Climate change effects on water allocations with season dependent water rights

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Abstract

Appropriative water rights allocate surface water to competing users based on seniority. Often water rights vary seasonally with spring runoff, irrigation schedules, or other non-uniform supply and demand. Downscaled monthly Coupled Model Intercomparison Project multi-model, multi-emissions scenario hydroclimate data evaluate water allocation reliability and variability with anticipated hydroclimate change. California's Tuolumne watershed is a study basin, chosen because water rights are well-defined, simple, and include competing environmental, agricultural, and urban water uses representative of most basins. We assume dedicated environmental flows receive first priority when mandated by federal law like the Endangered Species Act or hydropower relicensing, followed by senior agricultural water rights, and finally junior urban water rights. Environmental flows vary by water year and include April pulse flows, and senior agricultural water rights are 68% larger during historical spring runoff from April through June. Results show senior water right holders receive the largest climate-driven reductions in allocated water when peak streamflow shifts from snowmelt-dominated spring runoff to mixed snowmelt- and rainfall-dominated winter runoff. Junior water right holders have higher uncertainty from inter-annual variability. These findings challenge conventional wisdom that water shortages are absorbed by junior water users and suggest aquatic ecosystems may be disproportionally impaired by hydroclimate change, even when environmental flows receive priority.

Keywords: hydroclimate, prior appropriation, water allocation, streamflow, hydrology, adaptation

1 Introduction

Climate warming will affect hydrology in mountain regions by shifting snowfall to rainfall (Mote et al. 2005), causing earlier runoff timing, generally wetter, flashier winters, and drier summers that are prone to drought (Barnett and Lettenmaier 2005; Stewart et al. 2005; Sellami et al. 2016; Null et al. 2010). In the continental United States, climate warming is anticipated to warm air temperatures by approximately 2°C to 6°C by the end of the 21st century, depending on future carbon emissions (Wuebbles et al. 2014). Precipitation trends are more uncertain (Knutti & Sedláček 2013) which is exacerbated by increasing inter-annual variability (Cai et al. 2014; Kundzewicz et al. 2008) and climate extremes that vary spatially and temporally (Davis et al. 2015; De Paola et al. 2014).

Many studies have investigated the effects of changing hydroclimate on water resources management (Taylor et al. 2013; Milly et al. 2008; Kumar et al. 2016; Kundzewicz et al. 2008), but few have examined changing water right allocations in non-stationary climates. Overall, we know that water managers should no longer assume hydroclimatic stationarity (Milly et al. 2008). Less water will be stored as winter snowpack (Kundzewicz et al. 2008; Mote et al. 2005) and more than 1/6 of the world's population currently depends on snowmelt for water supplies (Barnett & Lettenmaier 2005). Reservoirs in dry climates are unlikely to reach capacity in most years so water resources management may be limited more by precipitation than by infrastructure (Christensen et al. 2004). Promising water management strategies for arid and semi-arid regions in the future likely include conjunctive management of surface and groundwater (Taylor et al. 2013), improving conveyance to improve flexibility (Null 2016), conservation (Kundzewicz et al. 2008), stormwater management or other alternative water sources (Kumar et al. 2016) and water markets (Grafton et al. 2011). Finally, hydroclimate changes are likely to reduce biodiversity, habitats, and resiliency for aquatic ecosystems (Palmer et al. 2008). These changes are exacerbated in watersheds that have been developed, partly because water year types, which determine dedicated environmental flows, are anticipated to skew toward drier years, reducing the range of hydrologic variability for aquatic species (Null & Viers 2013).

Less well understood is how climate-driven streamflow changes may affect seasonally-variable water right allocations to competing environmental, agricultural, and urban water users. Water rights that were developed for stationary climates may be poorly-equipped for climate change because adapting water right laws may be costly, subject to conflict, or undermine the stability they were intended to bolster (Tarlock 2012; Miller et al. 1997). Adapting water rights to climate change, or to increased uncertainty in general, has been the topic of recent legal and water policy research. Water policy adaptation may not occur incrementally (Garrote et al. 2016; Kates et al. 2012); rather, large transformations may be needed when change to human-environmental systems is considerable and resources or populations are vulnerable. Disjointed and piecemeal laws between surface water, groundwater, water quality, and environmental protection may further hinder innovative adaptation (Adler 2010). Water allocations that are dependent entirely on prior appropriation, or 'who got there first', may become unstable and irrational with climate change. Society should not wait until existing legal frameworks are pushed beyond their breaking point to consider modifying them (Miller et al. 1997). We identified one study that considered climate change alterations to water allocations based on

water rights. Schwartz evaluated the frequency and duration of shortages to junior water right holders with historical drought periods and climate-driven future simulations using California's State Water Project to assess water reliability (Schwarz 2015). Duration of future shortages is anticipated to become longer and more frequent, potentially exacerbating groundwater overdraft, subjecting more water right holders to shortages, incentivizing water transfers to reallocate water among users, and increasing reliance on stored water, when available. To date, no research has examined how climate-driven spatial and temporal changes to streamflows may re-allocate water between senior and junior water right holders with seasonally-varying appropriative water rights, common throughout the American West.

The objective of this paper is to analyze the effects of hydroclimate change on appropriative water rights that allocate water to competing urban, agricultural, and environmental water users. We highlight changes to senior and junior water right allocations if climate change alters the seasonality of water. Phase 5 of the Coupled Model Intercomparison Project's (CMIP5) multi-model, multi-emissions scenario ensemble provides downscaled climate-driven streamflow projections to quantify monthly water right allocations for 1951 - 2099. California's Tuolumne watershed is a study basin because water rights are clearly defined, relatively simple, and environmental, agricultural, and urban water users provide a realistic range of competing water uses. This research provides a needed synthesis of climate change, hydrology, dedicated environmental flow, water resources management, and water right regulatory frameworks to improve understanding of climate change effects on seasonally-varying appropriative water right allocations and highlight promising adaptations.

2 Water Rights and Climate Change

Water rights were designed to promote stability by defining water allocations for water users to quantify water reliability and invest in infrastructure (Adler 2010; Kates et al. 2012). Common water right frameworks around the world include riparian rights, prior appropriation, and public rights (Lukasiewicz & Dare 2016). Riparian rights, common in water abundant regions, such as parts of Europe and the eastern US, grant water to property-owners with land that abuts streams or other water bodies. Shortages are shared between water right holders (Barbanell 2001; Zhongjing et al. 2009). Prior appropriation is common in water scarce regions, such as the American West and parts of Japan, and specifies who has rights to divert water for beneficial uses based on priority (seniority) that water was first used. Junior water right holders receive no water until senior water right holders are allocated their full amount (Barbanell 2001; Zhongjing et al. 2009). A recent water right trend has been to recognize water for environmental benefits as a public water right. Australia reformed their water rights to allow more water for the environment and support ecosystems (Lukasiewicz & Dare 2016). On a smaller scale, the Public Trust Doctrine, which allows governments to hold resources for public use, is occasionally used to provide or maintain environmental benefits (Robie 2011). In this paper, we focus on appropriative water rights.

Water right frameworks are commonly disjointed over large regions, like much of Europe, where water law varies by country, and the US, where it varies by state. Some regions have adapted to changes in water supply through water markets, which allow those with water

rights to trade, sell, or lease their water, effectively re-allocating water to different users (Solanes & Jouravlev 2006).

Hydroclimate change has varied the magnitude and timing of streamflow. The seasonality of water rights is important to understand effects of hydroclimate change on water allocations. In many regions, water rights are not uniform throughout the year because of variable water supply and demand. For example, water right holders may receive more water during spring runoff to store in reservoirs or groundwater banks, or demand may be higher during irrigation season. Often, domestic and livestock water uses have rights to divert yearlong, while irrigation diversions may be restricted to the dry season (Fanning et al. 2014; Pahl et al. 2000). Indirectly, hydroclimate change could also affect environmental water purchases from irrigation-season water right holders to instream uses (Elmore et al. 2015) or other third party transactions (Postel & Richter 2012; Wheeler et al. 2010). Seasonal water rights may span state or international borders as well. For example, the Rio Grande Compact of 1938 constrains surface water diversions in Colorado State to the irrigation season. The restrictions are to limit river use by Colorado and deliver sufficient streamflows to downstream New Mexico, Texas, and Mexico (Paddock 2001). The South Platte River Compact between Colorado and Nebraska allocates a fixed amount of streamflow to Nebraska from April through September with shortages to Colorado water users (Bennett et al. 2000). Hydroclimate change may alter water allocations for these types of seasonally-varying water rights. Less water may be available and allotted during seasons that previously had higher flows. This has the potential to alter water allocated between senior and junior water right holders and disproportionately affect some water users.

3 Tuolumne Watershed and Water Rights

California's Tuolumne watershed is representative of a high-elevation, snowmelt-dominated basin. It drains the central west-slope Sierra Nevada Range (Figure 1), with a 4,267 km^2 drainage area and maximum elevation of 3,989 m. It has a Mediterranean-montane climate with warm, dry summers and cool, wet winters. Historically, snowline was approximately 1,000 m and snowpack provided natural water storage. Mean annual flow in the Tuolumne River is about 2,220 millions of cubic meters (mm^3), although considerable inter-annual and seasonal variability exist. Most Tuolumne River streamflow coincides with spring snowmelt between approximately April through June.

