Square Error (RMSE, cms), Normalized Root Mean Square Error (NRMSE, %), percent bias (PBIAS), Nash-Sutcliffe Efficiency (NSE), and Kling Gupta Efficiency (KGE). KGE scores, which combine correlation, variability bias and mean bias, greater than -0.41 indicate the model improves upon the mean flow benchmark (Knoben et al., 2019).

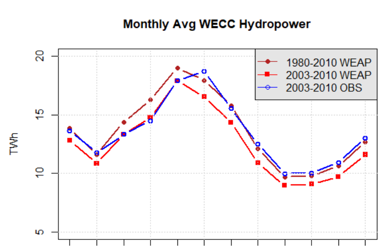
Hydropower generators are also configured individually to approximate annual and seasonal historical generation trends (Figure 3a); the resulting WWSM total 1980-2010 annual average generation is 164 TWh compared to the observed 162 TWh (Figure 3b). WWSM also captures monthly generation patterns well (Figure 3c, total generation-weighted R^2 of 0.84), although the peak generating month is shifted slightly early compared to observations; this is likely because WWSM does not explicitly incorporate the electricity market into the simulation (Hill et al., 2021).

Validating energy consumption related to water is challenging because comprehensive, disaggregated, and multi-year observational data is lacking. Recognizing these challenges, WWSM's historical results for total annual average energy use (45 TWh excluding water heating, and 70 TWh including water heating) are within the order of magnitude of the limited comparable estimates (such as Tidwell et al. (2014), 55 to 71 TWh excluding water heating). Further details on WWSM performance for streamflow, hydropower generation, energy use, and water supply deliveries by sector are in the SI.



@ >p(- 2) * >p(- 2) * @ a.
Annual generation and correlation & b. Annual total WECC hydropower





& c. Monthly avg. WECC hydropower

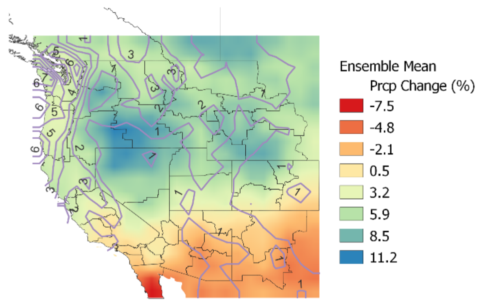
Figure 3. WWSM hydropower generation calibration results for his-

torical period over the WECC region. a. shows the correlation between the observed and WWSM simulated monthly hydropower for each of the 192 generators (the dark boundaries are the major drain basins of the WUS), b. is the annual generation as the sum of all hydropower generators, and c. is the monthly average of the WWSM simulated generation for the full period 1980 to 2010 and the shortened period 2003 to 2010 corresponding to the EIA observations.

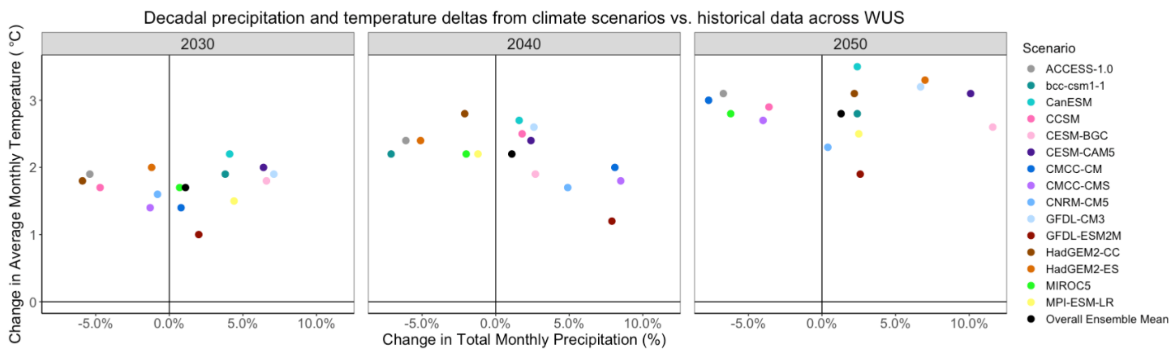
Climate Scenarios

To explore the impacts of climate change, the calibrated WWSM is run with an ensemble of future climate projections from the Coupled Model Intercomparison Project – Phase 5 (CMIP-5), following the general approach that has evolved in the literature making use of simulations from different General Circulation Models (GCMs) that consider the range of future climate uncertainty (Brekke et al., 2008; C. F. McSweeney et al., 2015; Carol F. McSweeney et al., 2012). We use a collection 10 climate projections from GCMs identified by the State of California's Department of Water Resources (DWR) as those that produce the most skillful simulations of global, regional, and California-specific climate features (Lynn et al., 2015) and 5 additional GCMs that performed well for the Southwest region and the Pacific Northwest region (Rupp et al., 2013). Each of the 15 models of the final ensemble (ACCESS-1.0, CCSM, CESM-BGC, CMCC-CMS, CMCC-CM, CESM-CAM5, CNRM-CM5, CanESM, GFDL-CM3, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, MIROC5, MPI-ESM-LR, bcc-csm1-1) is used to generate a climate scenario with monthly average temperature and monthly total precipitation by catchment and elevation band to force WWSM for the period 2020 to 2050 (Pierce et al., 2015). These GCM projections have been statistically downscaled based on the Locally Constructed Analog (LOCA) method (Lynn et al., 2015) and use the Representative Concentration Pathway (RCP) 8.5 level of emissions. We compare climate scenario results with a Reference scenario that represents "no climate change", constructed by repeating the historic climate of 1980 to 2010 (Livneh et al., 2013) for this future period.

