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Modeling the Water Systems of the Western US to Support Climate-Resilient Electricity System Planning

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Key Points:

- Interactions among hydro-climate, hydropower, and water's energy use are critical for evaluating Western US (WUS) water-energy climate risks
- Under climate change, our WUS 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

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Electricity and water systems in the Western US (WUS) are closely connected, with hydropower comprising 20% of total annual WUS generation, and electricity related to water comprising about 7% of total WUS electricity use. Because of these interdependencies, the threat of climate change to WUS resources will likely have compounding electricity impacts on the Western Interconnect grid. This study describes a WUS-wide water system model with a particular emphasis on estimating climate impacts on hydropower generation and water-related electricity 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 water-related electricity use increases up to 4%, and by up to 6% during the summer months, driven by growing agricultural demands met increasingly through a shift toward 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, with decreases in summer generation by up to nearly −30%. Water-related electricity use increases tend to coincide with hydropower generation declines, annually and seasonally, demonstrating the importance of concurrently evaluating the climate signal on both water-for-energy and energy-for-water to inform planning for grid reliability and decarbonization goals.

Plain Language Summary Electricity and water systems in the Western United States (WUS) have a strong dependency. 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. This study develops a WUS water system model to evaluate the impact of a set of climate change scenarios on the dynamic interplay between water availability and demand and hydropower generation and electricity use by the water sector by 2050. 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 in the Western Interconnect will benefit from this type of study by informing future grid buildouts that maintain reliability and decarbonization goals.

1. 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 7% of total electricity consumption across the WUS states and about 12% across the entire United 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 (Sanders & Webber, 2012; Tidwell et al., 2014). Simultaneously, hydropower is a key source of WUS electricity generation, comprising about 17% of WUS total annual electricity generation on average from 1990 to 2019, and making up as much as 77% of annual generation in Idaho (EIA, 2021).

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Both water and electricity systems are vulnerable to the impacts of climate variability and change, individually and often in reinforcing ways (Dyreson et al., 2022; McCabe & Wolock, 2007; Siirila-Woodburn et al., 2021). 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 electricity use, such as for pumping groundwater, which is especially drawn down during times of drought (Christian-Smith et al., 2015; 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 (North America Electric Reliability Corporation, 2021; Rastogi et al., 2019; S. W. D. Turner et al., 2019; Vine, 2012).

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 (Cline, 2021; De León, 2018; Morehouse, 2019). 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 electricity demand (Christian-Smith et al., 2015; Diffenbaugh et al., 2015; Gleick, 2017; Kern et al., 2020). Problematically, reduced water available for hydropower generators reduces the available dispatchable electricity generation for balancing intermittent solar and wind resources, challenging grid reliability, especially in California (EIA, U.S. Dept of Energy, 2022).

Literature in the emerging field of MultiSector Dynamics emphasizes the gap in understanding of the complexities of coupled human-Earth systems, multi-sector interactions, and compounding risks, especially in the context of these concurrent energy transitions and increased future climate shocks (Reed et al., 2022; Simpson et al., 2021). In particular, there is growing 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; Cohen et al., 2022; Craig et al., 2022; Harrison et al., 2016; Liu et al., 2017; Molyneaux et al., 2012; U.S. Department of Energy, 2014; Voisin et al., 2019; White et al., 2017), and a need for "modelling strategies that represent key human and natural system processes in a self-consistent manner (Siirila-Woodburn et al., 2021) to fully quantify water management and subsequent electric system implications." Further, there is a need for such coupled water and electricity systems models to evaluate the implications of climate change in the WUS and its sub-regions while exploring zero-emission grid pathways (Cohen et al., 2022; Wessel et al., 2022).

To that end, a number of studies have modeled varying aspects of climate change impacts on linked large-scale electricity and water systems across the US and the WUS, including on water supply availability and demand management across different sectors (Hejazi et al., 2015; N. Voisin et al., 2013), changes in hydropower generation with statistical models or process-based hydrology models (Bartos & Chester, 2015; Boehlert et al., 2016; Kao et al., 2015, 2022; Parkinson & Djilali, 2015; Wei et al., 2017; Zhao et al., 2021; Zhou et al., 2023), and impacts on coupled power systems operations and planning under climate change and associated extreme events (Cohen et al., 2022; Dyreson et al., 2022; S. W. D. Turner et al., 2019; N. Voisin et al., 2017). However, often hydropower impact models treat hydropower in isolation, without including climate change impacts on other dynamic aspects of the complex water systems that hydropower operates within, such as water demands for irrigation (Rheinheimer et al., 2023). Conversely, regional analyses of climate change impacts on water resources do not typically evaluate the electricity impacts of changing water resources.

There are no models that we are aware of which integrate physical hydrology with water management infrastructure and its energy-relevant components to represent both electricity supply and demand impacts mediated by the water system at the scale of the Western Interconnect, the major synchronized grid in western North America overseen by the Western Electricity Coordinating Council. To address this gap 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 water supply and demand representation, with hydropower generation and water sector electricity demand (D. Yates et al., 2005). WWSM is developed to (a) capture the regional interdependencies of the inter-basin water transfers and transmission networks of the WUS water and electrical systems, respectively, and simultaneously represent (b) the hydro-climate of the WUS and (c) "water-for-energy" (i.e., hydropower) as well as (d), "energy-for-water" (i.e., electricity 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;

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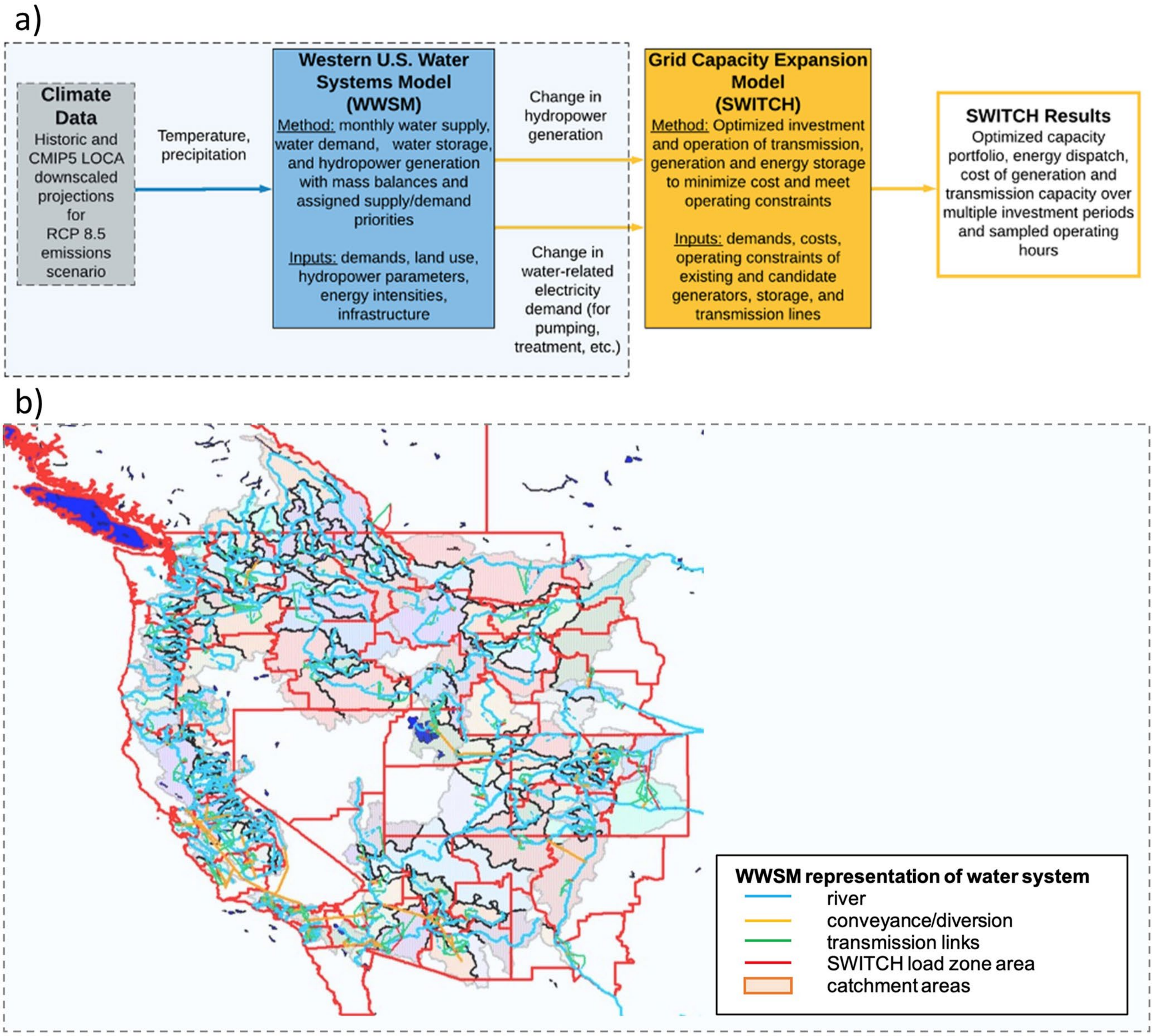