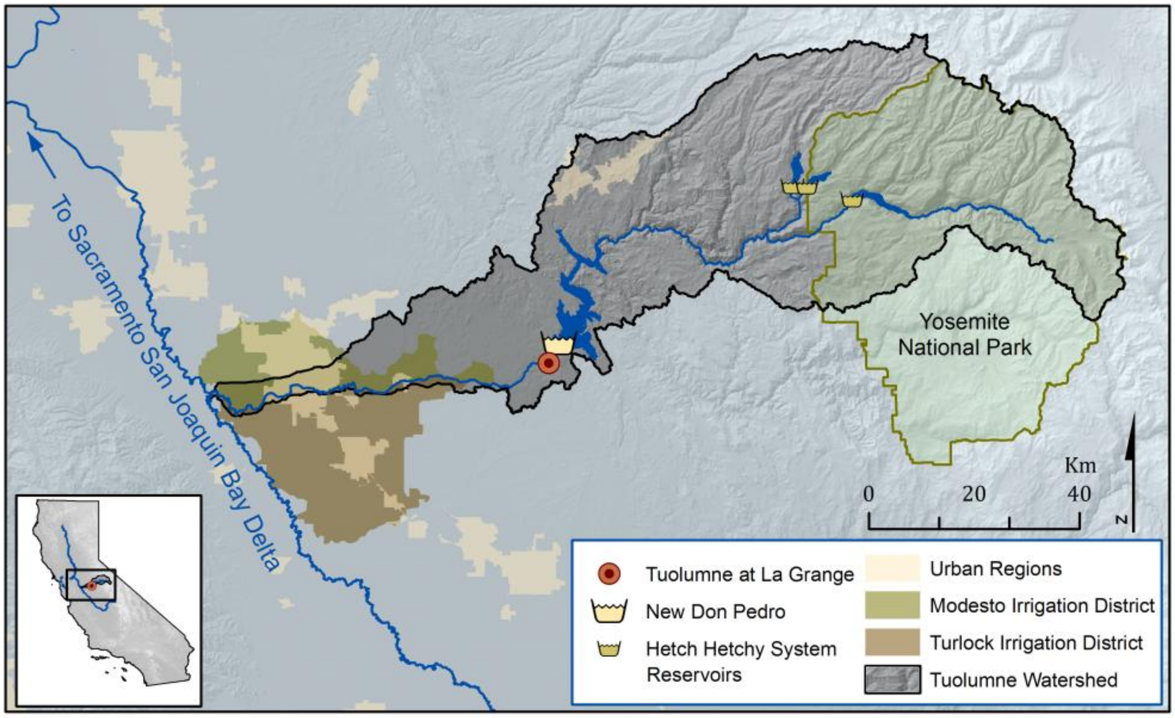

Figure 1. Tuolumne watershed and water infrastructure

California's Water Commission Act, passed in 1914, created the state's legal framework to issue permits regulating and governing state water rights (Hanak et al. 2011). It exempted appropriations that existed before the Act was passed, which are now referred to as 'pre-1914 rights'. Turlock and Modesto Irrigation Districts (TID and MID) have senior, pre-1914 water rights from the Tuolumne River. The San Francisco Public Utilities Commission (SFPUC) has more junior pre-1914 water rights established by the Raker Act, which authorized San Francisco to construct O'Shaughnessy Dam in Yosemite National Park. From June 15 through April 15, the irrigation districts are entitled to 68.4 cubic meters per second (m^3/s) of naturalized daily flows from the Tuolumne River. From April 15 through June 15, the irrigation districts are allocated 68% more water, or 115.1 m^3/s of daily flows. Excess water accrues to SFPUC, which provides water to 2.4 million people in the City and County of San Francisco, as well as wholesale water to Alameda, San Mateo, and Santa Clara Counties (Raker Act 1913; US DOE 1989).

The upper Tuolumne watershed is contained within Yosemite National Park, with two reservoirs but minimal other human development (Figure 1). Downstream of Yosemite National Park, considerable reservoir capacity exists to store seasonal runoff. SFPUC owns and operates the Hetch Hetchy Water System, which includes O'Shaughnessy (445 mm^3), Cherry (331 mm^3), and Eleanor (35 mm^3) Dams, and the Hetch Hetchy Aqueduct that conveys water to the San Francisco Bay Area and local Bay Area reservoirs. Turlock and Modesto Irrigation Districts own and operate the 2,504 mm^3 New Don Pedro Reservoir that provides water to 84,175 hectares of farmland, City of Modesto, and other Central Valley cities.

Naturalized flow estimates at the La Grange streamgage, located downstream of New Don Pedro Reservoir, approximate unregulated Tuolumne River streamflow for water allocation (CDEC 2016) (Figure 1). Most years SFPUC controls slightly more water than the irrigation districts, although SFPUC receives a larger proportion of streamflow in wet years and the irrigation districts receive a larger proportion in dry years.

The Tuolumne River historically supported thriving populations of steelhead trout and fall- and spring-run Chinook salmon, although today spring-run Chinook are extirpated from the river (Yoshiyama et al. 2000). The Tuolumne River downstream of New Don Pedro Reservoir has been listed as critical habitat for steelhead trout and Chinook salmon (National Marine Fisheries Service 1998). Monthly minimum instream flows based on water year types are required below New Don Pedro Reservoir, as negotiated for a 1996 settlement agreement which amended the 1966 Federal Energy Regulatory Commission (FERC) New Don Pedro hydropower license (FERC 2012)[1].

Water is allocated in this study first to federally-mandated environmental flow requirements, then to senior agricultural water right holders (irrigation districts), and finally to junior urban (SFPUC) water uses in San Francisco's Hetch Hetchy Water System. Agricultural water users typically have senior water rights and urban users more junior water rights in the American West, reflecting western human development trends over the past two centuries (Tarlock 2001). Dedicated environmental flows receive de facto priority when required for federal laws like the Endangered Species Act or FERC hydropower relicensing, but may also have junior water rights or no dedicated water rights at all, depending on basin and location.

4 Methods

4.1 Historical and Projected Climate-driven Streamflow Data

Downscaled monthly climate and streamflow data are from the CMIP5 multi-model, multi-scenario ensemble (Reclamation 2014; Reclamation 2013). CMIP completed 1/8 degree downscaling using the Bias-Correction and Spatial Disaggregation (BCSD) method (Wood et al. 2004). Streamflow projections are from calibrated Variable Infiltration Capacity models (VIC version 4.1.2) (Liang et al. 1994; Liang et al. 1996). The Tuolumne watershed above La Grange is approximately a hydrologic unit code [HUC] 8 sized basin. It was not a calibration basin for the VIC model in CMIP5 hydroclimate modeling, although the same size as some evaluation basins, which ranged from HUC 8 to HUC 2 (Reclamation 2014). See Reclamation (2013) for more detail on downscaled CMIP5 climate projections and Reclamation (2014) for additional information on CMIP5 streamflow projections. CMIP5 hydroclimate projections were chosen over CMIP3 projections because they are the most recently available projections from the climate science community and use an updated set of global greenhouse gas emissions scenarios, called radiative concentration pathways (RCPs).

This study uses 16 global climate models (GCMs) (Table 1) and 4 RCPs from CMIP5, for a total of 64 future hydroclimate projections. Including many GCMs produces results that are comparable to culling GCMs based on model skill (Mote et al. 2011). GCMs were included if all four emissions scenarios were available (RCP 2.6, 4.5, 6.0, and 8.5) to represent increasing

[1] The current license extends through April 30, 2016.

carbon emissions. Table 2 summarizes key differences between RCPs. See Van Vuuren et al. (2011) for underlying assumptions of each RCP including energy portfolio, technology development, economic development, population change, and land use change over the 21st century.

Table 1. Climate models and modeling institutions

Model Name	**Climate Modeling Group**
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration
CCSM4	National Center for Atmospheric Research
CESM1-CAM5	Community Earth System Model Contributors
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence
FIO-ESM	The First Institute of Oceanography, SOA, China
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory
GISS-E2-R	NASA Goddard Institute for Space Studies
HadGEM2-AO	National Institute of Meteorological Research/Korea Meteorological Administration
HadGEM2-ES	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
IPSL-CM5A-MR	Institut Pierre-Simon Laplace
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
NorESM1-M	Norwegian Climate Centre

Table 2. RCP description, radiative forcing, pathway, CO2 equivalent and population assumptions through 2100 (GHG = greenhouse gas)

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Description	Low emissions - ambitious GHG reductions through time	Intermediate emissions - relatively ambitious emissions reductions	Intermediate emissions - assumes a range of technologies and strategies to reduce GHG emissions	High emissions - no climate change policy to reduce emissions
Radiative forcing	Peaks at 3.1 W/m^2 and falls to 2.6 W/m^2	Rises to 4.5 W/m^2 by ~ 2075 and stabilizes	Rises to 6.0 W/m^2 and stabilizes by 2100	Steadily increasing to 8.5 W/m^2
Pathway	Overshooting and declines	Stabilizing without overshoot	Stabilizing without overshoot	Rising
CO^2 equivalent	Peaks at 490 ppm mid-century and declines by 2100	Stabilizes at 650 ppm	Stabilizes at 850 ppm	1370 ppm
Population	Peaks near 9 billion and declines	Stabilizes at 9 billion	Stabilizes at 10 billion	12 billion

Overall, average annual air temperatures in the Tuolumne watershed are projected to increase by an average of 1.8 °C, 2.7 °C, 2.9 °C, and 4.2 °C by the end of the 21st century for RCP 2.6, 4.5, 6.0, and 8.5, respectively (Figure 2). Average air temperature deviations are most pronounced after approximately year 2040. Air temperature standard deviation between GCMs varies between 0.7 – 1 °C for all RCPs. Future precipitation is more uncertain, although recent global climate model projections from CMIP5 result in more precipitation for California and the Upper Colorado River Basin than CMIP3 (Reclamation 2013; Ficklin et al. 2015). For the Tuolumne watershed, there is no clear precipitation trend between RCPs, but large standard deviations of 9 – 12 cm between GCMs reflecting uncertainty in future precipitation. Projected climate data for the Tuolumne watershed generally reflect historical variability in 1951 – 2000 (Figure 2). Time periods after 2000 mimic global anticipated climate change trends and variability (Knutti & Sedláček 2013).

