LETTER • OPEN ACCESS

Climate change impacts on hydrological services in southern California

View the article online for updates and enhancements.

Environmental Research Letters

LETTER

Climate change impacts on hydrological services in southern California

Emma C Underwood[1,2] , Allan D Hollander[1], Lorraine E Flint[3], Alan L Flint[3] and Hugh D Safford[1,4]

1   Department of Environmental Science and Policy, University of California, Davis, CA 95616, United States of America
2   Centre for Biological Sciences, University of Southampton, Southampton SO17 1BJ, United Kingdom
3   US Geological Survey, Placer Hall, 6000 J Street, Sacramento, CA 95819, United States of America
4   USDA Forest Service, Pacific Southwest Region, 1323 Club Dive, Vallejo, CA 94592, United States of America

E-mail: eunderwoodrussell@ucdavis.edu

Abstract

Water availability is one of the most critical issues facing southern California. Consequently, the role and management of intact watersheds on public lands that supply water are paramount. We undertake the first regional study of climate impacts on hydrological services (runoff, recharge, and climatic water deficit) across the four national forests of southern California—the Angeles, Los Padres, Cleveland and San Bernardino. We assess the exposure, sensitivity, and vulnerability of water resources by comparing current conditions (1981–2010) to mid-century (2040–2069) and end-of-century (2070–2099) using three general circulation models (GCMs) under RCP8.5. Half of the study area is projected to exceed 2015's drought conditions in 10%–30% of the years between now and end-of-century under the moderate GCM (CCSM4), and one-third of the area is projected to exceed 2015 in 50% of the years under the hotter, drier projection (MIROC-ESM). Under a moderate projection, mean runoff increased by $1.2\times$ by the end-of-century for three of the national forests, while mean recharge decreased by $0.9\times$ across all forests. Projected end-of-century climatic water deficit increased on average $1.1\times$ across the four forests. We assessed the vulnerability of watersheds by comparing the projected mean change between current and future climates with the current inter-annual variability using three categories of vulnerability. Under the moderate projection, one-third of the 385 watersheds were moderately vulnerable to changes in runoff and recharge ($+/-0.2$ to $+/-1\times$ the standard deviation of current inter-annual variability) and ~12 watersheds were highly vulnerable, suggesting an era of new hydrological conditions by the end-of-century. Half of the Forest Service's priority management watersheds had moderate or high vulnerability for runoff and recharge. Spatial data on hydrological services and their vulnerability can directly assist in climate-smart planning, allowing tradeoffs to be assessed between proposed management actions and their effect on hydrological services.

Introduction

Water demands in southern California continue to grow owing to the ever-increasing human population, estimated to reach nearly 25 million in the eight southern California counties by 2030 (http://dof.ca.gov/Forecasting/Demographics/projections/), and high levels of agricultural commodity production that contribute nearly $10 billion to California's economy (https://nass.usda.gov/Statistics_by_State/California/ Publications/AgComm/2014/2014cropyearcactb00.pdf). Viewed in the context of dwindling local water supplies, the need to import increasing amounts of water, and the potent impacts of land use change and climate change on water provision, water availability is one of the most pressing issues in southern California.

In the late 1800s, forest reserves in southern California were created owing to concerns from local communities over erosion, downstream flooding, and

water supply. Today, these national forests contain large swaths of intact vegetation, which the USDA manages to provide goods and services for people. As such, the quantification of hydrological services, such as water runoff and groundwater recharge and understanding how these will change under future climates, is of increasing interest to federal land managers (e.g. the Forest Service 2012 Planning Rule, Weidner and Todd 2011).

Compared to other regions of the US, annual precipitation in California has high inter-annual variability and is dependent on a relatively small number of storms (half of the total precipitation across much of southern California is received in ten days or less; Dettinger *et al* 2011). The majority of these storms are related to the flow of atmospheric rivers originating in the tropics or subtropics, carrying substantial water vapor and advected by linear wind systems to the west coast. Mountains along the California coast and inland create strong orographic uplift resulting in heavy and highly localized precipitation. Precipitation projections for California have considerable uncertainty because it lies in a transition zone between higher latitude regions which are projected to experience increases in precipitation, and subtropical regions which are projected to experience decreases (Meehl *et al* 2007).