Figure 1. Climate-Water-Energy integrated modeling schematic and Western U.S. Water Systems Model (WWSM) study area. (a) Climate-Water-Energy integrated modeling schematic. (a) WWSM study area. This paper focuses on the methodology of WWSM and its results within the outlined box of the overall integrated Climate-Water-Energy modeling framework in figure (a). Changes in hydropower generation and water-related electricity demand from WWSM are inputs into the SWITCH-WECC model, which are the subject of separate follow-ons studies. The map in figure (b) 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 within WWSM.

Wada et al., 2015). 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 is designed for the results on the changes in available hydropower generation and electricity demand related to water to serve as inputs to electricity planning models to determine the effect of water-related climate impacts on the Western Interconnect grid region (Figure 1a). WWSM could be linked with any capacity expansion model, but in particular, the geographic scope and resolution (50 urban water demand zones corresponding to 50 load zones and the individual representation of nearly 200 hydropower generators) 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 Western Interconnect (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 electricity demand (energy-for-water), under an ensemble of mid-century climate change projections for the entire WUS at a monthly timestep. 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 electricity 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 Western Interconnect. 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 electricity 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 electricity-relevant metrics.

2. The Western U.S. Water Systems Model (WWSM)

The WWSM's study area within the Western Interconnect region includes the major basins and tributaries 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 simulates 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 electricity generation and use attributes before running future climate scenarios. In a separate follow-on study, the changes in electricity use and hydropower generation under the climate scenarios relative to the baseline historical climate from WWSM are used to adjust the electricity use and monthly hydropower generation potential for each hydropower generator in SWITCH. The SWITCH model then optimizes the portfolio of generating and transmission capacity and dispatch for the 50 zones in the Western Interconnect. This paper focuses on the development of WWSM and electricity-related results from an ensemble of climate scenarios (the outlined shaded box in Figure 1b); the model coupling and data linkage between WWSM and SWITCH, and the analysis of future electricity infrastructure with SWITCH is detailed in the separate follow-on study.

2.1. 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). Water Evaluation and Planning 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, 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 WWSM configuration and data used in this study.

2.2. Rivers, Catchments, and Groundwater Basins

WWSM divides the WUS into the river basins identified through a collection of catchment objects disaggregated by 1,000-m elevation bands and categorized by land use-land cover (Agriculture, Forest, Grass and Shrub, Other, Urban, or Water) (ESA CCI Land cover website, 2022). 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, groundwater recharge, agricultural irrigation demand, and urban outdoor irrigation demand.

State and Federal agencies are the primary sources of data for the WWSM, including for parameterizing groundwater basins (Arizona Department of Water Resources, 2022; California Department of Water Resources (DWR), 2018; Colorado Water Conservation Board, 2023; Harrington & Bendixsen, 1999; Idaho Department of Water Resources, 2023; Montana Department of Natural Resources and Conservation, 2014; New Mexico Water Data, 2023; The Office of the Columbia River-Washington State Department of Ecology, 2023; The Western States Water Council (WSWC) 2023, The Water Data Exchange (WaDE) Program: Transforming Western Water Planning, Management, and Policy by Sharing States Water Data, 2023; USGS Water Data for the Nation, 2021; Office of Columbia River, Washington State Department of Ecology, 2022; Office of Columbia River Washington State Department of Ecology, 2022; Oregon Water Resources Department, 2019; Sullivan, 2017; Wyoming State Engineer's Office, 2023). WWSM couples surface and groundwater systems through stylized representation of an alluvial groundwater system (D. Yates et al., 2005), where surface and groundwater are coupled, and the model simulates the position of the groundwater table relative to the stream and thus whether it is a losing or gaining stream. 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 et al., 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. While groundwater is modeled as an unlimited resource, its use is regionally limited as a percentage of supply delivered based on historical patterns, effectively constraining its use around historical levels.

2.3. 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, 2021). WWSM indoor domestic per-capita water use is based on an average US value (60 gallons per capita per day, gpcd/220 L 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, 2021). 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, 2021).

For urban outdoor water demands, we make a simplifying assumption that a certain fraction of the urban identified land-cover areas is irrigated (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. Because consistent, spatially explicit data on sectoral urban water use, especially disaggregated between indoor and outdoor users, is limited (McManamay et al., 2021), further analysis is planned to evaluate the sensitivity of the results to different urban water demand assumptions.

Water demand for irrigated agriculture is modeled for the agricultural land area multiplied by the fraction irrigated within each catchment (Homer, 2020; Pervez & Brown, 2010). 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 Supporting Information S1.

2.4. Reservoirs, Diversions, Desalination, and Reuse

There are 133 major reservoirs 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, 2021). 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 (see references from Section 2.2), and each reservoir's surface evaporation is included in the mass balance to account for water loss (Zhao et al., 2021) 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; 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 (DWR), 2018).

One desalination plant in Carlsbad, California (Carlsbad Desal Plant, 2021), 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, 2022). 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).

2.5. Hydropower Generators

There are 192 individual hydropower generators in WWSM, which together provide about 48 GW of installed capacity, out of about 55 GW of total hydropower capacity in the US portion of the Western Interconnect (68 GW including Canadian hydropower). These generators produced on average 164 TWh annually from 2004 to 2018, out of 176 TWh from all US-based Western Interconnect hydropower generators over the same time period (EIA, 2021). In the US portion of the Western Interconnect, these are all the generators greater than 30 MW, the threshold used by California to denote large hydropower (Commission, 2023). Only one Canadian generator is included in WWSM, 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. The changes in hydropower generation under climate scenarios compared to a historical climate baseline in WWSM can be used to adjust the monthly generation available to be dispatched in a capacity expansion model (Figure 1).