The future period's ensemble mean percent change in precipitation and absolute change in temperature (ºC) relative to the historical climate has generally wetter conditions to the North and Northwest and drier conditions in the Southwest, with warming prevalent throughout the WUS, although more pronounced in the interior region and the upper Colorado basin (Figure 4a, Figure 4b) (Christensen, J.H., et al., 2013; K. et al., 2018). Comparing the models on average across the entire WUS study domain, there is strong agreement that the warming trend increases over time across all scenarios (Figure 4c). In each of the 2030, 2040, and 2050 decades, the ensemble mean shows a +1% increase in total WUS monthly precipitation relative to the 1980 – 2010 period. However, there is significant internal and inter-model variability on precipitation changes within the ensemble and over time, with about half the models projecting increases and half projecting decreases in each decade (i.e. range of ~-10% to +10% precipitation change in 2050 decade between models) and different directions of change over time (i.e. HadGEM2-ES -5% in 2040 and +7% precipitation in 2050) (Figure 4c). More details are in the SI.



a. Ensemble difference in precipitation



c. Decad

Figure 4. Summary of ensemble of climate scenarios. The change in ensemble a. average of daily precipitation for precipitation [%] and b. temperature [°C] derived from the historic period (1980 to 2010) relative to the future period (2020-2050) for all 15 GCMs. The contour intervals show the daily average A. precipitation [mm/day] and daily average B. temperature [°C] for the historic period over the domain. The change fields were resampled to a higher resolution using bilinear interpolation for the purpose of illustration. The ensemble members are the following GCMs: ACCESS-1.0, bcc-csm1-1, CCSM, CESM-BGC, CMCC-CMS, CMCC-CM, CESM-CAM5, CNRM-CM5, CanESM, GFDL-CM3, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, MIROC5, and MPI-ESM-LR. The map boundaries are the WECC load zone regions from the SWITCH capacity expansion model. c. The decadal 2030 (2026 – 2035), 2040 (2036 – 2045), and 2050 (2046 – 2055) average change in monthly precipitation [%] and monthly average temperature [°C] relative to historical period (1980 to 2010) for all 15 GCMs used for the climate scenarios, as well as the overall ensemble mean, across entire WUS study domain.

Results and Discussion

The large geographic extent of WWSM, and the inclusion of both hydrology and water resources infrastructure, allow for evaluation of how climate change impacts could propagate across the connected water systems of the WUS region. In addition to representing the coupled human-earth system related to water, WWSM evaluates how the climate signal on water affects both electricity use and generation, which is particularly important to inform grid planning to determine if, when, and how much generation, energy storage, and/or transmission infrastructure is needed to simultaneously adapt to climate change and meet decarbonization goals.

To address these challenges, we present results from the calibrated WWSM for streamflow, water supply deliveries to different sectors, hydropower generation, and energy use related to water under the climate scenarios compared to the Reference Scenario. While WWSM produces many more results related to the hydrology and water management of the WUS, we focus here on outcomes that are most relevant to connections with the energy system, as these are the features that can inform electricity system planning under climate change.

1.

Hydrological and managed water system

(a)

Streamflow

Streamflow is the key driver of hydropower generation and water supply deliveries and associated energy use. For the climate ensemble evaluated in this study, across nearly all the key basins in WWSM, annual average streamflow as well as managed flows decline under the climate scenarios for $2020 - 2050$ compared to historical average flows (Figure 5). California is somewhat an exception, where there is an ensemble average increase in runoff in the northern Sierra of about 4%, with a countering decline of about 3% in the southern Sierra basins (Ishida, 2017; Maloney, 2014), and thus additional water is delivered to the SWP and CVP under increasing demands due to warming. These minimal changes to streamflow in California headwaters are likely because the region's runoff is mainly driven by mid-to-late winter precipitation when temperature increases have less impact (David Yates et al., 2021).

Consistent with the literature (Warner et al., 2015) and based on ensemble precipitation and temperature trends (Figure 4), in the Northwest mean annual flows are slightly smaller than the historic period, while for the northeastern Missouri Basin mean annual flows decline by 12% (Sunde et al., 2017). The Colorado River, as measured by inflows into Lake Powell, shows a mean annual decline of 11% with a median decline of 14% (Milly & Dunne, 2020). Mean flows in the Sacramento/San Joaquin Delta remain close to historical levels, consistent with the runoff observations (Forrest et al., 2018). These changes in streamflow are driven by the patterns of precipitation declines primarily in the Southwest and Lower Colorado and warming most prominent in the Interior West (Upper Colorado) and in the Missouri River basin (Figure 4). Generally, increases in precipitation are overwhelmed by increased evaporative losses due to warming.