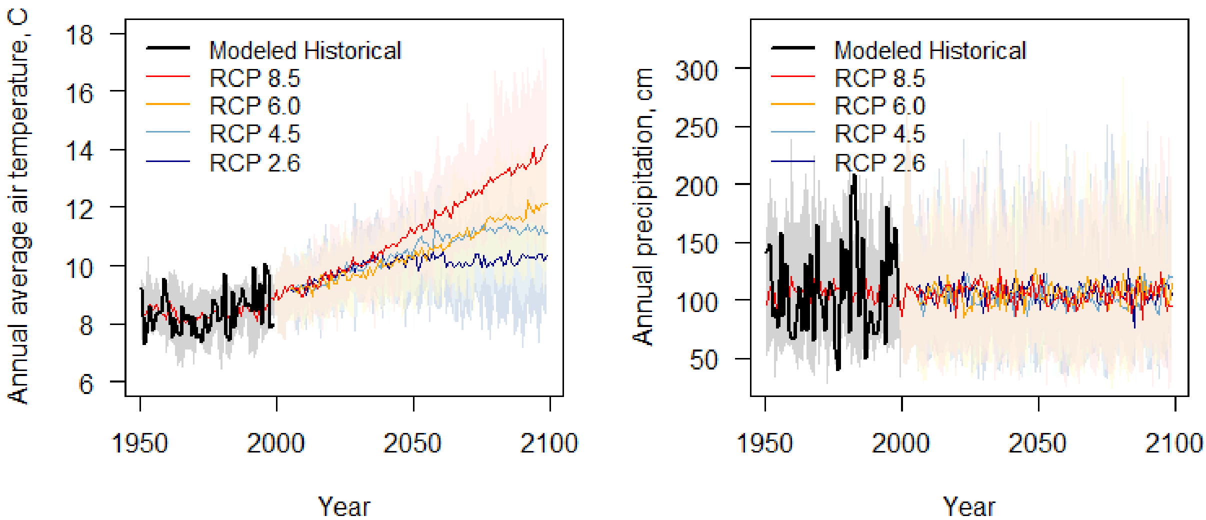

Figure 2. Comparison of Tuolumne watershed air temperature (left) and precipitation (right) projections. Lines show average GCM projection by RCP and colored shaded areas show GCM range by RCP. Gray shading shows observed historical data.

4.2 Water Right Allocation for Dedicated Minimum Instream Flows

Monthly environmental flows based on water year types are required below New Don Pedro Reservoir. Table 3 sums baseflow and April pulse flow requirements for total environmental flows. Typically, water year type forecasts are from the San Joaquin Index, which sums naturalized flows from the Stanislaus River below Goodwin Dam, Tuolumne River below La Grange Dam, Merced River below Merced Falls, and San Joaquin River inflow to Millerton Lake. Seasonal index coefficients account for snowmelt-dominated runoff, occasional large winter floods, and over-year reservoir storage capacity (CDEC 2016; Null & Viers 2013). Because analyzing CMIP5 streamflow for the other streamgage sites on the Stanislaus, Merced, and San Joaquin Rivers to estimate San Joaquin Index water year types was outside the scope of this study, the historical probability of each water year type based on 1906-1995 water years was used as a proxy for water year types from the San Joaquin Index (Tuolumne River Technical Advisory Committee 2016). Note that this method inherently assumes climatic stationarity and is discussed further in limitations (section 6).

Modeled annual streamflow for future water years was ranked by total streamflow, and the driest 6.4% of years were assumed to be critically dry (XC), the next driest years that occurred up to 14.4% of the time were assumed to be median critical (C) water years, and so on. This method does not reflect potential changes to the distribution of water year types from climate change (Null & Viers 2013). It also ignores strategies to adapt water year types to climate change (Rheinheimer et al. In press). The distribution of water year types changes insignificantly through time with the climate-forced streamflow data used here (Supplemental Figure 9). Maintaining the historical distribution of water year types with climate change is a necessary assumption for this analysis so that results focus on climate change effects on water

allocations from seasonally-varying water rights rather than changing water year type framework effects on water allocations.

Table 3. Monthly water allocation for environmental flows and agricultural uses (XC = critical water year and below, C = median critical water year, CD = intermediate critical-dry, D = median dry, DBN = intermediate dry-below normal, BN = median below normal, ANW = median above normal and wetter water years (Raker Act 1913; FERC 2012)

	Total instream flow requirements, m^3/s							**Irrigation**
Month	XC	C	CD	D	DBN	BN	ANW	**districts,** m^3/s
October	3.6	3.6	4.2	4.2	5.9	6.1	11.2	68.4
November	4.2	4.2	4.2	4.2	5.1	5.0	8.5	68.4
December	4.2	4.2	4.2	4.2	5.1	5.0	8.5	68.4
January	4.2	4.2	4.2	4.2	5.1	5.0	8.5	68.4
February	4.2	4.2	4.2	4.2	5.1	5.0	8.5	68.4
March	4.2	4.2	4.2	4.2	5.1	5.0	8.5	68.4
April	9.5	13.8	19.8	21.9	22.2	33.5	51.3	91.7
May	4.2	4.2	4.2	4.2	5.1	5.0	8.5	115.1
June	1.4	1.4	1.4	2.1	2.1	2.1	7.1	91.7
July	1.4	1.4	1.4	2.1	2.1	2.1	7.1	68.4
August	1.4	1.4	1.4	2.1	2.1	2.1	7.1	68.4
September	1.4	1.4	1.4	2.1	2.1	2.1	7.1	68.4
Annual average	***3.7***	***4.0***	***4.6***	***5.0***	***5.6***	***6.5***	***11.8***	***76.2***
Cumulative frequency of water year (%)	6.4	14.4	20.5	31.3	40.4	50.7	66.2	--

4.3 Water Right Allocation for Agricultural and Urban Uses

TID and MID senior water rights stipulate that the irrigation districts receive 68.4 m^3/s of estimated naturalized Tuolumne streamflow at the La Grange streamgage from June 15 through April 15. From April 15 through June 15, the irrigation districts are entitled to 115.1 m^3/s of naturalized Tuolumne River flow (Raker Act 1913). To estimate monthly water allocation to the irrigation districts, we assume up to 115.1 m^3/s to the irrigation districts in May, 91.7 m^3/s in April and June (68.4 m^3/s allocated for half the month, and 115.1 m^3/s allocated the other half), and 68.4 m^3/s for all other months (Table 3). Junior water right holder SFPUC receives all excess water for urban water demands.

Monthly water allocation priority rules are applied for each GCM and RCP (64 model runs total), resulting in environmental, urban, and agricultural water allocation estimates for each model run. 49-year time periods represent the historical period (WY 1951 – 1999), future near term (WY 2000 – 2049) and future far term (2050 – 2099) time periods with projected climate change and variability.

4.4 Statistical Analyses

Root mean square error, ratio of the root mean square error to the standard deviation of observed data, percent bias, and Nash-Sutcliffe efficiency evaluate the fit of monthly modeled data with observed data. Nonparametric Wilcoxon matched pairs tests determine if differences

between the observed and modeled historical period (water year [WY] 1951-1999) are significant. Kruskal-Wallis tests determine if mean differences in water allocations to urban, agricultural, and environmental users vary through time. All data analyses and statistics were completed with R statistical software (R Core Team 2013).

5 Results

5.1 Observed Versus Modeled Historical Streamflow

Overall, modeled monthly CMIP5 climate-driven streamflow represents the seasonality of historical monthly estimated naturalized flows in the Tuolumne River at La Grange well (Figure 3). The correlation coefficient between observed and modeled historical data is 0.94 (R^2 = 0.88) (Figure 4). Observed and modeled flows were not significantly different using a nonparametric Wilcoxon matched pairs test (p-value = 0.283). Root mean square error of monthly observed versus modeled flow is 42.5 m^3/s (0 m^3/s indicates perfect fit). Normalized by average monthly streamflow, the error is 52.6%. The ratio of root mean square error to the standard deviation of observed data is 0.48 (0 indicates perfect fit), percent bias is 5% (0% indicates perfect fit) and Nash-Sutcliffe efficiency is 0.77 (1 indicates perfect fit). These are common metrics to assess model fit for monthly hydrologic models and indicate very good model performance (Moriasi et al. 2007). However, modeled data overestimate seasonal high flows (Figures 3 and 4) by an average of 36.2 m^3/s (17.3%) and a maximum of 239.3 m^3/s (114.3%) in May, (Supplemental Figure 10).

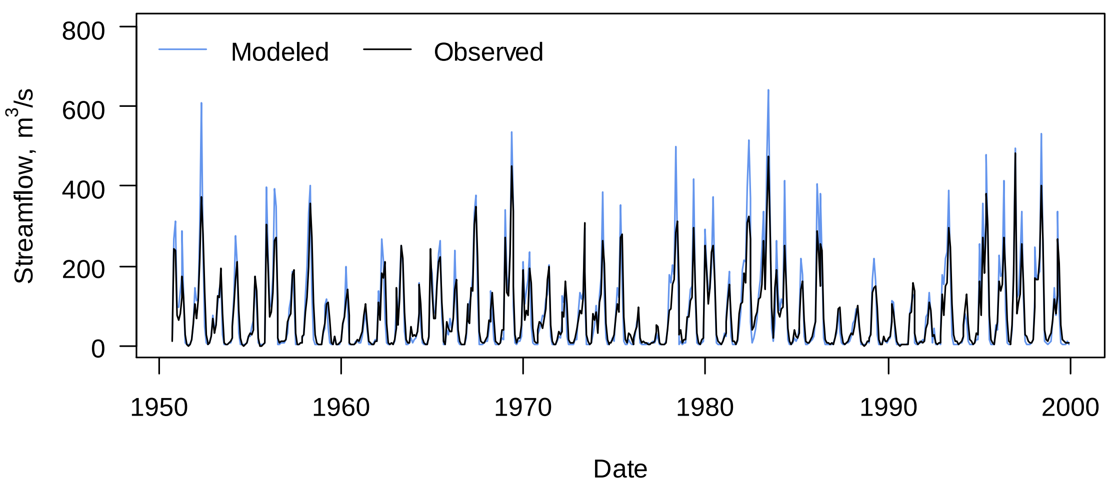

Figure 3. WY 1951 - 1999 estimated naturalized (Tuolumne at La Grange gage) versus modeled Tuolumne River streamflow at La Grange