A study from the North American Regional Climate Change Assessment Program, with the incorporation of regional climate models into general circulation models (GCMs) (Mearns *et al* 2013), find different regional responses to climate change in the southwest US compared to the west coast based on the ensemble means of 11 futures with results suggesting an imminent transition to more arid climate marked by more extremes (Yu *et al* 2015). Other studies focused on California predict rarer but more intense storm events and longer dry periods between storms (Cayan *et al* 2008, Dettinger *et al* 2011). These modified conditions are projected to increase the risk of flooding due to more intense storms, reduce spring and summer streamflows as temperatures warm, decrease snowpack, increase stream temperatures, as well as cause indirect effects on soil, vegetation, and fire regimes (Hayhoe *et al* 2004; Dettinger *et al* 2011, Yu *et al* 2015, Molinari *et al* 2018).
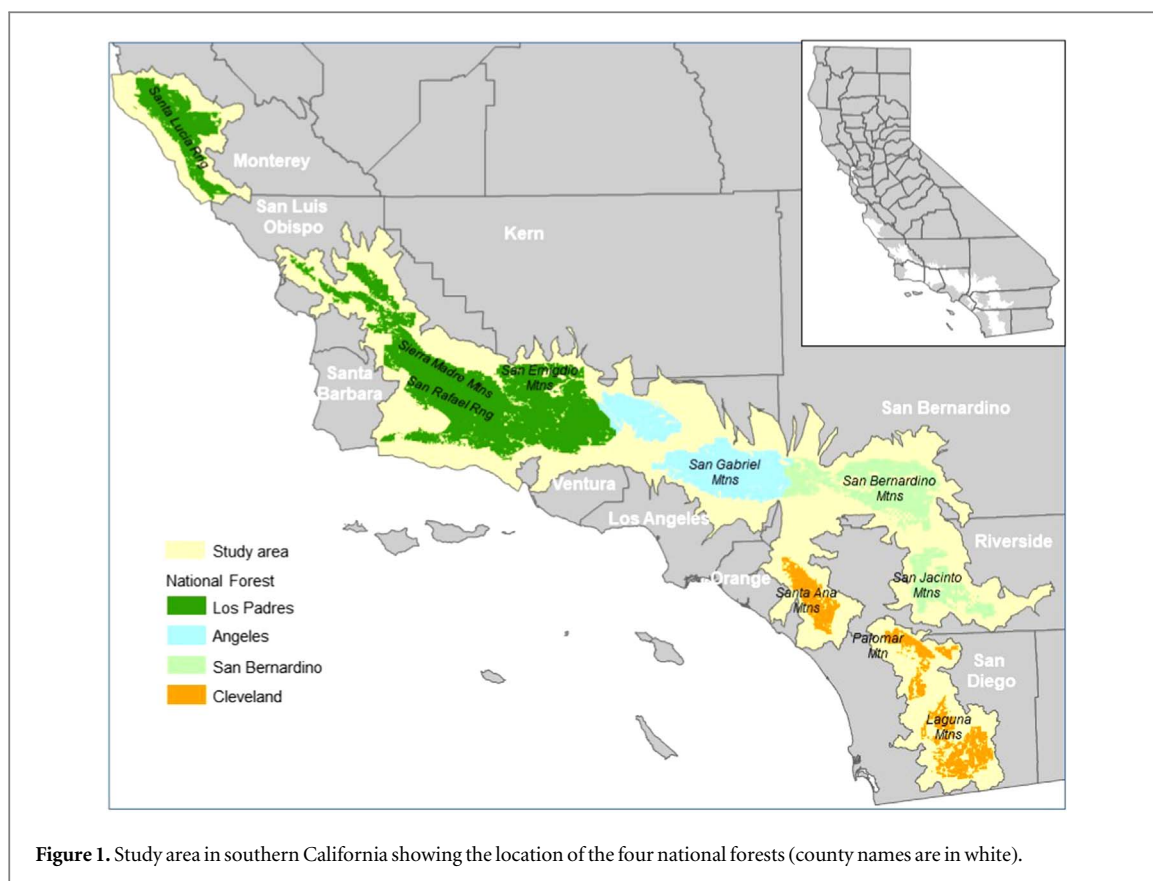
Determining the relative vulnerability of habitats and the services they provide to changes in climate is a critical input to provide guidance on resource management (Williams *et al* 2008). Vulnerability is defined as the susceptibility of a system to negative impacts (Smith *et al* 2000), which can be expressed as a combination to two primary components: exposure and sensitivity to climate change. This has generally been applied to species, for example, the intrinsic traits that govern the sensitivity of species or the exposure to extrinsic factors such as the degree of climate change effects at regional and local habitat scales. Here we apply these concepts to the impacts of climate change on water resources.

This study represents the first spatially explicit assessment of climate impacts on water resources on national forest lands in southern California. Our goal was to assess the impacts of climate change on water runoff, groundwater recharge, and CWD across watersheds in the national forests and to consider the implications of these changes for resource management. Specifically, we addressed four questions: (1) what are the projected changes in temperature and precipitation for the region, and how often are drought conditions projected to occur between now (1981–2010) and end-of-century (2070–2099)? (2) What are the projected changes in runoff, recharge and CWD by mid-century (2040–2069) and end-of-century? (3) How vulnerable are watersheds likely to be based on the projected change compared to the current range of inter-annual variability? And (4) how do Forest Service priority watersheds fare?

Materials and methods

The study area encompasses the four southernmost national forests in California—the Angeles, the Los Padres, the Cleveland, the San Bernardino—and extends to the boundaries of all HUC-12 (USGS Hydrologic Unit Code) watersheds that intersect national forest lands. Overall, the study area includes 385 HUC-12 watersheds and covers 35 158 km^2 (8 687 731 acres) (figure 1). The area supports a Mediterranean-type climate, with cool, wet winters and warm to hot, dry summers. Precipitation decreases and temperatures increase from north to south, and there is a strong gradient of warming temperatures moving inland from the coast. Elevations range from sea level to 3500 m.

We used outputs from the Basin Characterization Model (BCM, monthly data at 270 m spatial resolution; Flint *et al* 2013) to describe the effect of future temperature and precipitation on water provision services and CWD. We compare current conditions (mean calculated over the 30 years period 1981–2010) to mid-century (2040–2069) and end-of-century (2070–2099) conditions. The BCM is a regional water-balance model that combines precipitation and temperature data with topography, energy balance, soils, and geology to simulate the unimpaired responses of hydrology to change in climate, without regard to land use or urbanization. While some other hydrological models outperform the BCM at finer spatial scales such as plots, the BCM is widely accepted to be the most appropriate model for applications at the size of planning watersheds (CalWater 1999). Hydrologic outputs from the BCM under current climate conditions have been calibrated and validated with measured streamflow data from 159 largely unimpaired watersheds across the state (Flint *et al* 2013), where antecedent conditions of soil moisture and snowpack are developed with 1–2 year 'spinup' runtimes. In

Figure 1. Study area in southern California showing the location of the four national forests (county names are in white).

cases where basins are ungauged and not validated, the BCM can be used with a reasonable level of confidence for regional cross-comparisons between basins (Flint *et al* 2013). The BCM outputs have been utilized for investigating water resources (e.g. Flint and Flint 2012, Hanson *et al* 2012, Drexler *et al* 2013, Thorne *et al* 2015), biodiversity (e.g. Ackerly *et al* 2015, McCullough *et al* 2016), and wildfire and forest health (e.g. van Mantgem *et al* 2013, Anderegg *et al* 2015) in California and the western US.