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 filings and utility websites (Bureau of Reclamation, 2021; Form EIA-923 detailed data with previous form data (EIA-906/920), 2021; National Inventory of Dams, 2021; EIA, 2021). Additional detail is in

Supporting Information S1. We note that the EIA imputed monthly generation data from annual observations for some generators, which may obscure differences in actual seasonal generating patterns between generators, however, a preliminary analysis with an adjusted EIA data set (Turner et al., 2022) showed minimal differences in the data used to calibrate WWSM.

2.6. Electricity 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 electricity by multiplying energy intensity values (electricity 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 electricity use, water heating electricity use, agricultural electricity use), or averages across literature (desalination, treatment, wastewater treatment, reuse) as described below and the Supporting Information S1. The monthly changes in electricity use under climate scenarios compared to a historical climate baseline scenario can be added to total electricity use for a given region in a capacity expansion model like SWITCH to evaluate changes in generating capacity and electricity generation needed to meet demand.

2.7. 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): (a) environmental flows, (b) urban (both indoor and outdoor), (c) agriculture, (d) reservoir storage, and (e) 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: (a) reuse (when available, for urban outdoor use only), (b) surface water, (c) 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.

3. 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, 2022) 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, 2021) 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 Nash-Sutcliffe Efficiency (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 Kling Gupta Efficiency) because WWSM is driven by monthly water demands and not individual delivery contracts.

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).

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Table 1
Energy Intensity of Managed Water Cycle in Western U.S. Water Systems Model (WWSM)

Stages of managed water cycle with embedded electricity	Electricity use category	Energy intensity	Description
Supply	Groundwater pumping	0.005 kWh/m^3 per meter of lift	Calculated as $E = \frac{q\rho gh}{n}$, 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 and Allen (2022)
	Conveyance	0.005 kWh/m^3 per meter of lift	Calculated as $E = \frac{q\rho gh}{n}$, where: q is the simulated monthly volumetric flow rate; h is the lift height for specific projects (listed in Supporting Information S1); 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
Treatment	Potable water treatment (Urban)	0.3 kWh/m^3	Conventional drinking water treatment electricity applied for all urban (not agricultural) deliveries, averaged from literature
Distribution	Water distribution	Varies by urban demand node, see Supporting Information S1	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, 2021)
Use	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, 2019), typical irrigation technology by crop (Statewide Irrigation Systems Methods Surveys, 2019), and energy intensity by irrigation technology (Burt et al., 2003)
	Domestic water heating	Varies by urban demand node, see Supporting Information S1	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, 2021), the average hot water share in typical US residential homes (33.2%) (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)

Table 1
Continued

Stages of managed water cycle with embedded electricity	Electricity use category	Energy intensity	Description
Disposal	Wastewater treatment	0.5 kWh/m^3	Secondary wastewater treatment electricity applied to return flows from all urban indoor water averaged from literature
Reuse	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

Note. The first column shows the stages of the water cycle with embedded electricity 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; GEI Consultants/Navigant Consulting & GEI Consultants/Navigant Consulting, 2010; Klein et al., 2005; Liu et al., 2017; Stokes-Draut et al., 2017; Tarroja et al., 2014; Tidwell et al., 2014).

Validating electricity 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 electricity 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, electricity use, and water supply deliveries by sector are in Supporting Information S1.

4. 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, 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; McSweeney et al., 2012, 2015). 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 five 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 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 1980–2010 (Livneh et al., 2013) for this future period.

The future period's ensemble mean percent change in precipitation and absolute change in temperature (°C) 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 (Figures 4a and 4b) (Christensen et al., 2013; Hayhoe 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 about −10% to +10% precipitation

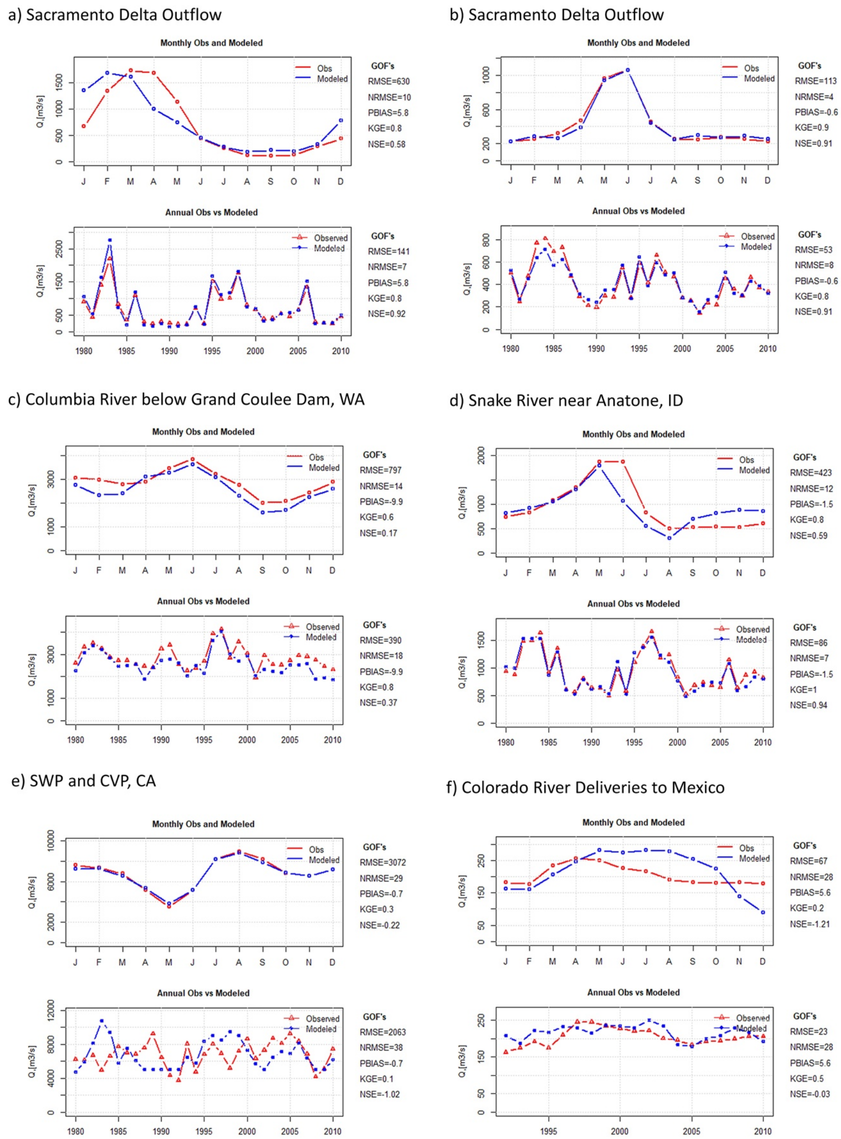

Figure 2. Annual and monthly observations compared to Western U.S. Water Systems Model simulation results for historical period for key streamflow locations. Monthly average (top) and annual average (bottom) (a) outflows of the Sacramento-San Joaquin Delta of California, (b) Colorado River inflows into Lake Powell, (c) Columbia River flows below Grand Coulee Dam, WA, (d) Snake River inflows near Anatone, ID, (e) Total diversions of the California State Water Project and Central Valley Project from the Sacramento-San Joaquin Delta, and (f) Total Lower Colorado River diversions, including from the Central Arizona Project (CAP), All-American Canal to California, and the Colorado Aqueduct (Colorado River Aqueduct) 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 statistics including Root Mean Square Error (cms), Normalized Root Mean Square Error (%), percent bias, Nash-Sutcliffe Efficiency, 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).