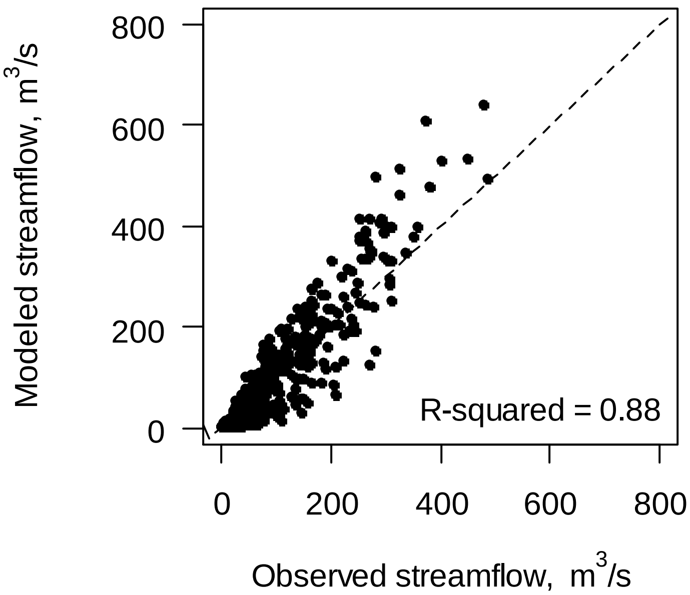

Figure 4. Linear correlation between modeled and historical estimated naturalized Tuolumne River streamflow at La Grange gage (WY 1951-1999)

5.2 Hydroclimate-Driven Water Allocations

Modeled average annual streamflow is reduced from climate change by nearly 5% from 1951 - 1999 through 2000 – 2049 (ranges from -1.5 to -6.8% depending on RCP), and by 8.6% from 1951 - 1999 through 2050 – 2099 (ranges from -4.4 to -11.4% depending on RCP) (Table 4). Considerable variability and uncertainty exists from different GCMs and RCPs. Total streamflow is significantly altered through time for about half of the 64 GCMs and emissions scenarios (Supplemental Table 6). Average monthly streamflow change is not uniform. Rather, climate warming increases average monthly streamflow from December through April and decreases snowmelt runoff in May through June as the hydrograph shifts from snowmelt-dominated to mixed snowmelt- and rainfall-dominated. These changes are most noticeable with more severe emissions scenarios (e.g., RCP 6.5 and 8.0) (Figure 5 top row, Supplemental Table 7).

Table 4. Modeled average monthly Tuolumne streamflow and water allocations to environmental flow, agriculture, and urban uses by time period (averaged for 16 GCMs, 4 emissions scenarios, and 49 years of inter-annual variability within each time period). Standard deviation (σ) between RCP scenarios is presented for averaged streamflow and water allocations.

	Total streamflow (m^3/s)			**Environmental flow (m^3/s)**			**Agriculture (m^3/s)**			**Urban (m^3/s)**		
Time Period	1951-1999	2000-2049	2050-2099	1951-1999	2000-2049	2050-2099	1951-1999	2000-2049	2050-2099	1951-1999	2000-2049	2050-2099
Oct	**5.8**	**6.5**	**7.4**	**4.5**	**4.3**	**4.2**	**1.3**	**2.0**	**2.8**	**0.0**	**0.2**	**0.4**
σ_{RCP}	*0.1*	*0.4*	*0.6*	*0*	*0.1*	*0.2*	*0.1*	*0.2*	*0.3*	*0*	*0.1*	*0.2*
Nov	**16.8**	**16.5**	**17.5**	**5.8**	**5.4**	**5.2**	**9.9**	**9.3**	**9.7**	**1.1**	**1.8**	**2.5**
σ_{RCP}	*0.1*	*0.4*	*1.0*	*0*	*0.1*	*0.1*	*0.1*	*0.2*	*0.3*	*0.1*	*0.2*	*0.8*
Dec	**41.8**	**48.5**	**52.9**	**6.3**	**6.1**	**5.9**	**20.6**	**21.8**	**22.5**	**14.9**	**20.6**	**24.4**
σ_{RCP}	*0.3*	*1.9*	*3.2*	*0*	*0*	*0.1*	*0.2*	*0.5*	*0.6*	*0.4*	*1.9*	*2.7*
Jan	**78.0**	**95.8**	**106.8**	**6.5**	**6.3**	**6.2**	**36.1**	**36.7**	**37.3**	**35.4**	**52.8**	**63.3**
σ_{RCP}	*0.9*	*5.5*	*11.9*	*0*	*0*	*0.1*	*0.1*	*0.8*	*0.7*	*0.8*	*4.8*	*11.4*
Feb	**98.3**	**101.1**	**118.3**	**6.6**	**6.3**	**6.2**	**45.7**	**45.3**	**45.8**	**46.0**	**49.4**	**66.3**
σ_{RCP}	*0.4*	*4.1*	*9.8*	*0*	*0*	*0.1*	*0.1*	*0.6*	*0.6*	*0.3*	*3.5*	*9.4*
Mar	**111.5**	**118.6**	**131.7**	**6.6**	**6.3**	**6.2**	**53.0**	**52.6**	**53.1**	**51.9**	**59.7**	**72.4**
σ_{RCP}	*0.9*	*4.0*	*7.1*	*0*	*0*	*0.1*	*0.3*	*0.4*	*0.6*	*0.9*	*3.8*	*6.8*
Apr	**149.7**	**160.4**	**166.9**	**37.4**	**35.1**	**33.9**	**47.4**	**48.7**	**48.7**	**64.9**	**76.7**	**84.3**
σ_{RCP}	*0.5*	*4.2*	*2.7*	*0.1*	*0.4*	*0.9*	*0.2*	*0.3*	*0.9*	*0.5*	*3.8*	*2.9*
May	**245.0**	**227.9**	**188.5**	**6.6**	**6.3**	**6.2**	**102.3**	**96.6**	**85.9**	**136.1**	**124.9**	**96.3**
σ_{RCP}	*1.1*	*3.0*	*25.0*	*0*	*0*	*0.1*	*0.3*	*0.6*	*6.8*	*1.2*	*2.7*	*18.1*
Jun	**173.1**	**114.9**	**71.7**	**4.5**	**4.2**	**4.0**	**64.5**	**49.0**	**33.6**	**104.1**	**61.8**	**34.1**
σ_{RCP}	*0.3*	*3.9*	*22.4*	*0*	*0.1*	*0.2*	*0.2*	*0.6*	*8.7*	*0.2*	*3.8*	*13.6*
Jul	**33.6**	**16.6**	**9.8**	**4.4**	**3.7**	**3.2**	**16.8**	**8.6**	**4.7**	**12.4**	**4.3**	**1.9**
σ_{RCP}	*0.9*	*1.2*	*3.7*	*0*	*0.1*	*0.3*	*0.1*	*0.6*	*2.0*	*0.8*	*0.5*	*1.4*
Aug	**4.0**	**3.0**	**2.7**	**2.7**	**2.3**	**2.1**	**1.2**	**0.6**	**0.6**	**0.1**	**0.1**	**0.0**
σ_{RCP}	*0.1*	*0.1*	*0.2*	*0*	*0*	*0.1*	*0.1*	*0.1*	*0.1*	*0*	*0*	*0*
Sep	**3.5**	**4.0**	**4.4**	**2.5**	**2.3**	**2.2**	**1.0**	**1.6**	**2.1**	**0.0**	**0.0**	**0.1**
σ_{RCP}	*0*	*0.2*	*0.3*	*0*	*0*	*0.1*	*0*	*0.2*	*0.2*	*0*	*0*	*0.1*
Avg	**80.1**	**76.2**	**73.2**	**7.9**	**7.4**	**7.1**	**33.3**	**31.1**	**28.9**	**38.9**	**37.7**	**37.2**
% Δ	**--**	**-4.9**	**-8.6**	**--**	**-6.1**	**-9.4**	**--**	**-6.8**	**-13.3**	**--**	**-3.1**	**-4.5**
$\sigma_{\%\Delta}$	**--**	**2.1**	**2.8**	**--**	**0.8**	**2.3**	**--**	**0.8**	**4.2**	**--**	**3.9**	**2.9**