In this study, we used water runoff (which occurs when available water exceeds soil storage and becomes streamflow or other flow) and groundwater recharge (which travels below plant roots to become baseflow and potentially recharge to the groundwater system) along with CWD from the BCM (the difference between potential (PET) and actual evapotranspiration (AET)). In the BCM PET is calculated using the Priestley–Taylor equation (Priestley and Taylor 1972) with topographic shading and cloudiness (Bristow and Campbell 1984) and AET is calculated as the declines in soil water content below field capacity at PET rate, until the soil water reaches wilting point. CWD is a key factor in determining the distribution of vegetation (Thornwaite and Mather 1955, Stephenson 1990) and has been used in multiple studies to describe habitat suitability and the distribution of plant species across the landscape (e.g. Ackerly *et al* 2015). CWD is particularly relevant in southern California given the potential effect of summer drought on vegetation due to limited soil moisture and primary production (Mooney 1977).

To assess the impact of climate change on water provision services and CWD we focused on GCMs from the Fifth Assessment IPCC report (IPCC 2014) under the business-as-usual mitigation scenario, Representative Concentration Pathway 8.5 (RCP8.5). Of the roughly 50 GCMs available globally, a subset has been identified as particularly relevant for resource managers in the western US. Flint and Flint (2014) selected 18 representative models for California and the Great Basin, Nevada, based on a cluster analysis and how well these climate models represented seasonal changes in current precipitation, air temperature, and El Niño effects in the Pacific Southwest (see also Flint *et al* 2015). From these 18 models, this study focused on three models identified based on stakeholder feedback in another California-specific project (http://climate.calcommons.org/crnb/about): the projection closest to the ensemble mean of the other 17 (CCSM4; National Center for Atmospheric Research. USA); a warmer wetter projection (CNRM-CM5; Centre National des Recherches Météorologiques, France); and a hotter drier projection (MIROC-ESM; Center for Climate System Research, Japan). Notably, the CCSM4 and CNRM-CM5 models were also selected as two of the ten models best-suited to research on California's Fourth Climate Change Assessment (http://water.ca.gov/climatechange/docs/2015/Perspectives_Guidance_Climate_Change_Analysis.pdf).

This process assessed the historical performance of each GCM at three spatial scales (global, southwestern US, and California) using the correlation and variance of mean seasonal spatial patterns, amplitude of seasonal cycle, diurnal temperature range, and annual- to decadal-scale variance.

We report results from three analyses designed to highlight the exposure, sensitivity, and vulnerability to climate change (*sensu* Williams *et al* 2008) of water resources in southern California watersheds. First, we assessed exposure by reporting projections for change in mean temperature and precipitation for the study area from the three chosen GCMs (data downloaded from http://climate.calcommons.org/dataset/2014-CA-BCM) using the BCM downscaled data for each GCM. As an alternative to reporting overall change in precipitation and temperature we also provide an example of the frequency with which droughts are projected to occur in the future. We take a single year (2015) that experienced severe 'hot drought' conditions (Swain 2015, Lifeng *et al* 2017), as characterized by its annual precipitation and maximum temperature, and calculated the number of times conditions at least this extreme are projected to occur between 2016 and end-of-century (2099) under the moderate, warmer wetter, and hotter drier climate projections with the downscaled climate used as an input to the BCM (Flint *et al* 2013). Specifically, we counted the number of years for the model period that had *both* an annual precipitation less than the 2015 value *and* a mean annual maximum temperature greater than the value in 2015 and report the percent of years between now and end-of-century where the 2015 hot-drought conditions are exceeded.

Second, we assessed the sensitivity of water provision services (runoff and recharge) and CWD to future climates under the three GCMs. To do this, we used BCM outputs forced under each GCM and calculated the difference between current conditions (1981–2010) and mid-century (2040–2069) and end-of-century (2070–2099) conditions. Third, we determined vulnerability by identifying areas of southern California vulnerable to climate change-driven alterations in water resources by highlighting those HUC-12 watersheds where future hydrologic conditions are projected to fall outside the range of current variation (calculated over the period 1981–2010). Our vulnerability measure was calculated by taking the difference between the 30-yr means of the current (1981–2010) and projected future (2070–2099) climates for recharge, runoff and CWD and dividing by the standard deviation of the current (1981–2010) period for each 270 m pixel within the study area and then spatially averaging the result for each HUC 12 watershed. We arbitrarily identified watersheds as 'low vulnerability' where this metric measured between −0.20 and +0.20 (i.e. the projected change in the 30-yr means was ⩽0.2× the current standard deviation);

watersheds where the projected change in the 30-yr means was between +/−0.2 and +/−1× the current standard deviation were identified as having 'moderate vulnerability', and those exceeding 1 standard deviation 'high vulnerability'.

Finally, to assess on-the-ground implications of projected vulnerability of hydrological services for resource managers, we report the vulnerability of US Forest Service 'priority watersheds' (HUC-12 scale) for runoff and recharge under the three GCMs. Priority watersheds have been identified by the Forest Service Watershed Condition Framework (WCF; Potyondy and Geier 2011) using 12 (non-climate) indicators of watershed condition. The Forest Service identified two priority watersheds on each national forest for restoration investment.

Results

Evaluating exposure to climate change in southern California

For the three chosen GCMs (red stars in figure 2), projected increases in mean annual temperature (30-yr means, 1981–2010 versus 2070–2099) ranged from +3.1 °C to +4.4 °C (figure 2). Projected changes in 30-yr means precipitation varied widely among the three GCMs, ranging from +3% under the moderate CCSM4 projection to +36.9% under the warmer wetter projection (CNRM-CM5), to a decrease of −32.7% under the hotter drier (MIROC-ESM) projection (table 1). For comparison, the ensemble means of all 18 models shown in figure 2 were +2.6 °C change in temperature and −1% change in precipitation.