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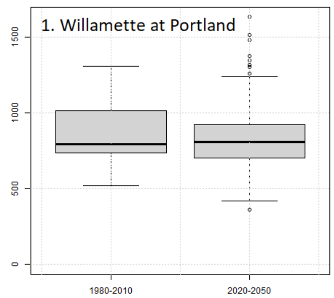

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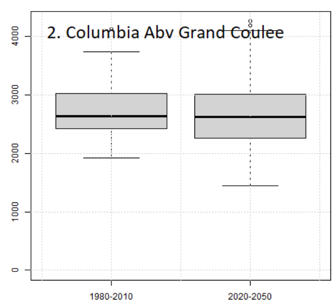

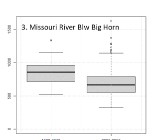

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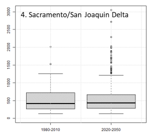
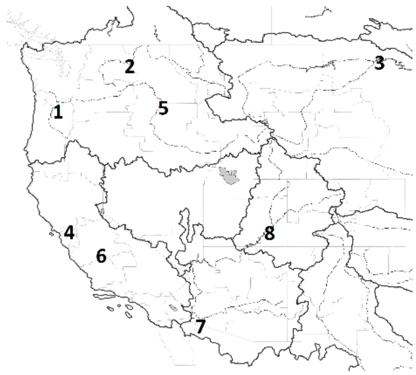

4. Sacramento/San Joaquin Delta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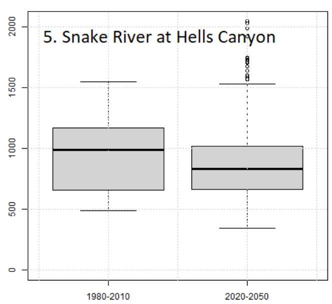
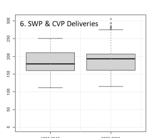

5. Snake River at Hells Canyon
2000
1500
1000
500
0
1980-2010
2020-2050


6. SWP & CVP Deliveries

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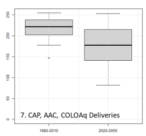

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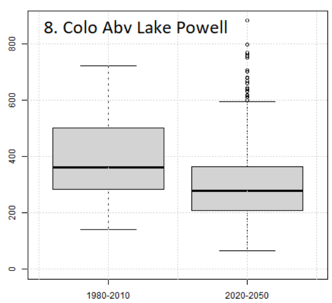
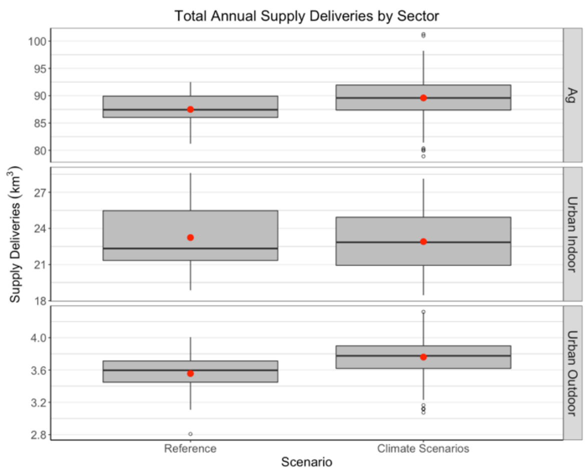


Figure 5. Annual average streamflow results for select WUS locations from WWSM under climate scenarios compared to Reference scenario. Annual average flows (cms) based on climate of the historic period (1980 to 2010) and from across all the climate scenarios for the future period (2020-2050) for select locations across the WUS. The dark boundaries are the major drain basins of the WUS, while the light boundaries are the WECC regions. Panel 6 is the sum of State Water Project (SWP) and Central Valley Project (CVP) deliveries. Panel 7 is the sum of Central Arizona Project (CAP), All American Canal (AAC), and the Colorado Aqueduct (ColoAq).

Water supply deliveries by sector

Water deliveries to end-users depend on interactions between supply availability (related to streamflow, groundwater and reservoir storage, and inter-basin water transfers), demand (which may be sensitive to temperature and precipitation changes), and allocation priorities of supply and demand. Accounting for these dynamics, for each climate scenario WWSM solves for water supply deliveries to each WUS demand node; here we summarize annual results aggregated across the study domain by sector for the climate ensemble to highlight broad trends in water resources expected by mid-century for the WUS as a whole. Additional work is needed to evaluate the sensitivity of these results to the underlying assumptions of population growth, priority levels, crop coefficients, and physical limits on groundwater supply, and to test scenarios of urban and agricultural conservation programs.