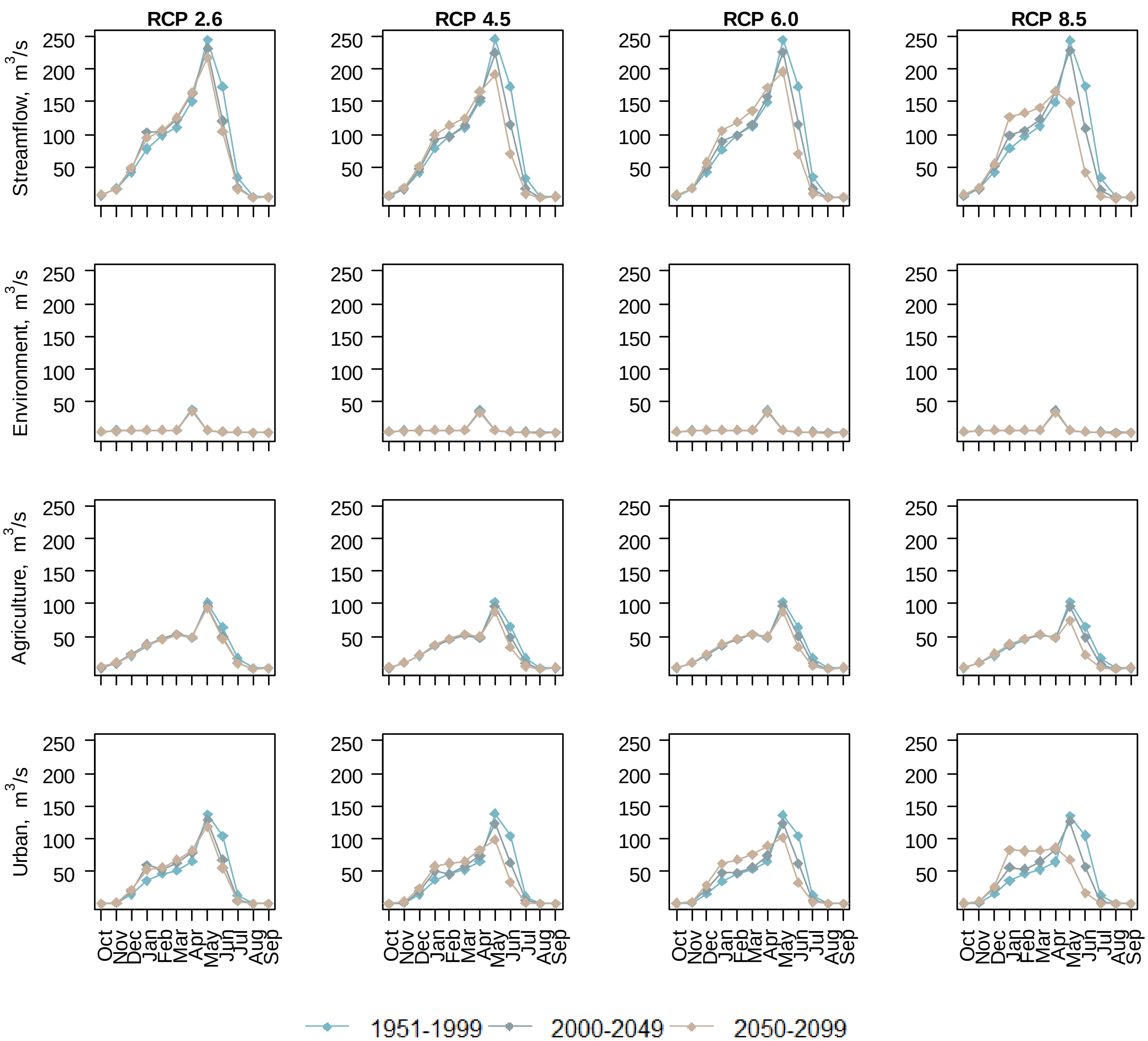

Figure 5. Modeled average monthly Tuolumne streamflow, environmental flow, agricultural water, and urban water allocation by RCP and time period

Monthly-varying environmental flows and water rights are such that projected streamflow reductions are not distributed evenly to all water uses. Instead, environmental flows and senior agricultural water right holders have larger average percentage reductions relative to junior urban uses. Water dedicated to environmental flows, agriculture, and urban uses is reduced by 6.1%, 6.8%, and 3.1%, respectively, from 1951 – 1999 through 2000 – 2049, and reduced by 9.4%, 13.3%, and 4.5%, respectively, from 1951 – 1999 through 2050 – 2099 when all GCMs, RCPs, and inter-annual variability are averaged (Table 4). Standard deviation between RCPs for these values is 2.1%, 0.8%, 0.8%, and 3.9% respectively, from 1951 – 1999 through 2000 – 2049, and 2.8%, 2.3%, 4.2%, and 2.9% respectively, from 1951 – 1999 through 2050 – 2099 (Table 4). Average monthly water allocation changes are nearly always statistically significant for environmental flows and are increasingly significant for agricultural and urban uses with higher GHG emissions scenarios, particularly for winter and spring months (Table 5).

Senior water right holders and environmental flows bear the brunt of hydroclimate change under existing seasonally-variable water rights and dedicated environmental flow frameworks.

Table 5. Kruskal-Wallis p-value evaluate monthly water allocation change to environmental flows, agriculture, and urban uses between RCP emissions scenarios and 1951-1999, 2000-2049, and 2050-2099 time periods for all GCMs. Bolded p-values are significant at a 95% confidence level.

	Environmental flow				**Agriculture**				**Urban**			
RCP	**2.6**	**4.5**	**6.0**	**8.5**	**2.6**	**4.5**	**6.0**	**8.5**	**2.6**	**4.5**	**6.0**	**8.5**
October	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	0.16	0.34	0.07	**< 0.05**	**< 0.05**	0.23	**< 0.05**	**< 0.05**
November	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	0.08	**< 0.05**	0.30	0.8	0.50	0.11	0.57	0.21
December	0.06	**< 0.05**	**< 0.05**	**< 0.05**	0.43	0.62	0.16	0.09	0.62	0.06	**< 0.05**	**< 0.05**
January	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	0.29	0.15	0.10	**< 0.05**	**< 0.05**	0.10	**< 0.05**	**< 0.05**
February	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	0.55	**< 0.05**	0.15	**< 0.05**	0.57	**< 0.05**	**< 0.05**	**< 0.05**
March	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	0.39	**< 0.05**	**< 0.05**	**< 0.05**	0.07	0.17	**< 0.05**	**< 0.05**
April	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	0.18	**< 0.05**	**< 0.05**	0.13	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**
May	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**
June	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**
July	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**
August	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	0.07	0.36	0.36	0.60
September	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	0.39	**< 0.05**	**< 0.05**	**< 0.05**	0.18	0.07	0.08	**< 0.05**

Projected future water allocation estimates are uncertain, although 16 GCMs represent climate model uncertainty, four emissions scenarios represent future carbon emission uncertainty, and time periods of 49 years represent inter-annual variability (Figure 6). In Figure 6, each line represents the non-exceedence probability of 49 years of total annual water deliveries to environmental, agricultural, and urban water uses. Lines that are the same color represent uncertainty between climate models (GCMs), which could also be described as the uncertainty in how climate processes and assumptions are represented in climate models. Each column represents RCPs as alternative emissions scenario pathways, or in other words, policy decisions that societies could make over the next century that may reduce or exacerbate climate warming from GHG emissions. Different colors show water allocation changes for each 49-year time period. Bold lines show average non-exceedence probability for all GCMs in a 49-year time period. The spread of individual lines indicates variability between GCMs and time periods. When lines are vertical or near vertical, there is high interannual variability within each 49-year time period. Overall, average environmental flows and agricultural allocations for future time periods transition downward in Figure 6 sub panels, indicating reduced water allocations with future climate-driven streamflow change. Figure 6 illustrates uncertainty and sources of uncertainty not apparent when all GCMs and RCPs are averaged, as in Table 4.

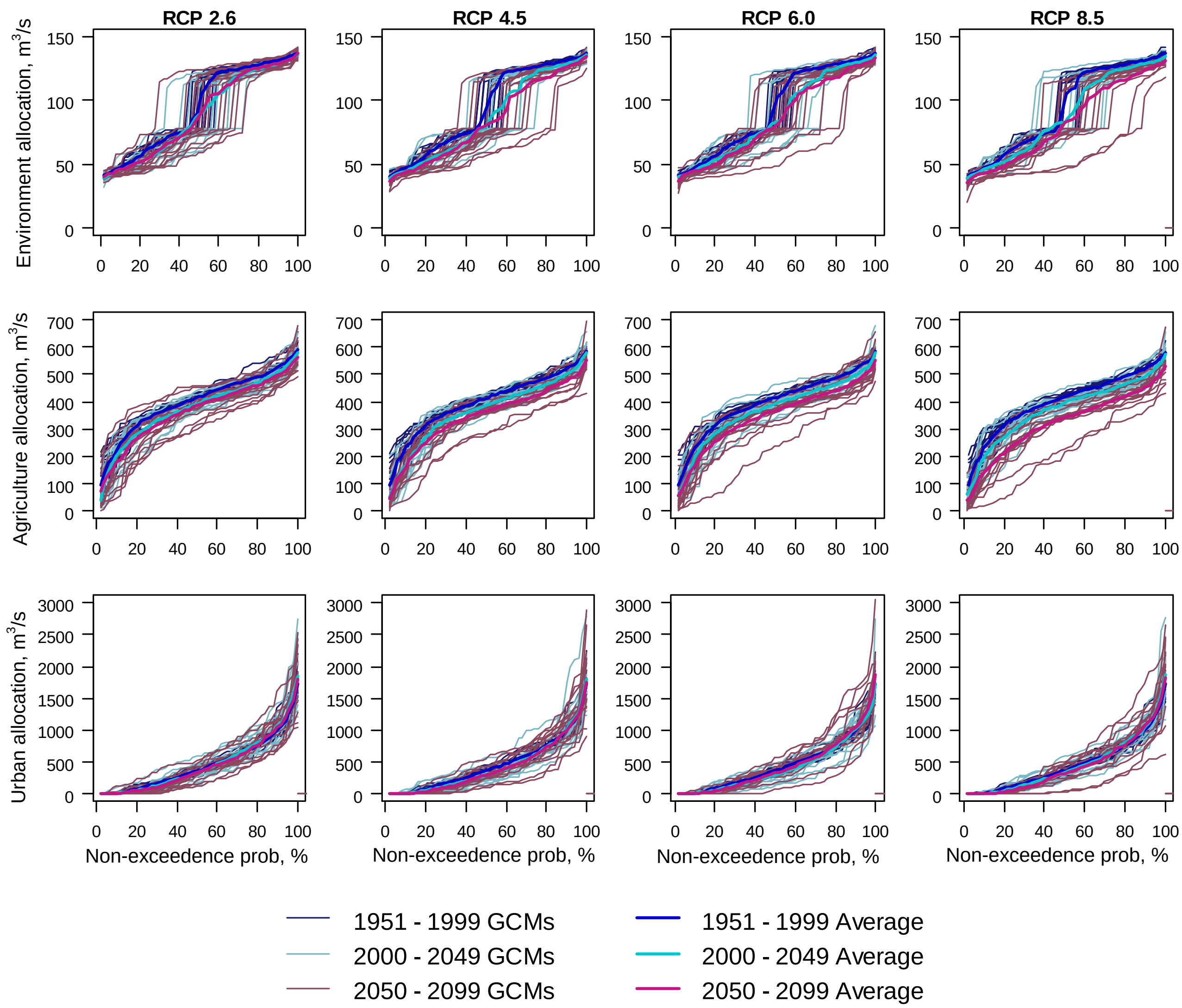

Figure 6. Total annual water allocation non-exceedence probability by water use and RCP. Note scale of y axes varies by water use.