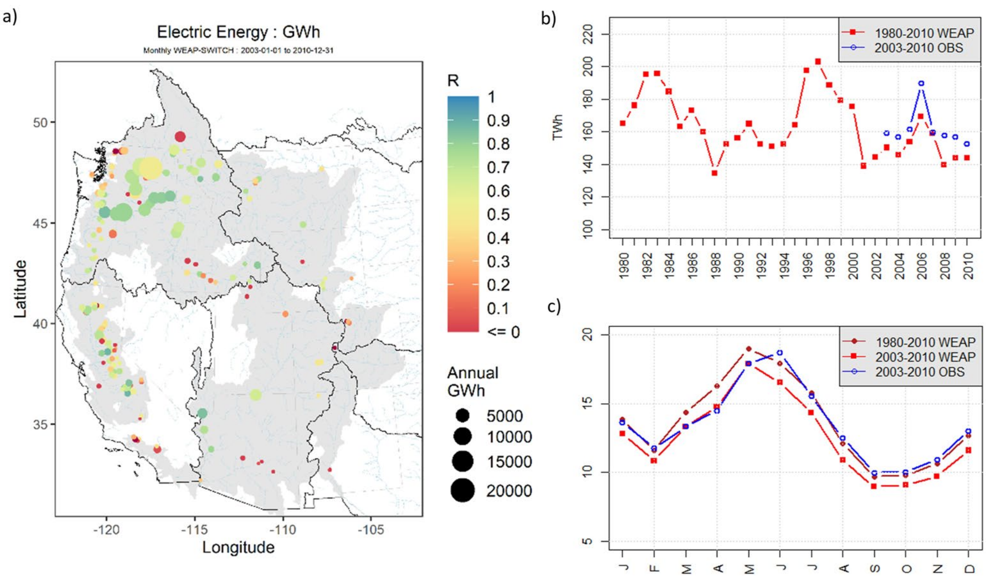

Figure 3. Western U.S. Water Systems Model (WWSM) hydropower generation calibration results for historical period over the Western Interconnect region. (a) Annual generation and correlation. (b) Annual total Western Interconnect hydropower. (c) Monthly avg. Western Interconnect hydropower. Figure (a) 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), figure (b) is the annual generation as the sum of all hydropower generators, and figure (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 Energy Information Administration observations.

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 Supporting Information S1.

5. 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 electricity 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 electricity system, as these are the features that can inform electricity system planning under climate change. Following other examples (Cohen et al., 2022), the monthly changes in hydropower generation, by generator, and the change in electricity use related to water, aggregated to the electric utility zone, for each climate scenario relative to the historical baseline climate from WWSM can be linked with a capacity expansion model to modify monthly potential hydropower generation and electricity demand forecasts.

5.1. Hydrological and Managed Water System

5.1.1. Streamflow

Streamflow is the key driver of hydropower generation and water supply deliveries and associated electricity 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

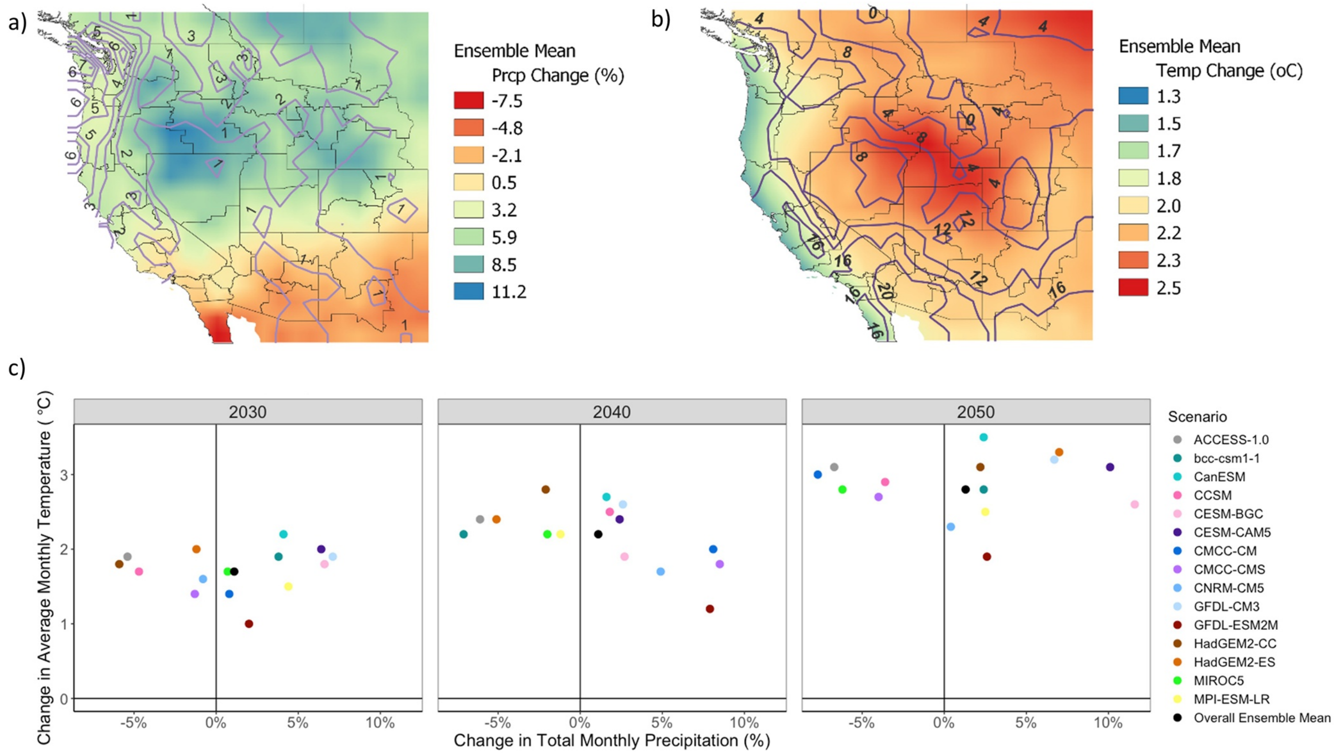

Figure 4. Summary of ensemble of climate scenarios. (a) Ensemble difference in precipitation. (b) Ensemble difference in temperature. (c) Decadal precipitation and temperature deltas from individual climate scenarios compared to historical data across Western US (WUS) domain. The change in ensemble average of daily precipitation for precipitation [%] in figure (a) and for temperature [°C] in figure (b) are derived from the historic period (1980–2010) relative to the future period (2020–2050) for all 15 General Circulation Models (GCMs). The contour intervals show the daily average figure (a) precipitation [mm/day] and daily average figure (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 Western Interconnect load zone regions from the SWITCH capacity expansion model. The figure (c) shows 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 (1980–2010) for all 15 GCMs used for the climate scenarios, as well as the overall ensemble mean, across entire WUS study domain.

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 et al., 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 (Yates et al., 2021).

Evaporative losses across the WUS generally increase and often exceed increases in precipitation (Zhao et al., 2021), with large variation in streamflow impacts across the region, for example, between the more humid Northwest and arid Southwest. 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).