Using 2015 drought conditions as a threshold, in the moderate projection (CCSM4) we found that most of the central portion of the study area exceeded drought conditions of 2015 (i.e. received less annual precipitation than 2015 *and* exceeded the mean maximum temperature of 2015) in <20% of the years between now and the end-of-century. However, 7% of the study area located in the northern region (the Santa Lucia Range on and adjacent to the Los Padres National Forest in Monterey County) and southern regions (the Cleveland National Forest in San Diego County) were projected to exceed drought conditions in >50% of the years between now and end-of-century (figure 3). Under the hotter drier projection (MIROC-ESM), about one-third of the study area exceeded drought conditions in >50% of the years, including the San Bernardino and San Gabriel mountains (figure 3). Under the warmer wetter projection (CNRM-CM5), 2015 drought conditions were experienced rarely across most of the study area, but with slightly higher probabilities in the southern region.
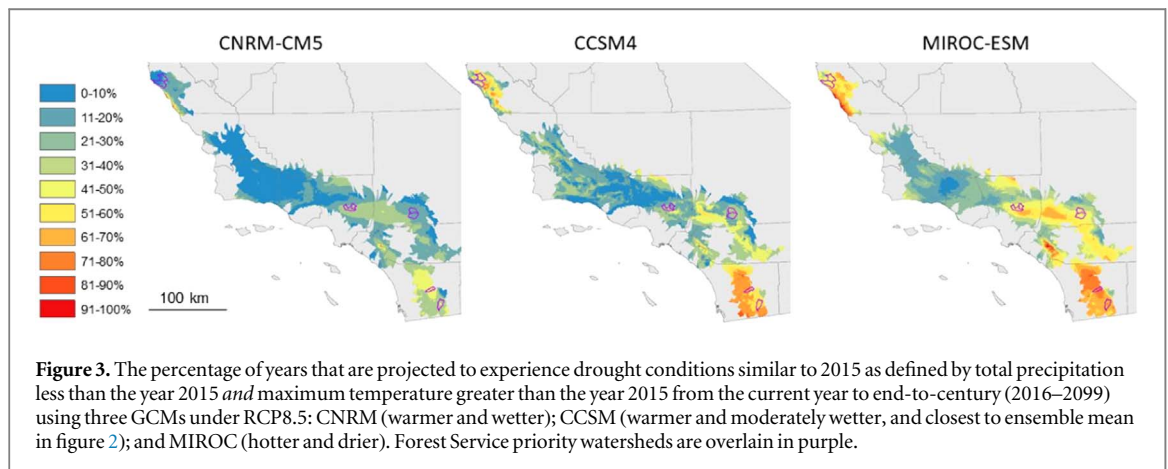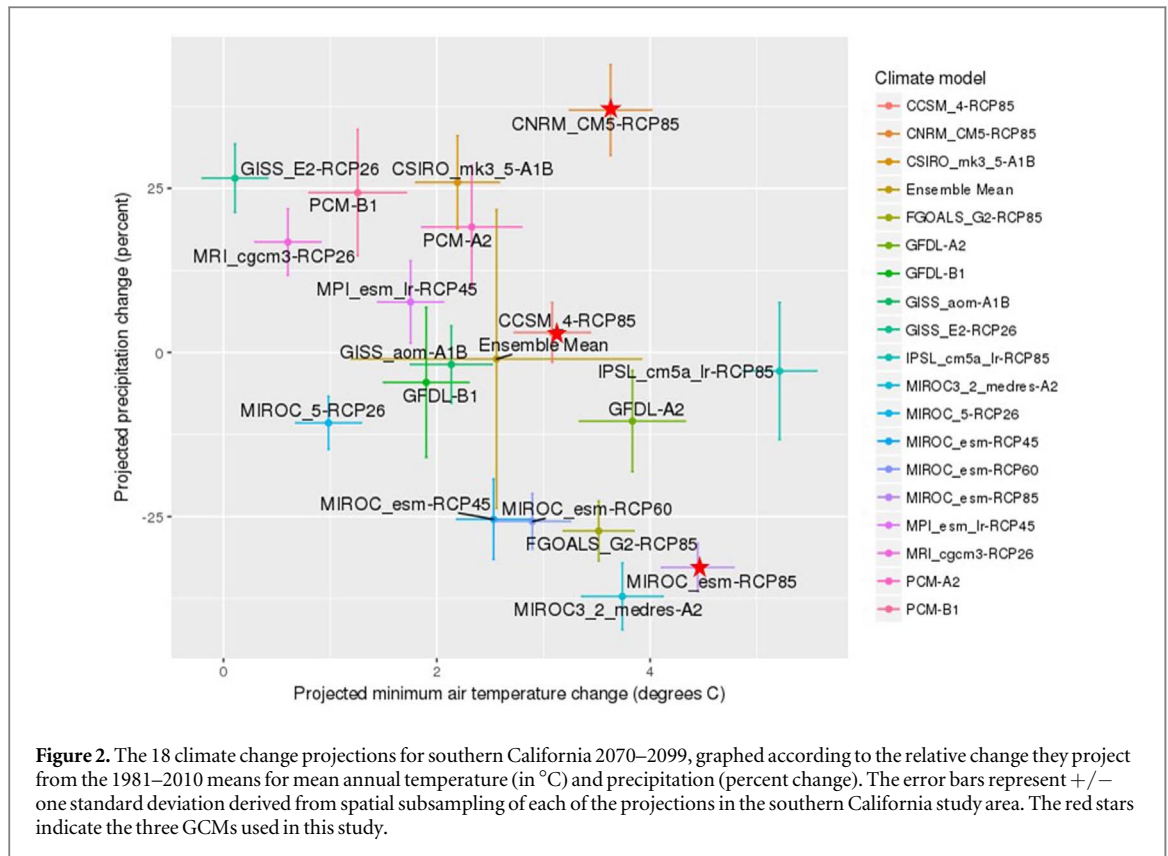
Figure 2. The 18 climate change projections for southern California 2070–2099, graphed according to the relative change they project from the 1981–2010 means for mean annual temperature (in °C) and precipitation (percent change). The error bars represent +/− one standard deviation derived from spatial subsampling of each of the projections in the southern California study area. The red stars indicate the three GCMs used in this study.

