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Climate change effects on water allocations with season dependent water rights

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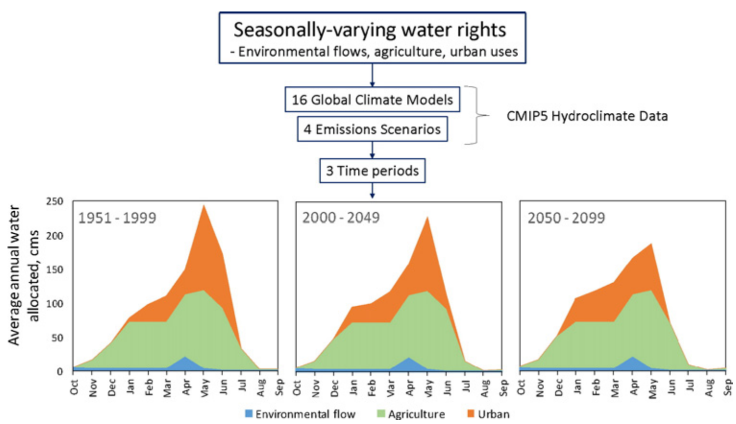
HIGHLIGHTS

- Appropriative rights allocate water to urban, agricultural, and instream uses.
- Senior water right holders have the largest climate-driven water reductions.
- Junior water right holders have most uncertainty from inter-annual variability.
- Findings are applicable to over-allocated basins with seasonally-varying water rights.

GRAPHICAL ABSTRACT



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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 that 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 that 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 that aquatic ecosystems may be disproportionally impaired by hydroclimate change, even when environmental flows receive priority.

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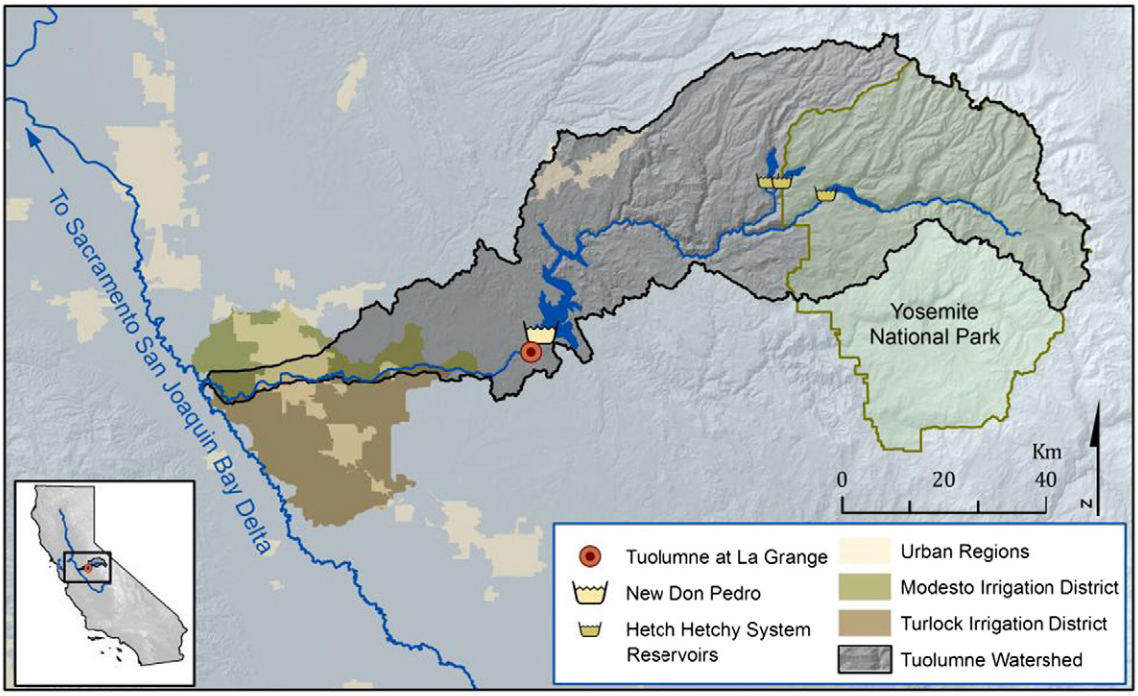

Fig. 1. Tuolumne watershed and water infrastructure.

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 et al., 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 and 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 >1/6 of the world's population currently depends on snowmelt for water supplies (Barnett et al., 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 and 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

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