5.1.2. 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

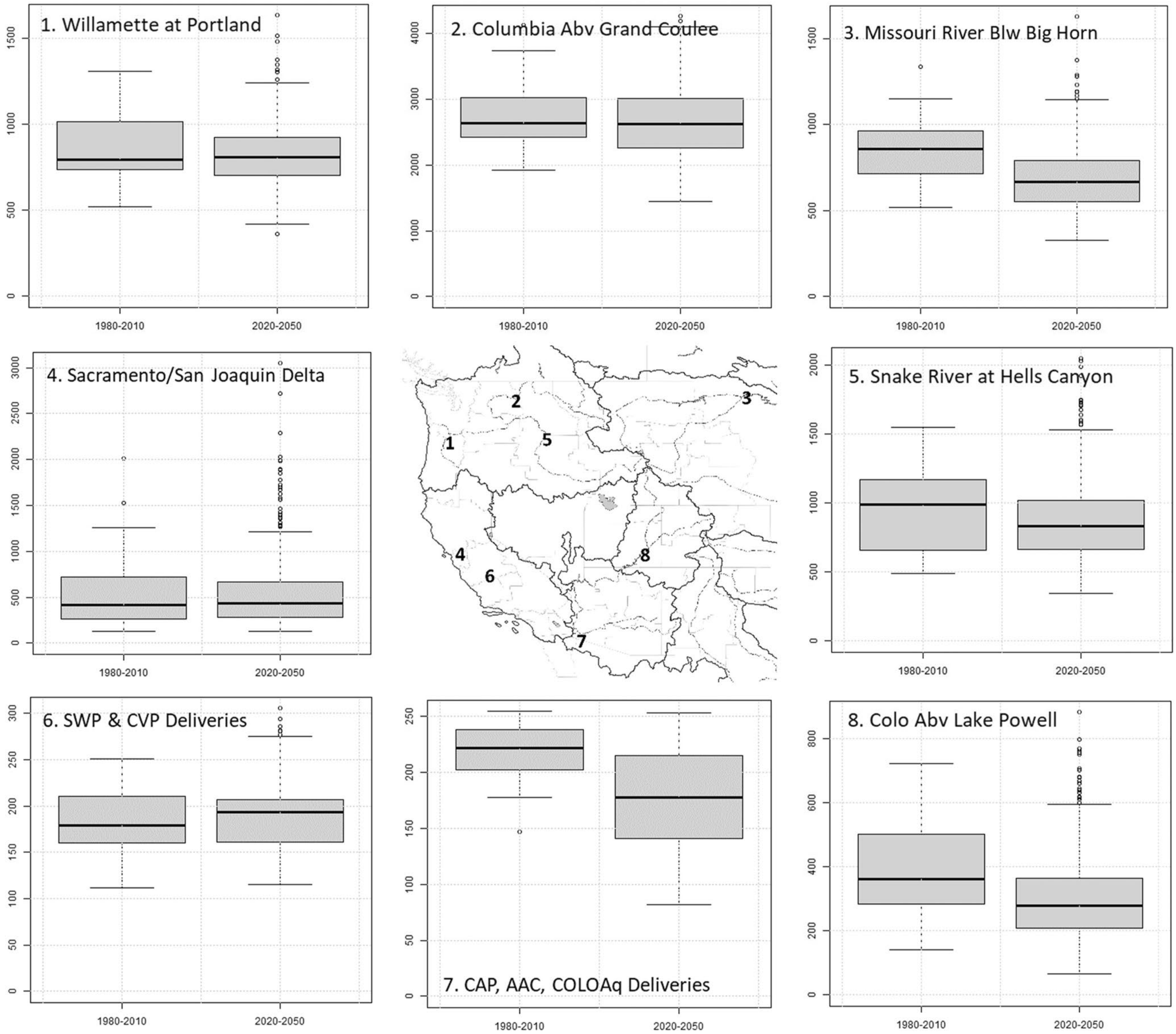

Figure 5. Annual average streamflow results for select Western US (WUS) locations from Western U.S. Water Systems Model under climate scenarios compared to Reference scenario. 1. Willamette at Portland. 2. Columbia River above Grand Coulee. 3. Missouri River below Big Horn. 4. Sacramento/San Joaquin Delta. 5. Snake River at Hells Canyon. 6. State Water Project (SWP) and Central Valley Project (CVP) Deliveries. 7. Central Arizona Project (CAP), All-American Canal (AAC), and Colorado Aqueduct Total Deliveries. 8. Colorado River above Lake Powell. Annual average flows (cms) based on climate of the historic period (1980–2010) 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 Western Interconnect regions. Figure 6 is the sum of SWP and CVP deliveries. Figure 7 is the sum of CAP, AAC, and the Colorado Aqueduct (ColoAq).

precipitation changes), and allocation priorities of supply and demand. Accounting for these dynamics, for each climate scenario WWSM solves for the available water supply and the water demand for each sector, and then allocates 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 (Figure 6). 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.