Figure 3. The percentage of years that are projected to experience drought conditions similar to 2015 as defined by total precipitation less than the year 2015 *and* maximum temperature greater than the year 2015 from the current year to end-to-century (2016–2099) using three GCMs under RCP8.5: CNRM (warmer and wetter); CCSM (warmer and moderately wetter, and closest to ensemble mean in figure 2); and MIROC (hotter and drier). Forest Service priority watersheds are overlain in purple.

Table 1. Direction and strength of exposure, sensitivity, and vulnerability of hydrological services in southern California. (1) Exposure: change in minimum temperature and precipitation relative to the change projected across 18 GCMs by end-of-century (2070–2099) (see figure 2); values were ranked and divided into three classes; low increase/decrease (−/+); moderate increase/decrease (−−/++); and high increase/decrease (−−−/+++). (2) Sensitivity: change in runoff, recharge, and CWD between current and end-of-century (see figures 4–6): 50%–100% change is low (−/+); 100%–200% is moderate (−−/++); and >200% is high (−−−/+++). (3) Vulnerability: assigned based on where the majority of the 385 watersheds fell across the high, medium and low vulnerability classes (see figures 7, 8) based on the change between current (1981–2010) and end-of-century (2070–2099) runoff, recharge, and CWD relative to the current range of variation experienced; low change (−/+); moderate change (−−/++); and high change (−−−/+++).

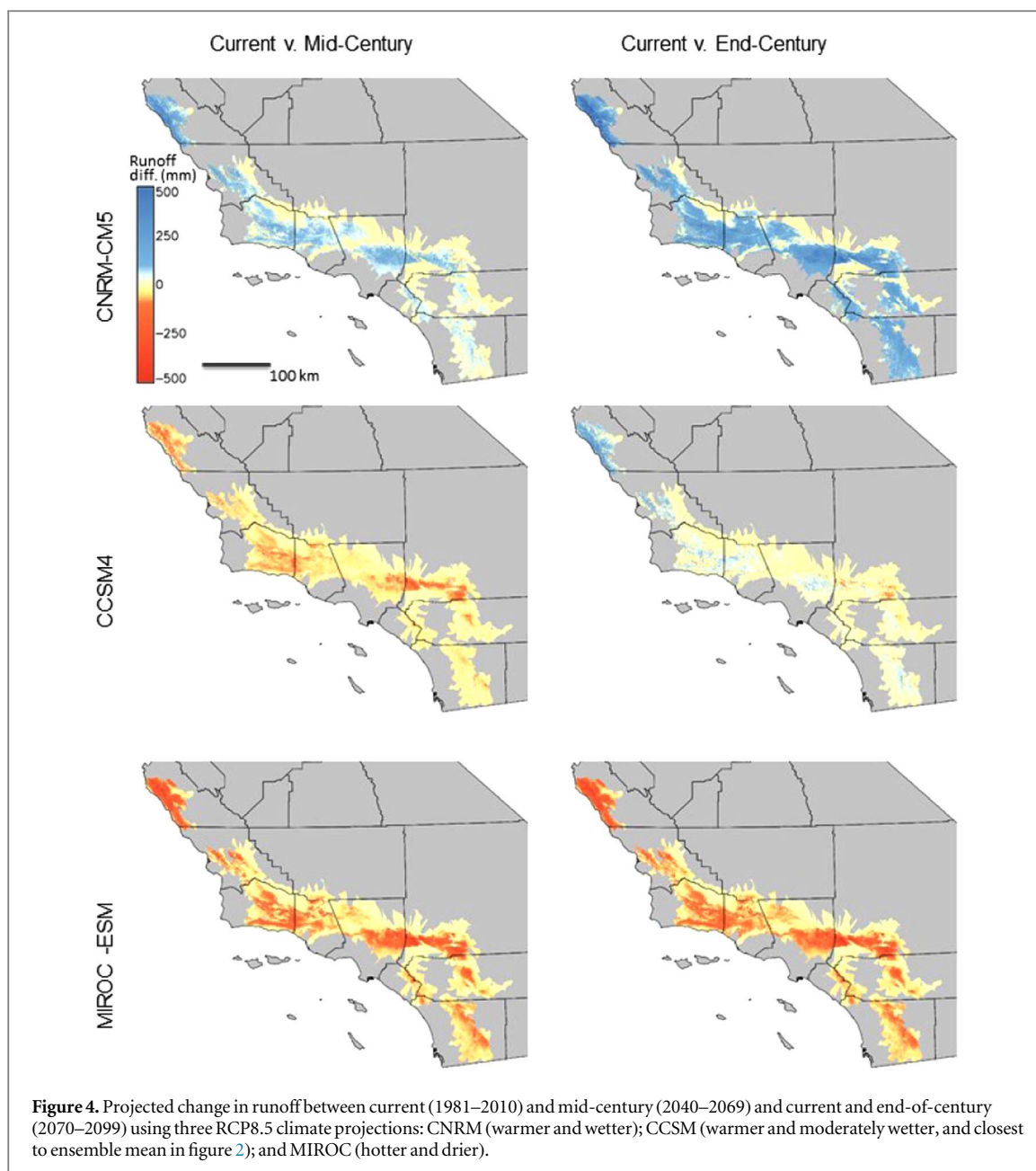|	CNRM-CM5 warmer, wetter	CCSM4 moderate	MIROC-ESM hotter, drier
Exposure—ppt	+++	+	−−−
Exposure—temp	+++	++	+++
Sensitivity—runoff	+	+	−−−
Sensitivity—rechg	+	−−	−−−
Sensitivity—CWD	+	+	+
Vulnerability—runoff	+++	+	−−
Vulnerability—rechg	++	+	−−
Vulnerability—CWD	++	++	+++