5.3 Hydroclimate-Driven Water Allocation Variability

Box and whisker plots highlight variability and uncertainty of water allocations to environmental flows, agriculture, and urban water uses through time by visualizing lumped uncertainty from GCMs, RCPs, and inter-annual variability (Figure 7). Overall, uncertainty of water allocations increases inversely with water allocation priority so the most junior urban water right holders have the most variability in water allocations. For example, average water allocated to urban uses in May is projected to decrease by approximately 39.8 m^3/s by the end of the 21st century (Table 4), but variability of May allocations vary widely and in some years little to no water is accrued to urban uses in May (Figure 7). Senior water right holders can expect less hydrologic uncertainty than junior water right holders. This analysis suggests that water allocated to senior water right holders (environmental flows and agriculture in this analysis) may remain consistent in March and April, although variability and uncertainty

increase in early summer months June and July when snowpack is reduced from climate change.

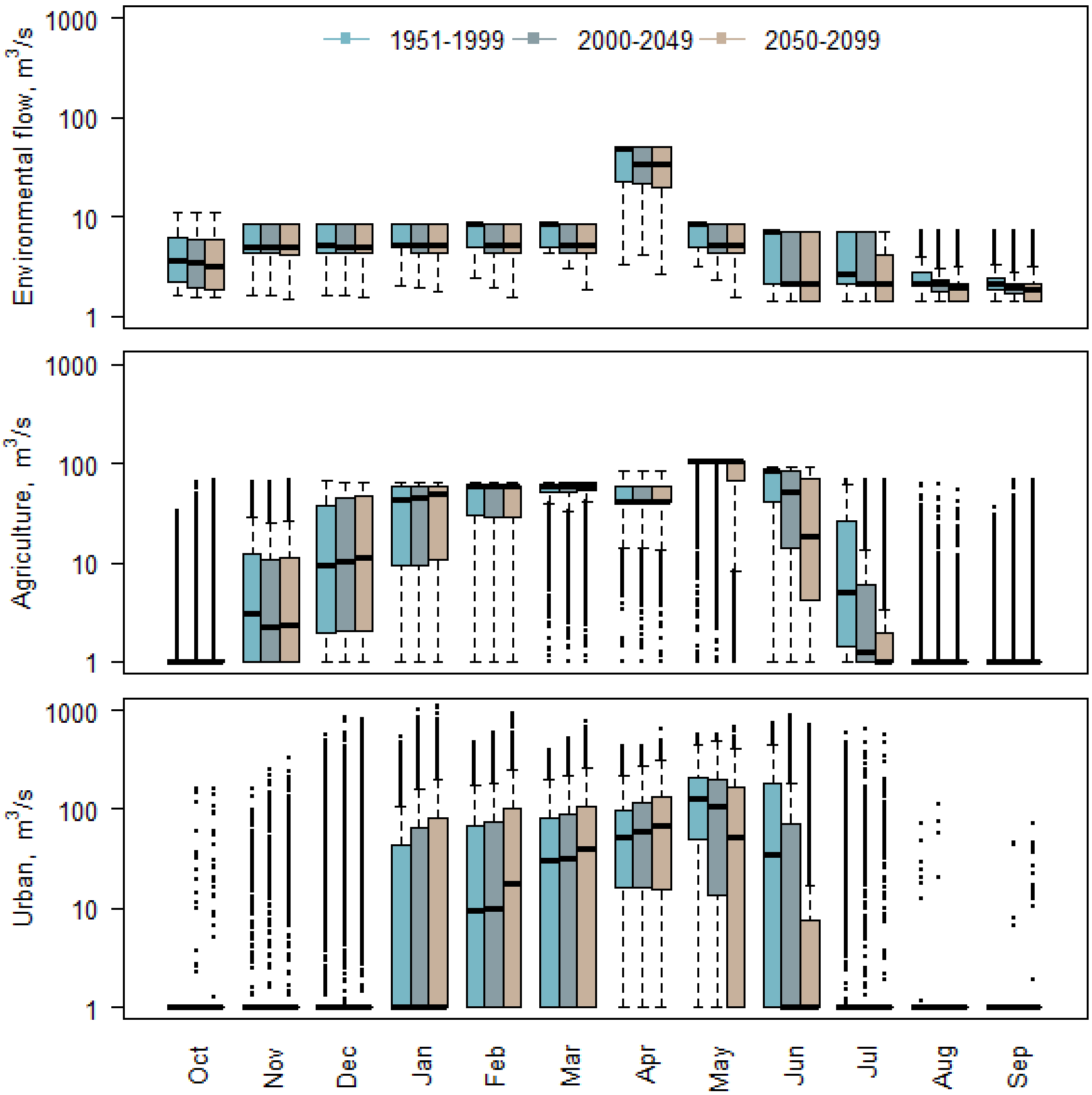

Figure 7. Water allocated to environmental flows (top), agriculture (middle), and urban (bottom) uses by month for 49-year time period. Note log-scale y-axes.

5.4 Wet Year Versus Dry Year Water Allocations

Future inter-annual variability and water allocation extremes are highlighted by comparing the average wettest and driest water years for all GCMs and RCPs (average of 64 model runs for wet and dry year types) (Figure 8). The driest water years are anticipated to become even drier with climate warming, leaving lowest priority urban uses receiving no significant streamflow during summer and 0.4 to 3.4 m^3/s from January through June in the driest years by the end of the century. This necessitates increased dependence on groundwater banking, water marketing, and reservoir storage to meet urban water demands. Agricultural uses receive a

monthly average of 4.9 m^3/s in extremely dry years, and even first priority instream flow requirements have shortages in summer months (Figure 8, left panels). Analyzing extremely dry years nuance previous results from section 5.2. Although senior water right holders have proportionately larger climate-driven water allocation reductions than junior water right holders on average, junior water right holders should expect larger water shortages in extremely dry years.

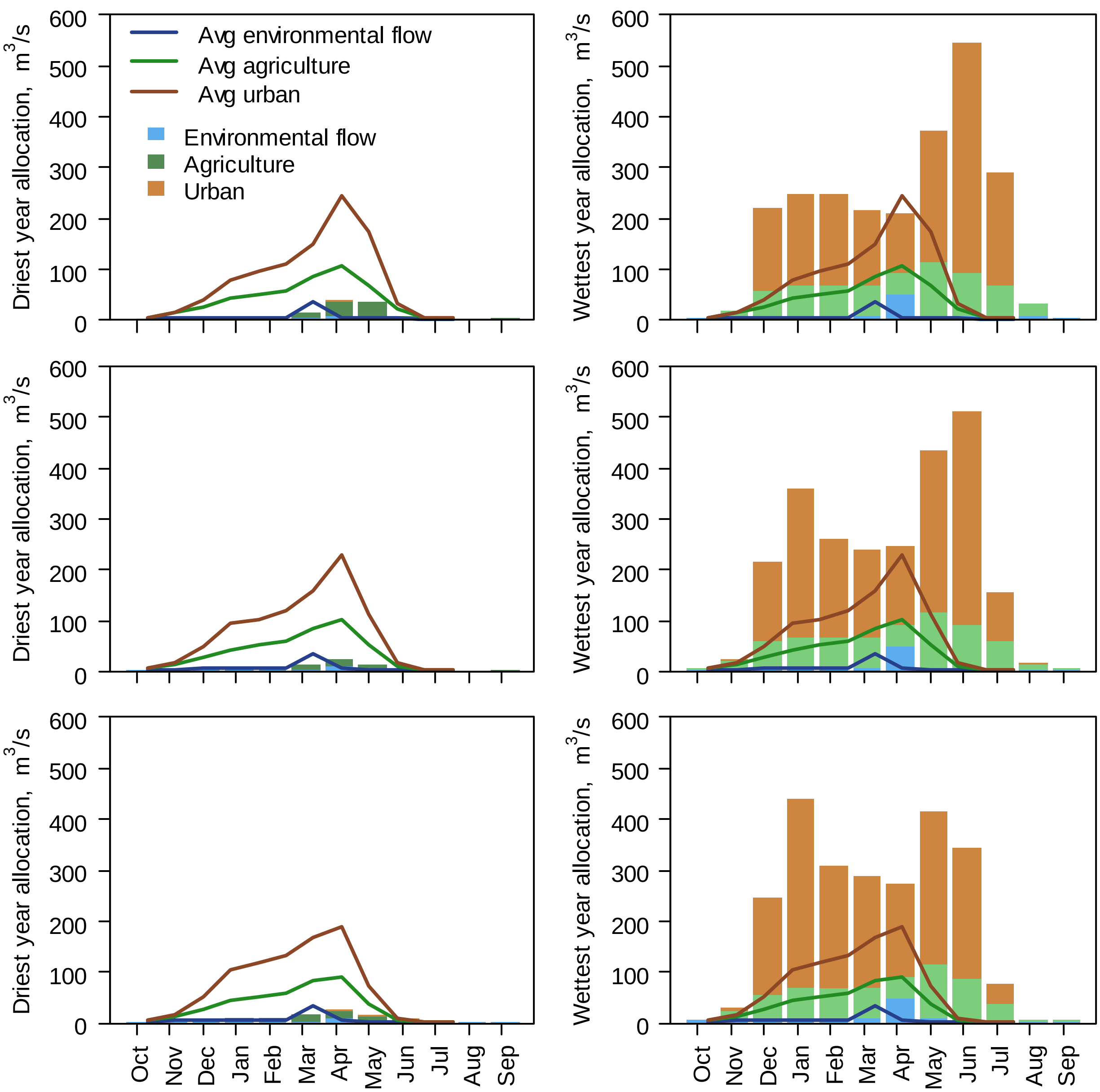

Figure 8. Driest (left) and wettest (right) water years for 1951-1999 (top), 2000-2049 (middle), and 2050-2099 (bottom) with stacked water allocations to environmental flows, agriculture, and urban water uses

In contrast, the wettest years for each GCM suggest in the future more streamflow will be available during winter when water is a hazard (Figure 8, right panels). Less water is available in summer as a resource, even in wet years. Wet years provide required water for instream flows,

including April pulse flows, agricultural users receive their full allotment, and urban users are allocated the majority of streamflow.