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

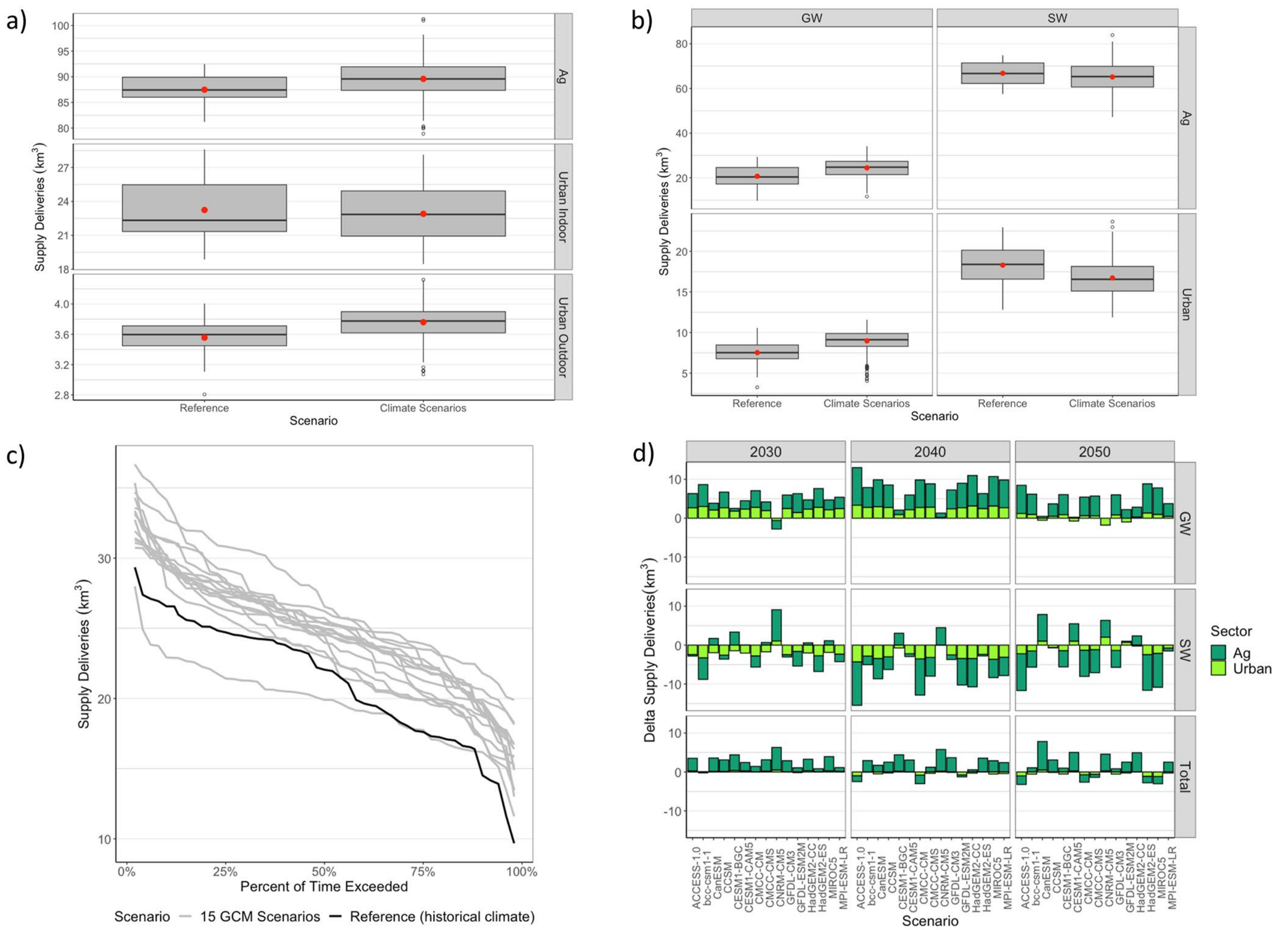

Figure 6. Western U.S. Water Systems Model results for total Western US (WUS) water deliveries under climate scenarios compared to Reference scenario. (a) Total WUS annual supply deliveries, by sector. (b) Total WUS annual supply deliveries, by sector, source. (c) Annual exceedance of groundwater supply deliveries for agricultural sector. (d) Average annual change in supply deliveries for each decade relative to Reference scenario, by sector and source. Figure (a) shows the total annual water supplies delivered [km^3] by sector across the WUS region from all water sources for climate scenarios compared to Reference scenario. Figure (b) shows total WUS annual supply deliveries by sector and source [km^3] for climate scenarios compared to Reference scenario. The urban sector includes both indoor and outdoor water use. Figure (c) shows the annual exceedance of total groundwater supply deliveries [km^3] to agricultural sector, for future period for climate scenarios (all General Circulation Models in gray) compared to Reference scenario (black). The figure indicates the percentage of years that certain levels of annual groundwater deliveries are exceeded under each scenario. (d) shows average annual change in supply deliveries for each decade relative to Reference scenario, by sector and source [km^3]. Water deliveries for each climate scenario reflect climatically-driven changes in water supply availability (for groundwater and surface water) as well as changes in demand for each sector. Demand is not always fully met, and therefore total deliveries decrease if supplies are not sufficient to meet growing demand. For figures (a) and (b), red points are mean values and black bars are median values, and GW = groundwater and SW = surface water, including withdrawals from rivers, inter-basin water transfers such as the State Water Project, non-potable reuse (for outdoor use), and desalination.

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 represent an upper limit of groundwater use, concurring 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, 2020). Groundwater pumping has a higher energy intensity than local surface water sources, thus substitution of supply sources also has implications for electricity 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 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 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 electricity savings that would result from water conservation (described in next section) by avoiding electricity use for conveyance, treatment, distribution, wastewater treatment, and water heating (Sowby & Capener, 2022; Spang et al., 2018; Stokes-Draut et al., 2017; J. K. Szinai et al., 2020).

5.2. 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 electricity used to pump, move, treat, heat, and dispose of water throughout the WUS, and the implications these changes have for electricity system planning.

5.2.1. Hydropower Generation

Streamflow and water availability drives hydropower generation, and thus across the ensemble of climate scenarios, streamflow declines in WWSM cause 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; Kao et al., 2015; Zhou et al., 2023), where climate projections suggest precipitation stays around historic levels or becomes slightly wetter (Figure 4).

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; Zhou et al., 2023), suggesting that generators supplied by runoff from snowmelt are particularly vulnerable to 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. First, 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 subsequently decrease hydropower, dispatchable natural gas generators may be used to replace lost hydropower generation, increasing costs, GHG emissions, and electricity market prices (Bartos & Chester, 2015; Christian-Smith et al., 2015; Gleick, 2017; Kern et al., 2020; Tarroja et al., 2019; Voisin et al., 2019; Wessel et al., 2022). Seasonal shifts in hydropower availability may also exacerbate peak generating capacity shortfalls 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 (Voisin et al., 2020), and which may see electricity market price spikes if electricity demand increases coincide with less reliable imports (Hill et al., 2021).