Figure 4. Projected change in runoff between current (1981–2010) and mid-century (2040–2069) and current and end-of-century (2070–2099) using three RCP8.5 climate projections: CNRM (warmer and wetter); CCSM (warmer and moderately wetter, and closest to ensemble mean in figure 2); and MIROC (hotter and drier).

Evaluating sensitivity of water provision services and CWD under three climate projections

Projections for water runoff from the BCM forced with the moderate GCM (CCSM4) suggested the majority of the study area may experience decreased runoff by mid-century (figure 4). By the end-of-century this modulates to a moderate increase in runoff across much of the study area, with three of the four national forests (excepting the San Bernardino) increasing by 1.1–1.2× (tables 1, 2). Under the warmer, wetter GCM (CNRM-CM5), runoff is projected to increase by both mid- and end-of-century. Under this projection, the amount of runoff at least doubles in all of the national forests, with the Cleveland increasing 2.6× by end-of-century (table 2). At the other extreme, the hotter drier GCM (MIROC-ESM) projects dramatic losses in runoff (figure 4, table 2), especially in higher elevation areas such as the San Bernardino and San Gabriel mountains. By end-of-century mean runoff across the four national forests under this GCM decreased to 0.4× the current mean.

In contrast to the increase in runoff at end-of-century, projected recharge under the moderate GCM decreased across all four national forests at both mid- and end-of-century, with the greatest reduction on the San Bernardino National Forest (0.8×) (tables 1, 2; figures 1, 5). Under the warmer wetter projection (CNRM-CM5), recharge increased by end-of-century in about three-fifths of the study area, increasing the most in the Cleveland (1.2×) and least in the San Bernardino National Forest (1.06×). As with runoff, the hotter drier GCM (MIROC-ESM) projected major decreases in recharge on almost all of the study landscape (figure 5, table 2), with a mean decrease of 0.5× the current mean across the four national forests.

Table 2. Current (1981–2010) and change in runoff, recharge, and climatic water deficit by end-of-century (2070–2099) under three climate projections: warmer, wetter (CNRM-CM5), moderate (CCSM4), and hotter, drier (MIROC-ESM) (outputs from the Basin Characterization Model). Runoff and recharge are reported as mean by area (million m^3) and climatic water deficit is reported as volumetric total (mm yr^{-1}). Detrended Standard Deviation (DSD, in mm) is the standard deviation over the 30-yr time series of the input climate data, after correcting for the trend in the data. ANF = Angeles National Forest, CNF = Cleveland National Forest, LPNF = Los Padres National Forest, and SBNF = San Bernardino National Forest.

	Current (mean by area)	Current DSD	CNRM-CM5 (*warmer wetter*) chg in mean by area	CNRM-CM5 (*warmer wetter*) DSD	CCSM4 (*moderate*) chg in mean by area	CCSM4 (*moderate*) DSD	MIROC-ESM (*hotter, drier*) chg in mean by area	MIROC-ESM (*hotter, drier*) DSD
					Runoff			
ANF	459.9	196.8	573.1	363.9	51.9	204.4	−286.5	76.7
CNF	169.4	142.8	268.1	261.5	34.3	179.7	−114.7	57.8
LPNF	1365.5	194.5	1451.6	337.1	302.7	217.8	−724.8	82.0
SBNF	530.6	198.4	536.2	358.2	−0.6	214.8	−328.8	90.7
	Current (mean by area)	Current DSD	CNRM-CM5 chg in mean by area	CNRM-CM5 DSD	CCSM4 chg in mean by area	CCSM4 DSD	MIROC-ESM chg in mean by area	MIROC-ESM DSD
					Recharge			
ANF	269.7	77.3	37.0	66.6	−14.1	61.7	−137.0	44.2
CNF	80.9	41.3	15.9	35.3	−3.4	37.3	−44.5	25.4
LPNF	1306.9	126.9	210.6	113.2	−46.9	101.5	−619.1	71.0
SBNF	295.3	69.9	18.3	70.5	−53.2	62.0	−175.3	40.2
	Current (vol. total)	Current DSD	CNRM-CM5 chg in vol. total	CNRM-CM5 DSD	CCSM4 chg in vol. total	CCSM4 DSD	MIROC-ESM chg in vol. total	MIROC-ESM DSD
					Climatic Water Deficit			
ANF	964.7	127.6	72.4	95.8	87.3	82.4	176.0	85.0
CNF	991.2	113.0	83.0	95.8	93.1	91.9	209.7	90.6
LPNF	930.4	111.2	84.5	90.5	100.1	75.3	178.5	82.8
SBNF	846.6	118.0	105.8	98.4	116.5	94.0	226.1	88.8