@ >p(- 2) * >p(- 2) * @ a. Total WUS annual supply deliveries, by sector



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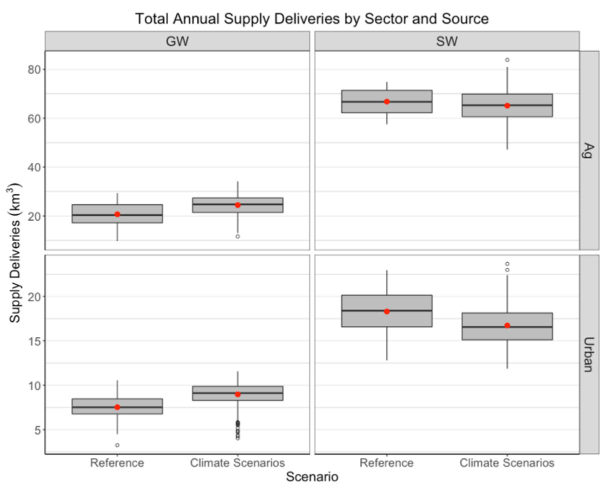
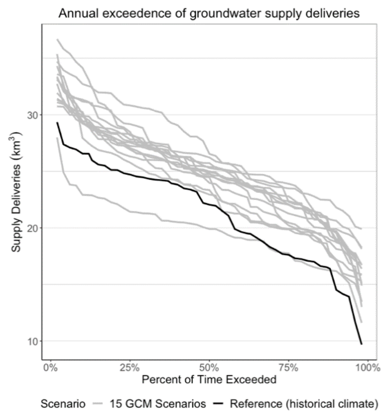
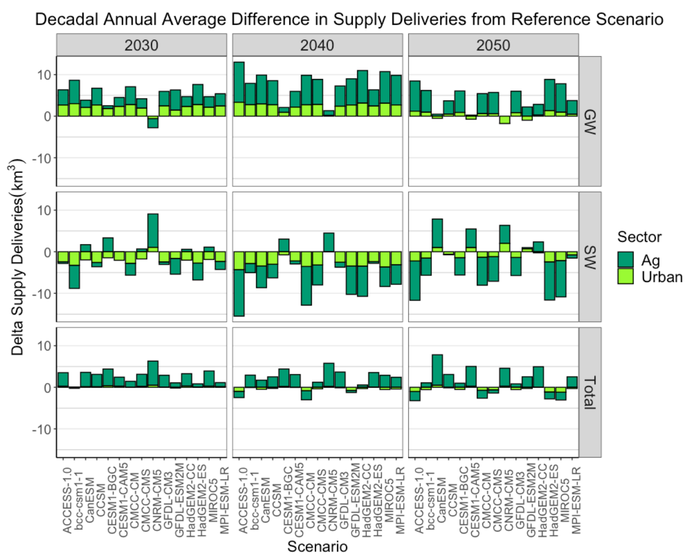
b. Total WUS annual supply deliveries, by sector and source





c. Annual exceedance of groundwater supply deliveries for agricultural sector & d. Average annual change in supply deliveries for each decade



relative to Reference scenario, by sector and source

The agricultural sector is the largest water user in the WUS, and with warming and drying, deliveries in WWSM under the climate scenarios rise to meet growing irrigation demands if there is available water. Over the study period, annual WUS supply deliveries for agricultural irrigation increase on average by +2% (2 km^3) for the ensemble compared to the Reference scenario annual average of 88 km^3 (Figure 6a). However, under the climate scenarios, with increasing demand and decreasing surface water availability (Figure 5), groundwater becomes a larger share of the overall water supply (Figure 6b). This supply substitution occurs for all sectors but is especially stark for agricultural users, wherein all but one climate scenario has groundwater use exceeding that of the

Reference in nearly all years (Figure 6c). Further, by the 2050 decade, growing agricultural demands may not be fully met in the warmest/driest scenarios in the ensemble (such as ACCESS-1.0 and CMCC-CM, Figure 4b) because they have lower priority and supply is simultaneously more limited from decreasing surface water and groundwater reaching physical capacity limits, which we have assumed remain constant according to the historic period estimates. These results concur with other findings, that without groundwater management and/or water conservation, WUS groundwater storage will continue to decline (Alam et al., 2019; Famiglietti et al., 2011), and point to a future application of WWSM to evaluate policies such as California's Sustainable Groundwater Management Act ("SGMA Groundwater Management," n.d.). Groundwater pumping has a higher energy intensity than local surface water sources, thus substitution of supply sources also has implications for energy use which we discuss in the next section.

Like the agricultural sector, water demand for urban outdoor use is also sensitive to climate warming and drying, but supply deliveries increase under all climate scenarios because urban users have higher priority. Urban outdoor water use shows an ensemble average increase of +6% (0.2 km^3) and a range of increases across the scenarios from +2% to +7% (+0.1 km^3 to +0.3 km^3) from a Reference annual average of 4 km^3 (Figure 6a). In contrast, the urban indoor sector has minimal changes, -3% to +1% (-0.7 km^3 to +0.2 km^3) relative to the Reference (23 km^3). This is expected because indoor use is not directly sensitive to climate change, thus increases in absolute water use are generally from the population growth rate assumption we have imposed (Figure 6a). However, indoor water supply deliveries are indirectly affected under the climate scenarios if there is a shortage, such that demands cannot be met and there is endogenous conservation. This can be seen in the 2050 decade as the water system reaches its limits in the driest/warmest scenarios (such as ACCESS-1.0, Figure 4b), when surface and groundwater deliveries decline and agricultural deliveries also decrease (Figure 6d). In those scenarios, we can further quantify the energy savings that would result from water conservation (described in next section) by avoiding energy use for conveyance, treatment, distribution, wastewater treatment, and water heating (Sowby & Capener, 2022; Spang et al., 2018; Stokes-Draut et al., 2017; Szinai et al., 2020).