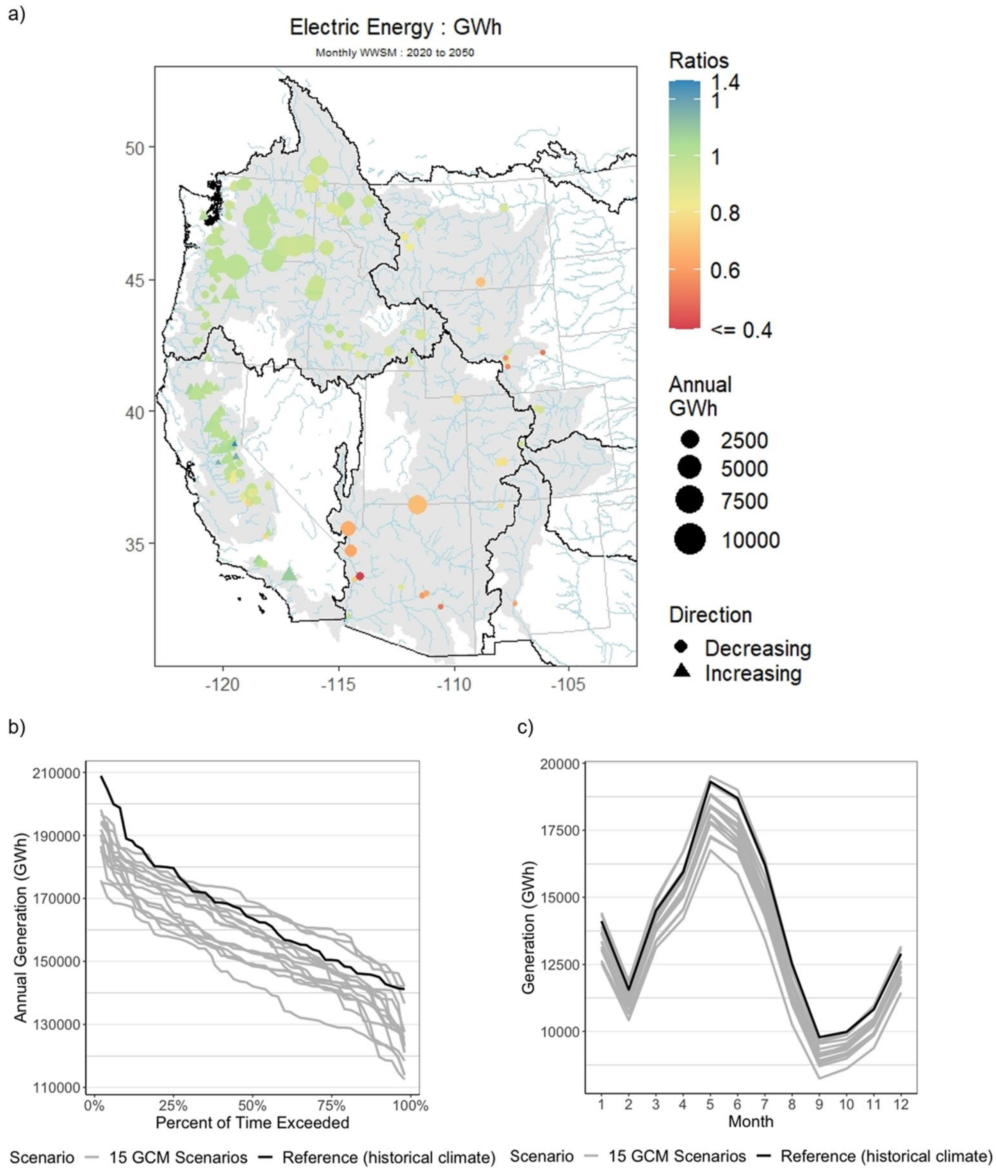

Figure 7. Western U.S. Water Systems Model hydropower generation results for climate scenarios compared to Reference scenario. (a) Annual Change in Generation as Ratios (2020–2050 relative to 1980 to 2010) by generator. (b) Western Interconnect annual hydropower exceedance. (c) Western Interconnect average monthly hydropower generation. The size of the points in figure (a) indicates the Reference average annual generation, and the colors indicate the average annual ratio of change across the ensemble of climate scenarios. Circles have decreasing and triangles have increasing generation relative to Reference. Figure (b) shows the annual exceedance percentages of hydropower generation Western Interconnect-wide, for future period for climate scenarios (all General Circulation Models (GCMs) in gray) compared to Reference scenario (black). The figure indicates the percentage of years that certain levels of annual hydropower generation are exceeded under each scenario. Figure (c) shows the average monthly total Western Interconnect hydropower generation 2020–2050, with the climate scenarios (all GCMs in gray) compared to the Reference scenario (black).

5.2.2. Electricity Demand for Water

As climate change affects water demands and supply deliveries from various sectors and sources, the associated electricity use is also affected. Over the future study period, the total average annual electricity 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 to +4 TWh) across the climate scenarios. For comparison, the impact of climate change on water-related electricity use is up to about 6% of the 55 to 71 TWh of historical annual electricity use associated with water estimated across the WUS (excluding water heating) (Tidwell

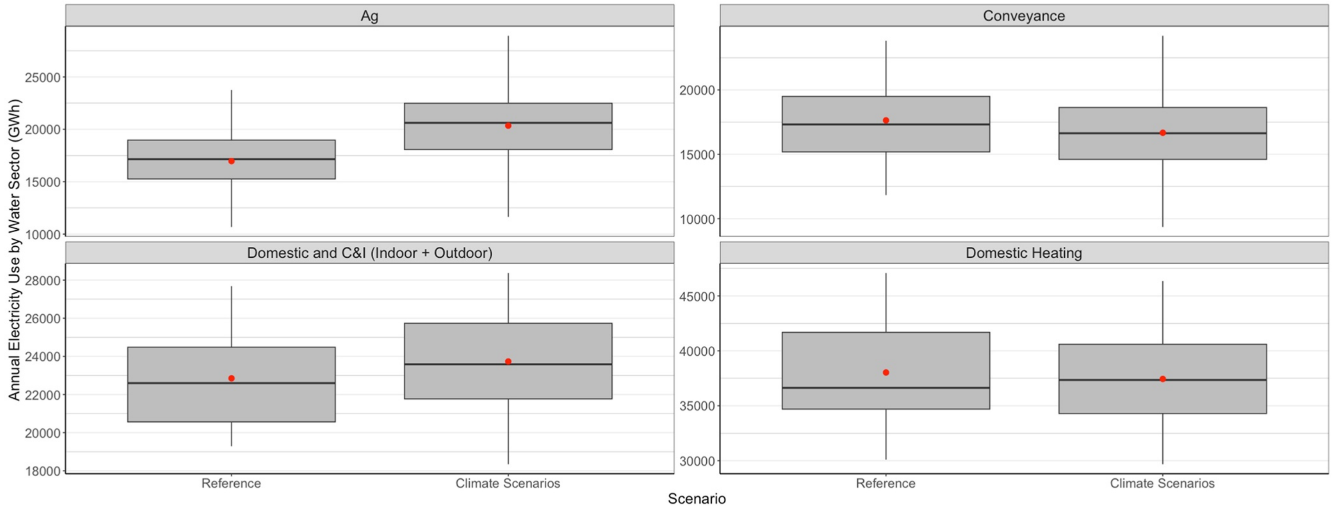

Figure 8. Western U.S. Water Systems Model annual total water-related electricity use by sector from reference and climate scenarios. Energy for agricultural (ag) water includes electricity for groundwater pumping, local surface water deliveries, and irrigation. Energy for conveyance includes electricity for non-gravity-fed inter-basin water transfers to lift and transport water to either agricultural or urban water users. Energy for domestic and C&I water includes electricity for groundwater pumping, reuse (for outdoor use only), and desalination; water treatment; water distribution; and wastewater treatment (for indoor users only) for both indoor and outdoor users unless otherwise indicated. Energy for domestic heating includes electricity for residential water heating. The red points are the mean values and the black bars are the median values of annual electricity use.

et al., 2014) and up to 0.1% of the historical 3,500 TWh estimated for the water services across the entire US (Sanders & Webber, 2012). We disaggregate these results into electricity use for agricultural water (includes electricity for groundwater pumping, local deliveries, and irrigation), domestic and C&I (urban) indoor and outdoor water (electricity related to 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 annual electricity use related to water is relatively small, especially relative to estimated increases in electricity use because of more air-conditioning demand under climate change (+2 to +9% increase in electricity demand estimated for the Southwest by 2050 (McFarland et al., 2015)), among these disaggregated categories, there are significant and sometimes offsetting results which could benefit from being explicitly embedded in electricity grid planning alongside other impacts under future climate scenarios.

The strongest climate signal on electricity demand related to water (Figure 8) comes from the agricultural sector, which increases +20% (3 TWh) annually on average across the ensemble, with most of that increase occurring in the summer months. Among individual scenarios, annual agricultural electricity use increases up to +32% (5 TWh), and only one scenario (CNRM-CM5) of 15 shows a decrease in average annual agricultural electricity use (−9%, −2 TWh). These changes are driven by the level of groundwater pumping of each scenario relative to the Reference. The electricity 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). Because groundwater is allowed to fill surface water supply gaps in the model according to historical patterns, these results on electricity use should be considered an upper estimate of the electricity footprint of groundwater pumping, without management interventions.

Although electricity for agricultural water in the WUS is the most sensitive to climate warming, the largest overall electricity user is the urban sector (Figure 8), driven by domestic water heating (Sanders & Webber, 2012) as well the electricity for potable indoor and outdoor use. This domestic and C&I electricity use increases +4% (0.9 TWh) annually 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, electricity use for domestic water heating throughout the WUS has minimal change because it is not directly sensitive to climate warming, but electricity use decreases with lower urban water use in scenarios where WWSM imposes endogenous conservation; the resulting ensemble average annual domestic water heating electricity use decreases −2% (0.6 TWh). We note that electricity use for domestic water heating is also likely to increase across the US over this time because of electrification policies and subsidies that encourage switching from natural gas to electric heat pump water heaters (Clean Energy for All, 2023); the impact of this technology transition is not modeled here but will be the subject of future sensitivity analyses. Finally, with surface water supplies being constrained under most climate scenarios, deliveries of many inter-basin water transfers are also reduced. Because several of the large conveyance projects (i.e., CAP, and CRA) use a significant amount of electricity to lift and move water, the resulting ensemble annual average of conveyance electricity decreases by −5% (1 TWh) (David Yates et al., 2021). These electricity savings from reduced conveyance deliveries offset some of the increase in groundwater pumping electricity use.

These results demonstrate how the electricity-focused WWSM may help in estimating the magnitude of electricity 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 electricity 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 electricity impact of substitution effects between sources.