Under the moderate (CCSM4) and warmer, wetter (CNRM-CM5) GCMs, CWD increased at mid-century, and by end-of-century the mean increased by 1.11×, 1.09×, and 1.21× respectively under CCSM4, CNRM-CM5, and MIROC-ESM projections (table 2, figure 6). Under the hotter, drier (MIROC-ESM) projection, the entire study area experienced increased CWD (figure 6, tables 1, 2).
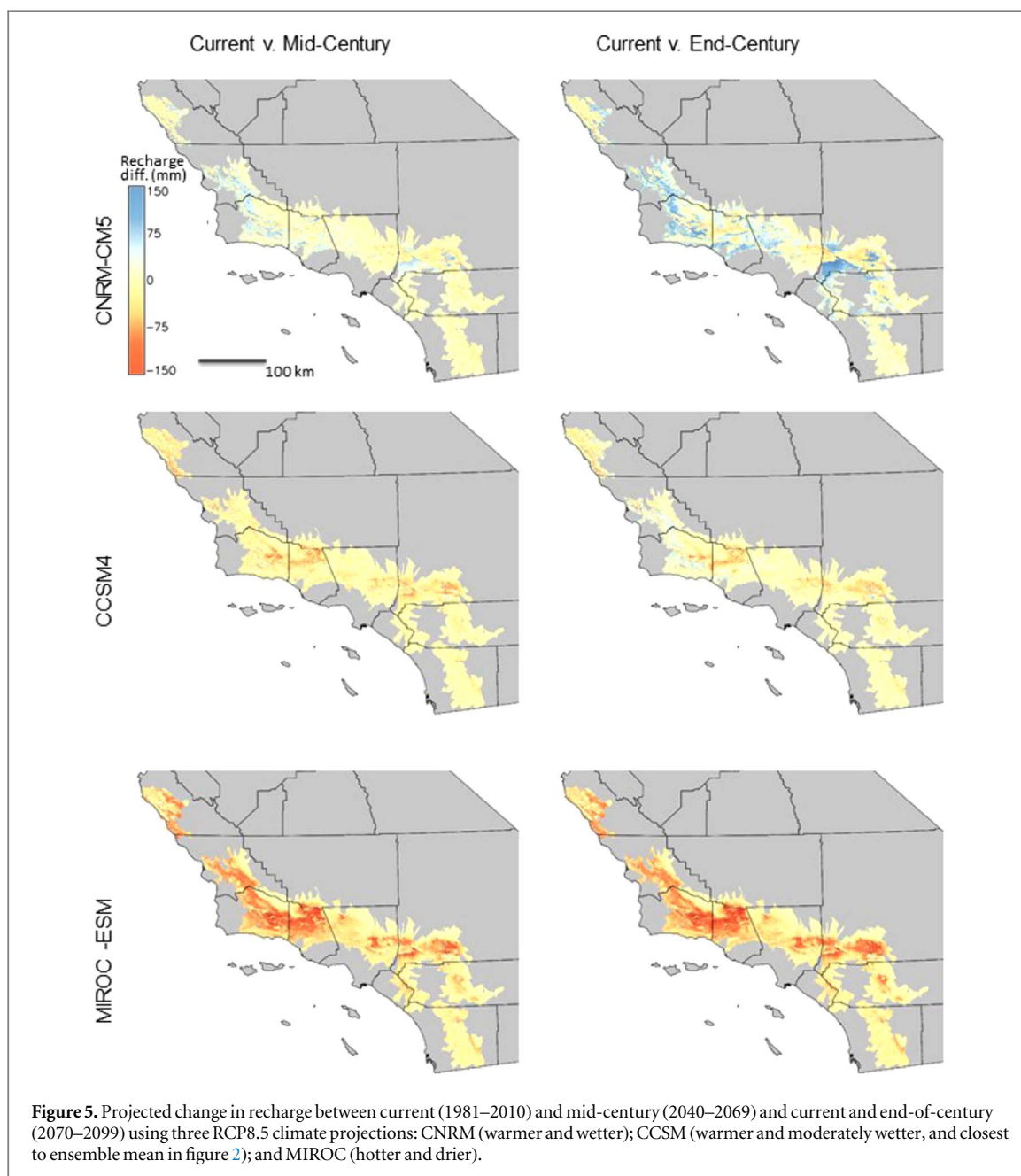
Evaluating vulnerability of water provision services and CWD

The vulnerability assessment for runoff under the moderate GCM (CCSM4) showed about two-thirds (257) of the 385 watersheds had low vulnerability and one-third (115) of watersheds had moderate vulnerability (predominantly increases in runoff), most of them in the northern Los Padres National Forest. 13 watersheds had high vulnerability with our index of change exceeding +/−1× the SD of the current variability (figures 7, 8, table 1), suggesting they will experience new hydrological conditions by the end-of-century. Under the warmer wetter GCM (CNRM-CM5) no watersheds were categorized as low vulnerability and two-thirds had high vulnerability, with a further 70 exceeding +/−2× the SD of current variability (all changes were increases in runoff).

Furthermore, the Detrended Standard Deviation (DSD) (an indication of future variability) associated with the runoff under this scenario, was high. Under the MIROC-ESM projection virtually all watersheds (96%) had moderate vulnerability and, in contrast to CCSM4 and CNRM-CM5, these were due to decreases in runoff (figures 7, 8).

For recharge under the moderate GCM (CCSM4), similar to runoff, about two-thirds of the 385 watersheds had low vulnerability and one-third (115) moderate vulnerability (generally decreases) occurring largely in the San Bernardino National Forest (figures 7, 8). In contrast to runoff, under the warmer wetter projection (CNRM-CM5) more watersheds had low versus moderate vulnerability, and 68 had high vulnerability (predominantly increases). Under the hotter drier GCM (MIROC-ESM) 337 watersheds had moderate vulnerability to decreased recharge, and the remainder had high vulnerability (figure 8).