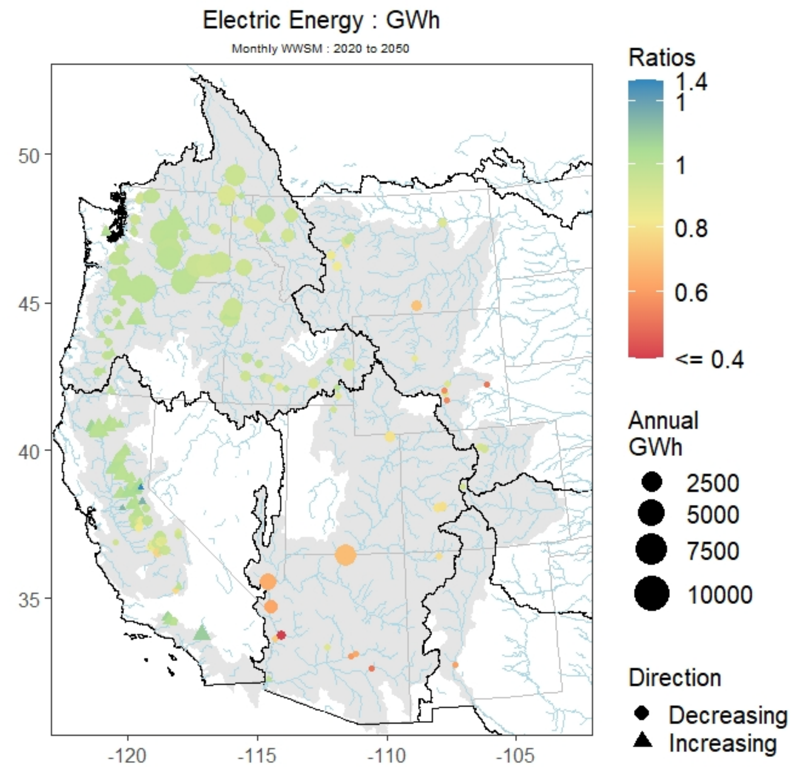
Electricity generated and used in the water sector

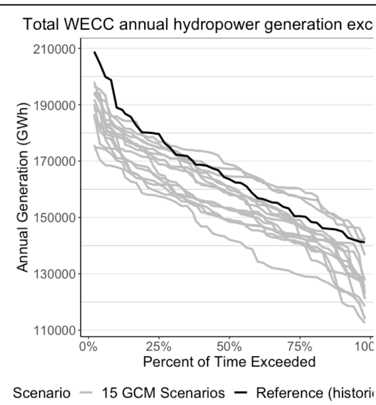
Here we evaluate how changes in streamflow, groundwater use, and water demands under climate change affect water available for hydropower generation, as well as the energy used to pump, move, treat, heat, and dispose of water throughout the WUS, and the implications these changes have for energy system planning.

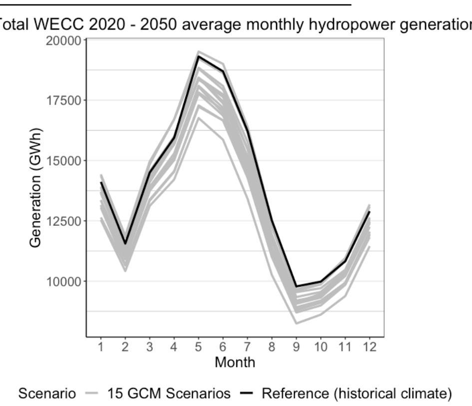
Hydropower generation

Across the ensemble of climate scenarios, WWSM shows a declining trend in total annual hydropower generation in the WUS. Annual generation levels are lower than those of the Reference scenario in about 75% of the years of the study period for all but three GCMs in the ensemble (Figure 7b). There are also no scenarios that produce total annual generation levels at the high end of the Reference (around 210 TWh), suggesting that grid planners will have to adjust estimates of both average and peak hydropower availability. However, there is geographic variation, with the greatest declines for generators in the Southwest (Figure 7a) and some loss in the northeast Missouri River basin, as a consequence of reduced flows (Figure 5), compared to modest declines or increases in generation in the Pacific Northwest (Boehlert et al., 2016), where climate projections suggest precipitation stays around historic levels or becomes slightly wetter (Figure 4).

a. Annual Change in Generation as Ratios (2020 to 2050 relative to 1980 to 2010).







c.