6 Limitations

Like all modeling studies, this research has assumptions and uncertainties which limit findings. First, previous research indicates that CMIP5 climate and streamflow data underrepresent decadal to multi-decadal variability, including the probability of extreme floods and droughts (Ault et al. 2013). As such, our findings likely underestimate water allocation impacts from extreme floods and droughts anticipated with climate change. Next, for environmental flow allocations, we applied the historical probability that each water year type occurs based on 1906-1995 water years. This method assumes climatic stationarity of water year types. Future water year type frequencies varied somewhat with climate change in this study, although those changes are statistically insignificant. When water year types are calculated for larger geographic regions, such as for the San Joaquin Index, it is probable that water year type distributions will change significantly with climate change as investigated in prior research (Null & Viers 2013; Rheinheimer et al. In press). This will further affect dedicated environmental flows and the interaction of water year type frameworks with water right laws merits future study. Finally, future streamflows and water allocations are uncertain from climate modeling assumptions and variability, future policy decisions that will affect GHG emissions, and interannual variability that will likely include more extreme climate events. Although there are multiple sources of hydroclimate uncertainty, some results presented here, such as Table 4, do not distinguish between them and average future water allocations as a tool to inform and simplify water management and water law decision-making. When GCMs and emissions scenarios are averaged in Table 4, values are poor representations of extreme GCMs and emission scenarios, particularly RCP 2.6 and 8.5 (Table 4). We reiterate that root mean square error of historical period model fit is 42.5 m^3/s and modeled seasonal runoff is overestimated by an average of 36.2 m^3/s and a maximum of 239.3 m^3/s in May. Thus, results presented in subsequent sections are a conservative estimate for water supply reliability that may overestimate water allocation to junior urban water uses during seasonal high flow periods and, similarly, overestimate the benefits of reservoir storage.

7 Discussion

Several studies have demonstrated future hydrologic change and uncertainty to mountain regions from climate warming (Barnett et al. 2008). We quantify the degree to which the appropriative water doctrine that dominates western American water law is sensitive to hydroclimatic non-stationarity for seasonally-varying water rights. Flashier rivers with reduced snowpack and more winter rainfall will affect water allocations where water rights vary seasonally or monthly. Junior water rights are likely to have more variability and uncertainty between years. Surprisingly however, when water rights vary seasonally, the uneven future temporal distribution of streamflow may benefit junior water right holders and harm senior water right holders or environmental flow requirements that receive priority (Table 4, Supplemental Table 7). Agricultural water users with irrigation season rights from April through October may be impacted in similar systems if peak runoff shifts from spring to winter months. Agricultural (and sometimes mining) water rights typically have seniority in the American West reflecting human development patterns (Tarlock 2001). Our research challenges and nuances

the widespread belief that water shortages will always be allotted to junior water right holders. Shifting the location of streamflow through altered evapotranspiration rates is another likely outcome of climate change that could affect water rights and diversion locations and merits additional research.

Aquatic ecosystems are likely to be altered by climate warming, despite dedicated environmental flows. Our research suggests environmental flows receive larger proportional reductions than junior water right holders, even when environmental flow receive priority (Table 4, Supplemental Table 7). Streamflows are not always available for spring pulse flows with changing hydroclimate conditions, and negotiated environmental flows lack flexibility. Further, more frequent dry water year types anticipated in the future may reduce the hydrologic variability for which aquatic and riparian species are adapted (Dai 2013; Null & Viers 2013). Explicitly analyzing hydroclimate change effects on water right regulatory frameworks confirms previous research that climate change should be considered in Federal Energy Regulatory Commission (FERC) hydropower relicensing, which typically stipulates environmental baseflows and pulse flows for 30-50 year timeframes, to maintain desired aquatic and riparian ecosystems (Viers 2011). Further, regulatory frameworks that incorporate flexibility will be beneficial to manage environmental flows and instream habitats with climate change. In systems where environmental flows have junior water rights or no water rights, environmental flows may be highly variable and uncertain.

Climate change may destabilize water rights to some degree (Tarlock 2012). Legal frameworks to issue permits regulating and governing water rights were developed assuming stationary conditions that increasingly do not represent the future. Water is over-allocated in many large basin, such as Australia's Murray-Darling Basin, China's Yellow River, and the Colorado and San Joaquin Rivers in the U.S. (Christensen & Lettenmaier 2007; McKay 2005; Grantham & Viers 2014). Climate change could increase conflict between competing water uses (Schwarz 2015; Adler 2010).

Multiple options exist to adapt water law to hydrologic non-stationarity. Reforming water right priorities, as occurred in Australia and China (Speed 2009; Grafton et al. 2013), incentivizing water markets to redistribute water through willing buyers and sellers (Brennan 2006; Grafton et al. 2011), maintaining the historical proportions of water allocations to competing water users by adjusting the timing of existing appropriative water rights as hydrographs shift from snowmelt-dominated to rainfall-dominated, and centralizing governance to manage water rights and streamflows by deciding the portfolio of water deliveries to competing environmental, agricultural, and urban uses (Grafton et al. 2013; Davis et al. 2015) are potential water law and policy adaptations to hydroclimate change. Relying solely on surface reservoir storage to mitigate climate-driven streamflow changes will be challenging and likely a poor adaptation in arid regions where water systems are increasingly limited by precipitation (Christensen et al. 2004; Pittock & Finlayson 2011; Taylor et al. 2013) and where flashier runoff and streamflow mean reservoirs do not reach capacity in much of most years (Null 2016). More research at the intersection of climate change, hydrology, aquatic ecology, water resources management, and water law is needed to better identify promising adaptations.

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8 References

Adler, R.W., 2010. Climate change and the hegemony of state water law. *Stan. Envtl. LJ*, 29.

Ault, T.R. et al., 2013. The continuum of hydroclimate variability in western North America during the last millennium. *Journal of Climate*, 26(16), pp.5863–5878.

Barbanell, E., 2001. *Common-property Arrangements and Scarce Resources : Water in the American West*, Westport, Conn: Greenwood Publishing Group.

Barnett, J.C., Lettenmaier, D.P. & Adam, T. P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066), pp.303–309.

Barnett, T.P. et al., 2008. Human-Induced Changes in the Hydrology of the Western United States. *Science* , 319 (5866), pp.1080–1083.

Bennett, L.L., Howe, C.W. & Shope, J., 2000. The interstate river compact as a water allocation mechanism: efficiency aspects. *American Journal of Agricultural Economics*, 82(4), pp.1006–1015.

Brennan, D., 2006. Water policy reform in Australia: lessons from the Victorian seasonal water market*. *Australian Journal of Agricultural and Resource Economics*, 50(3), pp.403–423.

Cai, W. et al., 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, 4(2), pp.111–116.

CDEC (California Data Exchange Center), 2016. WSIHIST. Available at: http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST [Accessed April 4, 2016].

Christensen, N.S. et al., 2004. The effects of climate change on the hydrology and water resources of the Colorado River basin. *Climatic change*, 62(1-3), pp.337–363.

Christensen, N.S. & Lettenmaier, D.P., 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrol. Earth Syst. Sci.*, 11(4), pp.1417–1434.

Dai, A., 2013. Increasing drought under global warming in observations and models. *Nature Climate Change*, 3(1), pp.52–58.

Davis, J. et al., 2015. When trends intersect: The challenge of protecting freshwater ecosystems under multiple land use and hydrological intensification scenarios. *Science of The Total Environment*, 534, pp.65–78.

Elmore, L.R., Null, S.E. & Mouzon, N.R., 2015. Effects of environmental water transfers on stream temperatures. *River Research and Applications*. DOI: 10.1002/rra.2994.

Fanning, W. et al., 2014. *Water rights in Montana*, Missoula, MT. Available at: https://courts.mt.gov/portals/113/water/UM_WaterRightsStudy.pdf.

FERC (Federal Energy Regulatory Commission), 2012. *2012 Lower Tuolumne River annual report*, Available at: http://elibrary.ferc.gov/idmws/file_list.asp?document_id=14101678.

Ficklin, D.L. et al., 2015. Assessing differences in snowmelt-dependent hydrologic projections using CMIP3 and CMIP5 climate forcing data for the western United States. *Hydrology Research*,

p.nh2015101.

Garrote, L., Granados, A. & Iglesias, A., 2016. Strategies to reduce water stress in Euro-Mediterranean river basins. *Science of The Total Environment*, 543, pp.997–1009.

Grafton, R.Q. et al., 2011. An integrated assessment of water markets: a cross-country comparison. *Review of Environmental Economics and Policy*, 5(2), pp.219–239.

Grafton, R.Q. et al., 2013. Global insights into water resources, climate change and governance. *Nature Climate Change*, 3(4), pp.315–321.

Grantham, T.E. & Viers, J.H., 2014. 100 years of California's water rights system: patterns, trends and uncertainty. *Environmental Research Letters*, 9(8), p.84012.

Hanak, E. et al., 2011. *Managing California's water: from conflict to reconciliation*, Public Policy Institute of California.

Kates, R.W., Travis, W.R. & Wilbanks, T.J., 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences*, 109(19), pp.7156–7161.

Knutti, R. & Sedláček, J., 2013. Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, 3(4), pp.369–373.

Kumar, V. et al., 2016. Adaptation strategies for water supply management in a drought prone Mediterranean river basin: Application of outranking method. *Science of The Total Environment*, 540, pp.344–357.

Kundzewicz, Z.W. et al., 2008. The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal*, 53(1), pp.3–10.

Liang, X. et al., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research: Atmospheres*, 99(D7), pp.14415–14428.

Liang, X., Wood, E.F. & Lettenmaier, D.P., 1996. Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. *Global and Planetary Change*, 13(1), pp.195–206.

Lukasiewicz, A. & Dare, M.L., 2016. When private water rights become a public asset: Stakeholder perspectives on the fairness of environmental water management. *Journal of Hydrology*, 536, pp.183–191.

McKay, J., 2005. Water institutional reforms in Australia. *Water policy*, 7(1), pp.35–52.

Miller, K.A., Rhodes, S.L. & MacDonnell, L.J., 1997. Water allocation in a changing climate: institutions and adaptation. *Climatic Change*, 35(2), pp.157–177.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Zbigniew, W., et al., 2008. Stationarity Is Dead : Whither Water Management ? *Science*, 319(5863), pp.573–574.

Moriasi, D.N. et al., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE*, 50(3), pp.885–900.