5.2.3. Aggregate Changes in Electricity Generation and Use

Climate change does not affect electricity supply and demand in isolation, therefore, for a complete view of water-related impacts of climate change on the electricity sector, we evaluate how, over time, each climate scenario concurrently affects hydropower generation and electricity use. In addition to comparing the annual percentage changes in hydropower and water-related electricity 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 (electricity supply) are subtracted from changes in water-related electricity use (electricity demand). This aggregate energy balance metric quantifies the overall magnitude of the electricity 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 electricity use either exacerbate or offset each other (J. K. Szinai et al., 2020).

Our results show that throughout the 2030 to 2050 decades, under the majority of the 15 scenarios, the water system creates compounding climate impacts for the electricity system. Although there is significant variability because of natural inter-annual climate variability of the GCMs and the non-linearity of climate signals and management responses across the scenarios, in most cases, decreasing hydropower generation (up to −21%) coincides with increasing electricity demand related to water (up to +5%) annually. These result 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 electricity use related to water, and increased hydropower. At a monthly and seasonal scale, which directly informs future grid buildout and capacity expansion models, by the 2050 decade we also find that the largest monthly total decreases in hydropower generation (up to nearly −20%) (see Figure 7c above and Figure 9) are in the summer months and are exacerbated by up to about +6% average monthly increases in electricity use related to water.

6. 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 Western Interconnect grid region. To do so, we develop WWSM, a novel large-scale, climatically-driven water systems model that can (a) 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 (b) estimate the subsequent hydropower generation and electricity use associated with all stages of the managed water cycle under future climate scenarios; and (c) produce results that can be linked with an electricity capacity expansion model to develop generation and transmission capacity infrastructure investment and operational decisions that are robust to a range of future climate scenarios.

To quantify electricity-water vulnerabilities under climate change, this paper applies the calibrated WWSM to an ensemble of climate scenarios and presents a sample of water and electricity results. Compared to historical conditions, the ensemble of 15 climate scenarios suggest that the 2020–2050 period will see increased

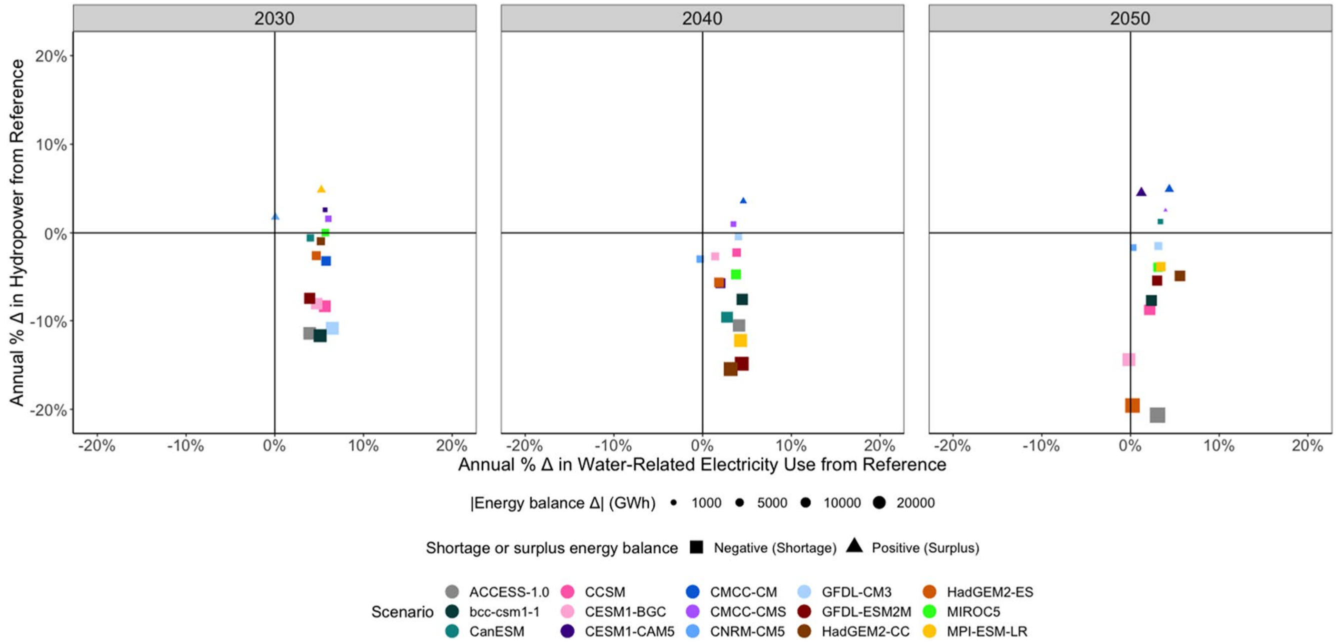

Figure 9. Average annual Western Interconnect-wide change in water-related electricity use, hydropower generation, and overall change in energy balance compared to Reference scenario. The change in the energy balance is calculated as the difference between the annual change in hydropower generation compared 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 electricity use) and triangles represent a surplus change (increases in hydropower exceed increases in electricity use). The size of the symbol is the absolute value of the change in the energy balance in GWh. The colors denote the General Circulation Model of each climate scenario. 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 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.

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. This reliance on groundwater as a backstop for declining surface water is consistent with historical patterns and represents an upper limit of use absent changes in aquifer management regimes. 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 notable effects on both hydropower and electricity use across the WUS. Across the ensemble, by 2050 total Western Interconnect annual 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 electricity use side, higher irrigation water demands and shifts to groundwater drive the increases of net electricity use, despite some decreases in urban electricity use from constrained deliveries and decreases in conveyance electricity from reduced surface water available. Although these changes in electricity use related to water (up to +4% annually) are relatively small compared to total electricity use, they amplify other projected increases in electricity use under climate change, such as for air-conditioning, especially in summer months.

When viewed concurrently, changing hydropower availability and increasing electricity demands for the water sector may create compounding climate impacts for the Western Interconnect grid, especially approaching the mid-century when changes are more pronounced. For the majority of climate scenarios, both annual and summer peak hydropower generation decreases coincide with increases in the electricity use related to water. These concurrent annual and seasonal dynamics we identify suggest that grid infrastructure planning, especially for meeting decarbonization goals, could benefit from explicitly embedding both changes in hydropower generation and water-related electricity use with other impacts in climate scenarios. Therefore, follow-up studies are needed to evaluate how the grid buildout and operations in the Western Interconnect region can be designed to maintain climate resilience that is robust to the range of these projected water-related changes.

Overall, WWSM is a tool that enables exploration a wide range of climate stressors, interactions of infrastructure and environmental change, system tipping points, and uncertainties about the propagation of climate impacts across regions, sectors, and systems (Reed et al., 2022). 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. 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 multi-sector interactions. With a better understanding of these uncertainties, the WWSM can also be applied to evaluate the electricity impacts of and the extent of needed climate adaptation measures in the water system (Brown et al., 2019), 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.

Data Availability Statement

The WWSM model (version 1.0.0), the input data files used for WWSM calibration and for the climate scenarios in this paper, and the results files referenced in this paper are available for download from a public "WWSM-WEAP-SWITCH" repository (J. Szinai, 2022) published on GitHub (https://github.com/jszinai/WWSM-WEAP-SWITCH). The WWSM was developed within the WEAP software version 2022.0002 (Jack Sieber, Stockholm Environment Institute, 2022), 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. Figures were made with R version 4.2.3 (R: The R Project for Statistical Computing, 2023).

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