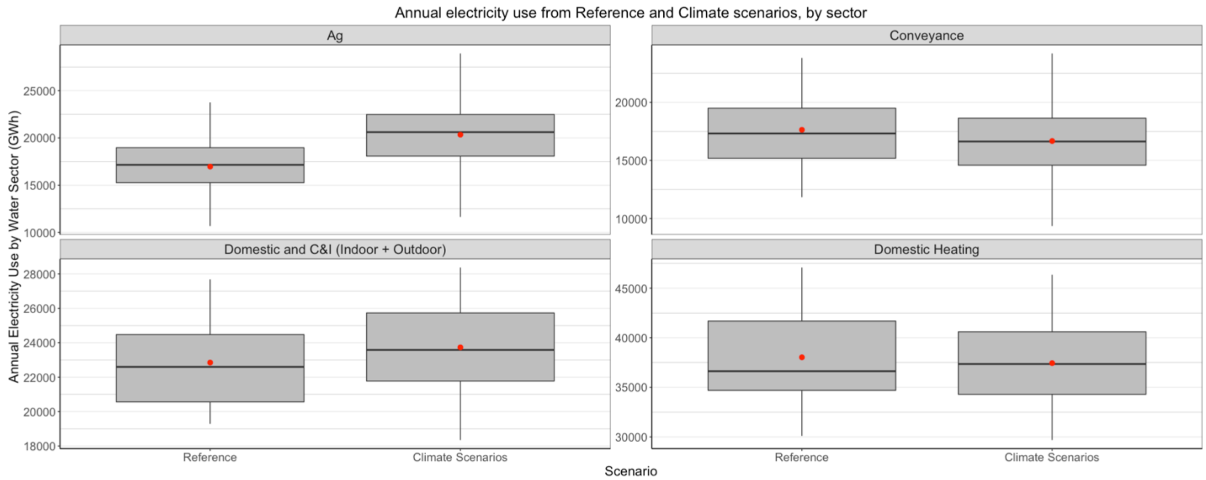
WECC annual hydropower exceedance

WECC average monthly hydropower generation

In addition to annual declines throughout the WUS, climate warming decreases generation especially over the summer months, and increases in the spring months in some scenarios (Figure 7c). This pattern is consistent with prior work (Boehlert et al., 2016; Hill et al., 2021), suggesting that generators supplied by runoff from snowmelt are particularly vulnerable snowmelt occurring earlier in the year (Hayhoe et al., 2004; Rhoades et al., 2018; Siirila-Woodburn et al., 2021). Decreases in annual and summer hydropower, especially in certain power-exporting regions, are likely to challenge grid decarbonization efforts. Firstly, hydropower is not only a carbon-free generating source, but also one that can be dispatched and operated in a flexible way to buffer intermittent solar and wind generation at sub-hourly time scales (Chang et al., 2013). With climate impacts that decrease streamflow and hydropower, dispatchable natural gas generators may be used to replace lost hydropower generation, increasing costs, GHG emissions, and electricity market prices (Christian-Smith et al., 2015; Gleick, 2017; Kern et al., 2020; Tarroja et al., 2019; Wessel et al., 2022). Seasonal hydropower changes may also exacerbate peak capacity needs when higher loads for air-conditioning during summer months are already expected (Kern et al., 2020), and in regions like California, increase springtime curtailment of solar generation (Tarroja et al., 2019; Wessel et al., 2022). Finally, declining hydropower generation is likely to have regionally propagating effects on grid operations in California, which has historically relied on imported electricity from Colorado River (i.e. Hoover Dam) and Pacific Northwest hydropower (Dyreson et al., 2022), and which may see electricity market price spikes if electricity demand increases coincide with less reliable imports (Hill et al., 2021).

Energy demand for water

As climate change affects water demands and supply deliveries from various sectors and sources, the associated energy use is also affected. Over the future study period, the total average annual energy use related to the WUS water sector across the ensemble increases +3% to 98 TWh from the Reference scenario average of 95 TWh, with changes ranging from -0.3% to +4 % (-0.3 TWh to +4 TWh) across the climate scenarios. We disaggregate these results into energy use for agricultural water (includes energy for groundwater pumping, local deliveries, and irrigation), domestic and C&I (urban) indoor and outdoor water (energy related for groundwater pumping, reuse, or desalination; distribution; treatment; and wastewater treatment), conveyance (non-gravity-fed inter-basin transfers to either agricultural or urban users), and domestic water heating. While the change in total energy use related to water is relatively small, among these disaggregated categories, there are significant and sometimes offsetting results.



The strongest climate signal on energy demand related to water (Figure 8) comes from the agricultural sector, which increases +20% (3 TWh) on average across the ensemble. Among individual scenarios, annual agricultural energy use increases up to +32% (5 TWh), and only one scenario (CNRM-CM5) of 15 shows a decrease in average annual agricultural energy use (-9%, -2 TWh). These changes are driven by the level of groundwater pumping of each scenario relative to the Reference. The energy use for groundwater extraction increases not only with greater volumes, but also with increasing aquifer depths, creating an amplifying effect on electricity demand as surface water supplies are constrained and groundwater fills supply gaps (Figure 6).

Although energy for agricultural water in the WUS is the most sensitive to climate warming, the largest overall energy user is the urban sector, driven by domestic water heating (Figure 8) as well the energy for potable indoor and outdoor use. This domestic and C&I energy use increases +4% (0.9 TWh) across the ensemble of climate scenarios compared to the Reference, corresponding to the increase in supply deliveries on average for outdoor use, as well as shifts to more energy-intensive groundwater. In most cases, energy use for domestic heating throughout the WUS has minimal change because it is not directly sensitive to climate warming, but energy use decreases with lower urban water use in scenarios where WWSM imposes endogenous conservation; the resulting ensemble average domestic heating energy decreases -2% (0.6 TWh). Finally, with surface water supplies being constrained under most climate scenarios, deliveries of inter-basin water transfers are also affected and the resulting ensemble average of conveyance energy decreases by -5% (1 TWh). Because several of the large conveyance projects (i.e. CAP, and CRA) use a significant amount of energy to lift water, energy savings from these deliveries offset some of the increase in groundwater pumping energy.