Mote, P. et al., 2011. Guidelines for constructing climate scenarios. *Eos*, 92(31), pp.257–258.

Mote, P.W. et al., 2005. Declining mountain snowpack in western North America*. *Bulletin of the American meteorological Society*, 86(1), pp.39–49.

National Marine Fisheries Service, 1998. *Factors contributing to the decline of Chinook Salmon: an addendum to the 1996 West Coast steelhead factors for decline report*, Portland, OR.

Null, S.E., 2016. Water Supply Reliability Tradeoffs between Removing Reservoir Storage and Improving Water Conveyance in California. *JAWRA Journal of the American Water Resources Association*.

Null, S.E. & Viers, J.H., 2013. In bad waters: Water year classification in nonstationary climates. *Water Resources Research*, 49(2), pp.1137–1148.

Null, S.E., Viers, J.H. & Mount, J.F., 2010. Hydrologic response and watershed sensitivity to climate warming in California's Sierra Nevada. *PLoS One*, 5(4), p.e9932.

Paddock, W.A., 2001. The Rio Grande Compact of 1938. *University of Denver Water Law Review*, 5(1).

Pahl, R., Duerr, N. & Morros, P., 2000. *Walker River Basin Irrigation Diversions: Summary of historic surface water irrigation diversions*, Available at: http://walkerprogram.org/additional_info/Pahl_Report_Combined.pdf.

Palmer, M.A. et al., 2008. Climate change and the world's river basins: anticipating management options. *Frontiers in Ecology and the Environment*, 6(2), pp.81–89.

De Paola, F. et al., 2014. Intensity-Duration-Frequency (IDF) rainfall curves, for data series and climate projection in African cities. *SpringerPlus*, 3(1), p.133.

Pittock, J. & Finlayson, C.M., 2011. Australia's Murray–Darling Basin: freshwater ecosystem conservation options in an era of climate change. *Marine and Freshwater Research*, 62(3), pp.232–243.

Postel, S. & Richter, B., 2012. *Rivers for life: managing water for people and nature*, Island Press.

R Core Team, 2013. R: A language and environment for statistical computing. *R Foundation for Statistical Computing*. Available at: http://www.r-project.org/.

Raker Act, 1913. *An act granting to the city and couty of San Francisco certain rights of way in, over, and through certain public lands, the Yosemite National Park, and Stanislaus National Forest, and certain lands in the Yosemite National Park, the Stanislaus National F*, United States Senate Sixty-Third Congress First Session.

Rheinheimer, D.E., Null, S.E. & Viers, J.H., Climate-adaptive water year typing for instream flow requirements in California's Sierra Nevada. *Journal of Water Resources Planning and Management*.

Robie, R.B., 2011. Effective Implementation of the Public Trust Doctrine in California Water Resources Decision-Making: A View From the Bench. *UCDL Rev.*, 45, p.1155.

Schwarz, A.M., 2015. California Central Valley Water Rights in a Changing Climate. *San Francisco Estuary and Watershed Science*, 13(2).

Sellami, H. et al., 2016. Quantifying hydrological responses of small Mediterranean catchments under

climate change projections. *Science of The Total Environment*, 543, pp.924–936.

Solanes, M. & Jouravlev, A., 2006. Water rights and water markets: lessons from technical advisory assistance in Latin America. *Irrigation and drainage*, 55(3), pp.337–342.

Speed, R., 2009. A comparison of water rights systems in China and Australia. *Water Resources Development*, 25(2), pp.389–405.

Stewart, I.T., Cayan, D.R. & Dettinger, M.D., 2005. Changes toward earlier streamflow timing across western North America. *Journal of climate*, 18(8), pp.1136–1155.

Tarlock, A.D., 2001. Future of Prior Appropriation in the New West, The. *Nat. Resources J.*, 41, p.769.

Tarlock, A.D., 2012. Takings, water rights, and climate change. *Vt. L. Rev.*, 36(Rev. 731).

Taylor, R.G. et al., 2013. Ground water and climate change. *Nature Climate Change*, 3(4), pp.322–329.

Tuolumne River Technical Advisory Committee, 2016. Current Flow Schedule. *Accessed March 2016*. Available at: http://tuolumnerivertac.com/Water Year Flow.pdf.

U.S. Department of the Interior & Bureau of Reclamation, 2013. *Downscaled CMIP3 and CMIP5 climate projections: Release of downscaled CMIP5 climate projections, comparison with preceding information, and summary of user needs*, Available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf.

U.S. Department of the Interior & Bureau of Reclamation, 2014. *Downscaled CMIP3 and CMIP5 Hydrology Projections - Release of hydrology projections, comparison with preceding information and summary of user needs*, Available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf.

US DOE (US Department of Energy), 1989. *Hetch Hetchy, Striking a Balance: a review of the Department of the Interior's survey of water and power replacement concepts for Hetch Hetchy*, Washington D.C.

Viers, J.H., 2011. Hydropower Relicensing and Climate Change1. *Journal of the American Water Resources Association*, 47(4), pp.655–661.

Van Vuuren, D.P. et al., 2011. The representative concentration pathways: an overview. *Climatic change*, 109, pp.5–31.

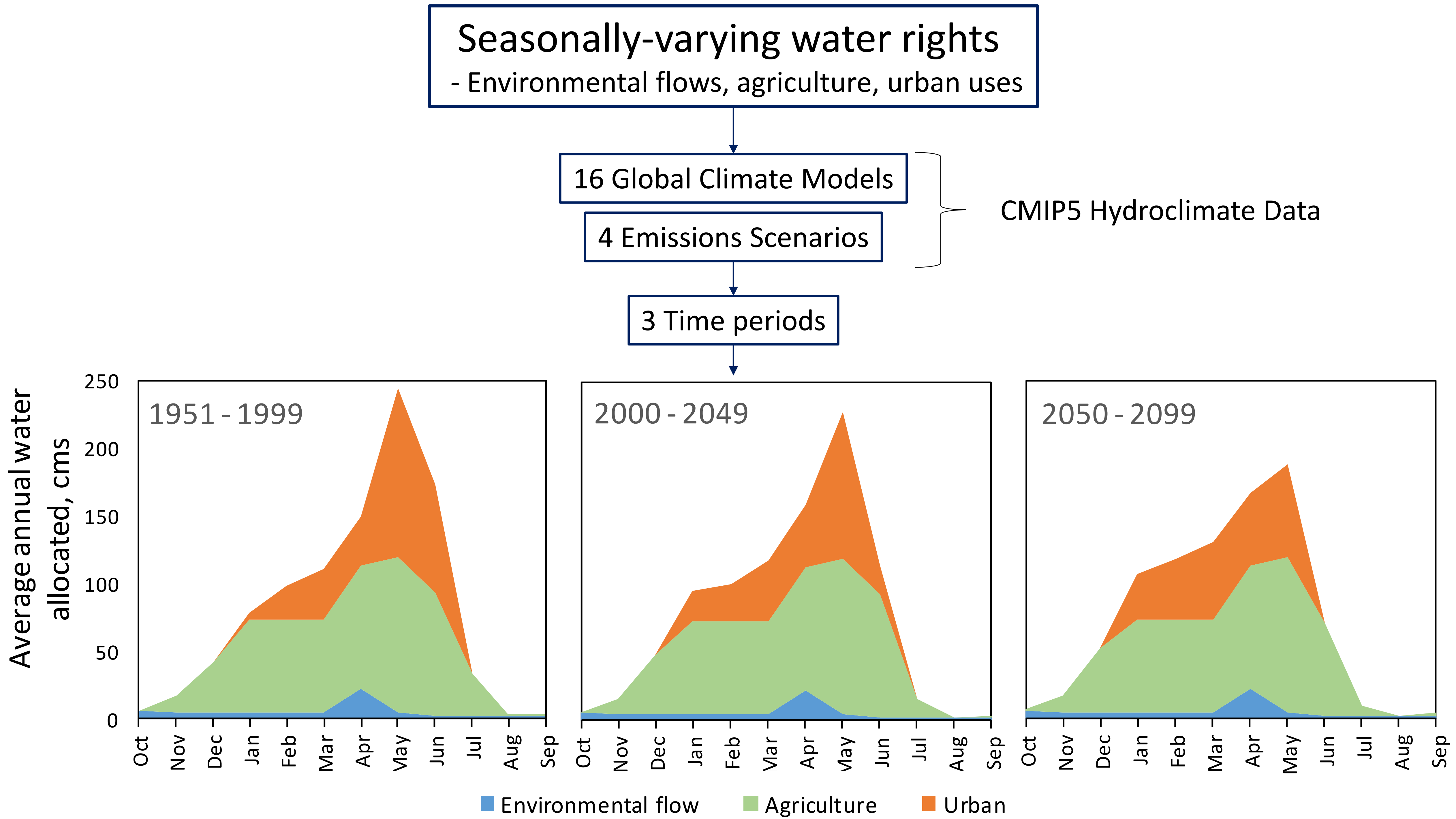
Wheeler, S. et al., 2010. The changing profile of water traders in the Goulburn-Murray Irrigation District, Australia. *Agricultural Water Management*, 97(9), pp.1333–1343.

Wood, A.W. et al., 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. *Climatic change*, 62(1-3), pp.189–216.

Wuebbles, D. et al., 2014. CMIP5 climate model analyses: climate extremes in the United States. *Bulletin of the American Meteorological Society*, 95(4), pp.571–583.

Yoshiyama, R.M. et al., 2000. Chinook salmon in the California Central Valley: an assessment. *Fisheries*, 25(2), pp.6–20.

Zhongjing, W., Hang, Z. & Xuefeng, W., 2009. A Harmonious Water Rights Allocation Model for Shiyang River Basin, Gansu Province, China. *Water Resources Development*, 25(2), pp.355–371.


Seasonally-varying water rights
- Environmental flows, agriculture, urban uses
16 Global Climate Models
4 Emissions Scenarios
CMIP5 Hydroclimate Data
3 Time periods
Average annual water allocated, cms
250
200
150
100
50
0
1951 - 1999
2000 - 2049
2050 - 2099
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Environmental flow
Agriculture
Urban