These results demonstrate how the energy-focused WWSM may help in estimating the magnitude of energy savings that can be achieved from more targeted water conservation programs in the urban sector, especially to reduce hot water (very energy-intensive) and outdoor water (likely to rise under climate change) demand. WWSM also allows for quantifying the energy saving co-benefits of groundwater management policies that limit pumping to allow aquifers to recover to sustainable depths. Further, the results highlight the value of WWSM to holistically evaluate the potential water supply mix under climate scenarios, and the net energy impact of substitution effects between sources.

Aggregate changes in energy generation and use

Climate change does not affect energy supply and demand in isolation, therefore, for a complete view of water-related impacts of climate change on the energy sector, we evaluate how, over time, each climate scenario concurrently affects hydropower and energy use. In addition to comparing the percentage changes in hydropower and water-related energy use by climate scenario and decade compared to the Reference, we calculate an absolute "energy balance" metric (in GWh), wherein average annual changes in hydropower (energy supply) are subtracted from changes in water-related energy use (energy demand). This aggregate energy balance metric quantifies the overall magnitude of the energy impact of climate change from WUS water resources; a balance that results in a shortage (demand exceeds supply) or surplus (supply exceeds demand), indicates whether the changes to hydropower and energy use either exacerbate or offset each other (Szinai et al., 2020).

Our results show that throughout the 2030 to 2050 decades, the majority of the 15 climate scenarios indeed present challenges for the electricity system. Although there is significant variability, in most cases, decreasing hydropower generation (up to -21%) coincides with increasing energy demand related to water (up to +5%), resulting in rising overall energy (im)balances that concentrate in the "worst case" lower right quadrant for each decade (Figure 9). It is noteworthy that across the three decades, no climate scenarios are in the "best case" upper left quadrant, with both decreasing energy use related to water, and increased hydropower. These results demonstrate the importance of comprehensively assessing climate impacts on coupled energy and water systems because energy use changes typically exacerbate hydropower changes. Further, the shifts in relative position between scenarios across the decades in terms of both hydropower and energy use highlight the natural inter-annual climate variability of the GCMs and the non-linearity of climate signals and management responses across the scenarios.

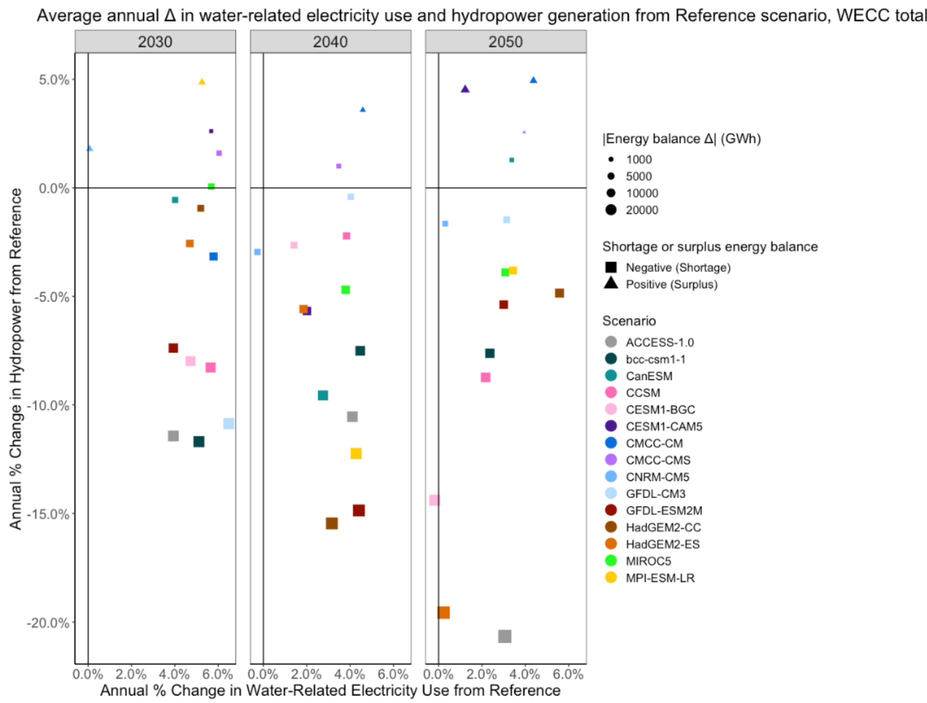


Figure 9. Average annual WECC-wide change in water-related electricity use, hydropower generation, and overall change in energy balance compared to Reference scenario. The change in the energy balance is calculated as the difference between the annual change in hydropower generation compared to the Reference scenario minus the annual change in water-related electricity use compared to the Reference scenario. Circles represent a total negative/shortage in this energy balance (decreases in hydropower exceed decreases in energy use) and triangles represent a surplus change (increases in hydropower exceed increases in energy use). The size of the symbol is the absolute value of the change in the energy balance in GWh. The colors denote the GCM of each climate scenario. The upper right quadrant includes scenarios with an increase in water-related electricity use, and an increase in hydropower generation. The upper left quadrant includes scenarios with a decrease in water-related electricity use, and an increase in hydropower generation, representing the most offsetting effect that climate warming could have on the water sector. The lower left quadrant includes scenarios with a decrease in water-related electricity use, and a decrease in hydropower generation. Finally, the lower right quadrant includes scenarios with both an increase in water-related electricity use, and an increase in hydropower generation, representing the most compounding effect of climate warming on the water sector.

Conclusion

This study introduces a modeling framework that can be used to improve our understanding and quantify the potential changes in electricity use and generation related to water, with the goal of informing electricity system planning and decarbonization efforts in the WECC grid region. To do so, we develop WWSM, a novel large-scale, climatically-driven water systems model that can 1) assess the impacts of an ensemble of climate scenarios on the physical hydrology and water supply deliveries to various sectors over the WUS geographic area, and 2) estimate the subsequent hydropower generation and electricity use associated with all stages of the managed water cycle under future climate scenarios; and 3) be used to explore energy use and generation results within the context of electricity capacity expansion, to develop infrastructure investment and operational decisions that are robust to a range of future climate scenarios.

To quantify energy-water vulnerabilities under climate change, this paper applies the calibrated WWSM to an ensemble of climate scenarios and presents a sample of water and energy results. Compared to historical conditions, the ensemble of 15 climate scenarios suggest that the 2020 − 2050 period will see increased precipitation in the North and Northwest and decreased precipitation in the Southwest, with warming throughout the entire WUS, but more concentrated in the interior region. These conditions in the WWSM result in decreased streamflow and managed flows in many of the major basins in the WUS, especially along the Colorado, with the exception of the Pacific Northwest and in California Northern Sierra headwaters, which have modest declines or even slight increases in streamflow. With increased warming and drying, agricultural water demand increases throughout the WUS, and with lower surface water availability, supply deliveries shift to groundwater. In the urban sector, if population levels grow annually throughout the WUS in parallel with warming, there are years when the model forces conservation endogenously, because water demand exceeds available supplies.

Under these climate scenarios, water resource changes have significant effects on both hydropower and energy use across the WUS. Across the ensemble, by 2050 total WECC hydropower generation could decrease 20% or increase 5%, however, 11 of 15 climate scenarios show decreases compared to historical levels. Further, the ensemble shows trends of hydropower generation decreases over the summer, which may exacerbate efforts to integrate solar and wind generation by adding to renewable energy curtailment as well as carbon-free, flexible generating (or storage) resource needs. On the energy use side, higher irrigation water demands and shifts to groundwater drive the increases of net electricity use, despite some decreases in urban energy use from constrained deliveries and decreases in conveyance energy.

When viewed concurrently, changing hydropower availability and increasing energy demands for the water sector may create compounding challenges for the electricity grid, especially approaching the mid-century when changes are more pronounced. For the majority of climate scenarios, hydropower generation decreases coincide with increases in the energy use related to water. These findings suggest that electricity grid planners should factor water-related climate impacts into infrastructure planning because additional generating resources may be needed to both replace lost supply and meet rising energy demands, while ensuring that decarbonization goals are still met. Therefore, follow-up studies are needed to evaluate how the grid buildout and operations in the WECC region can be designed to maintain climate resilience that is robust to the range of these projected water-related changes. Finally, while we consider the model as complete, we also acknowledge many areas of potential improvement and advancement, as attempting to develop a water systems model that captures the complexity of the represented water systems over the entire WUS is a challenging task.

While WWSM is meant to be an accurate representation of the key dynamics of the WUS water system and its connection with the electricity system, there are many remaining uncertainties including future climate conditions, model structure/physics, hydrological and resource management representation, and boundary conditions. Therefore, additional research is needed to thoroughly explore the magnitudes and sources of these uncertainties through sensitivity analysis or other uncertainty characterization techniques that are suited to complex multisector interactions. With a better understanding of these uncertainties, the WWSM can also be applied to evaluate the energy impacts of climate adaptation measures in the water system, such as urban water conservation, crop switching and/or land fallowing, water recycling, and reservoir operational changes, because these are not well understood and could have feedback effects on grid planning.

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Open Research

The WWSM model (version 1.0.0), the input data files in used for WWSM calibration and for the climate scenarios in this study, and the results files referenced in this study are available for download from a public "WWSM-WEAP-SWITCH" repository (DOI: 10.5281/zenodo.7145299, available at https://github.com/jszinai/WWSM-WEAP-SWITCH). The WWSM was developed within the WEAP software platform, which is developed and maintained by the Stockholm Environmental Institute (SEI). An evaluation version of the WEAP software, which allows users to open and view WWSM's saved results, is available for free without a license purchase from SEI. To open and view the WWSM, you must first register on the WEAP website and download and install WEAP software from https://www.weap21.org/. A free tutorial on using the WEAP software is available on the WEAP website.

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