For CWD, under the moderate projection (CCSM4) 333 of 385 watersheds had moderate vulnerability (related to increases), which increased to 95% of watersheds under the warmer, wetter projection (CNRM-CM5) (figures 7, 8). In contrast, under the hotter drier GCM (MIROC-ESM) 96% of watersheds had high vulnerability to increased CWD, with 15

Figure 5. Projected change in recharge between current (1981–2010) and mid-century (2040–2069) and current and end-of-century (2070–2099) using three RCP8.5 climate projections: CNRM (warmer and wetter); CCSM (warmer and moderately wetter, and closest to ensemble mean in figure 2); and MIROC (hotter and drier).

watersheds exceeding 2× the SD from the current variability.

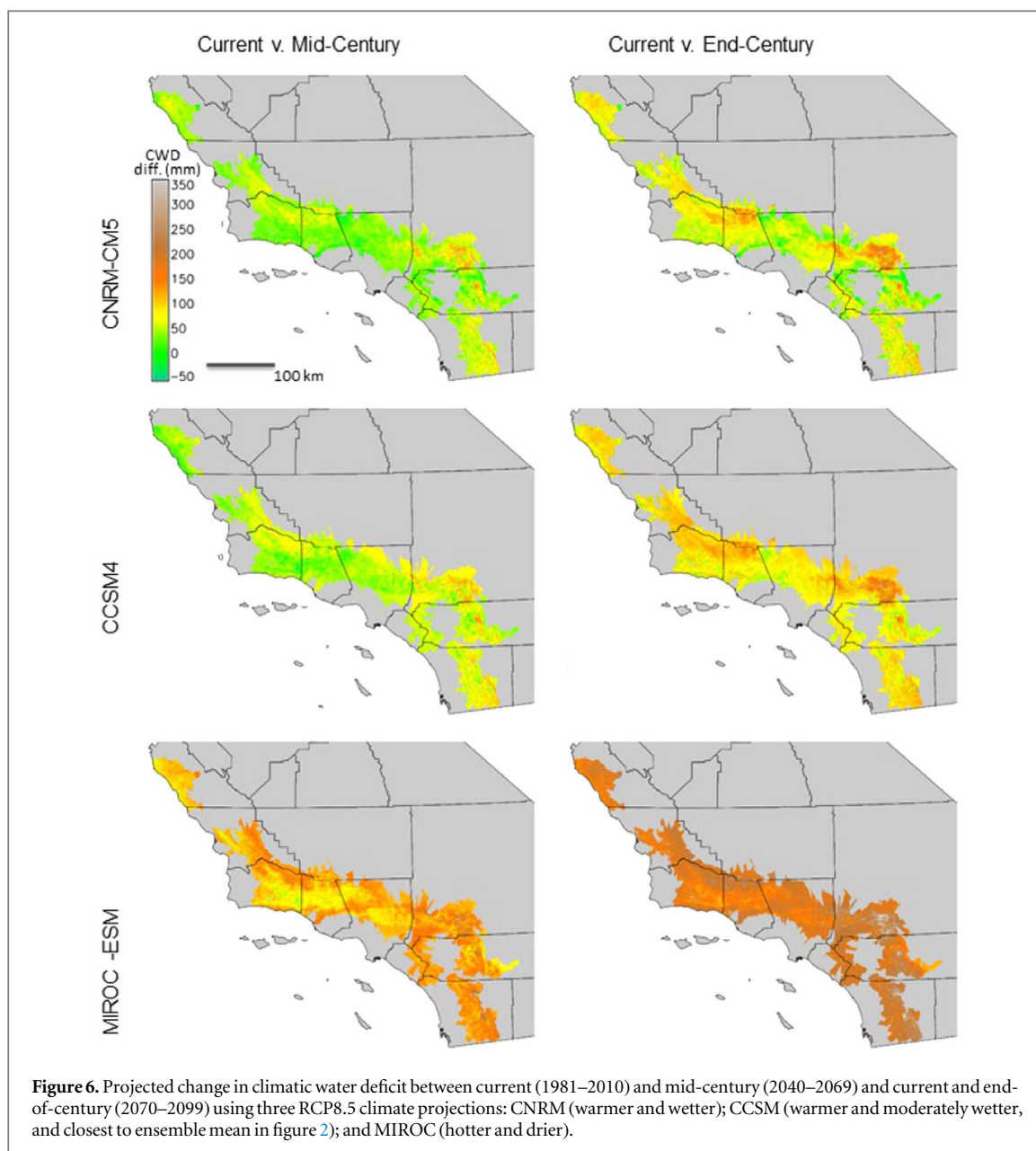**Evaluating vulnerability of Forest Service priority watersheds**

We overlaid the two Forest Service Watershed Condition Framework (WCF) priority watersheds for each national forest on the vulnerability maps (figure 7). For runoff in CCSM4 (moderate projection), half of the eight priority watersheds were projected to be low vulnerability at end-of-century, but the other four, including both priorities in the Los Padres National Forest, met our standard for moderate vulnerability. For recharge, six of the eight priority watersheds had moderate vulnerability. Under the warmer, wetter projection (CNRM-CM5) all eight priority watersheds were highly vulnerable to increased runoff. In contrast,

all but one watershed showed low vulnerability for recharge. Finally, under the hotter, drier (MIROC-ESM) projection, all eight priority watersheds were highly vulnerable for decreased runoff and recharge.

Discussion

In this study we evaluated the climate change exposure, sensitivity, and vulnerability of watersheds intersecting southern California's four national forests in southern California.

In terms of *exposure*, all three GCMs project warmer temperatures in the study region (strongest in MIROC-ESM), however, precipitation varied dramatically from +36.9% to −32.7% across the three projections (table 1). Our analysis also indicated drought conditions, such as those experienced in 2015, are

Figure 6. Projected change in climatic water deficit between current (1981–2010) and mid-century (2040–2069) and current and end-of-century (2070–2099) using three RCP8.5 climate projections: CNRM (warmer and wetter); CCSM (warmer and moderately wetter, and closest to ensemble mean in figure 2); and MIROC (hotter and drier).
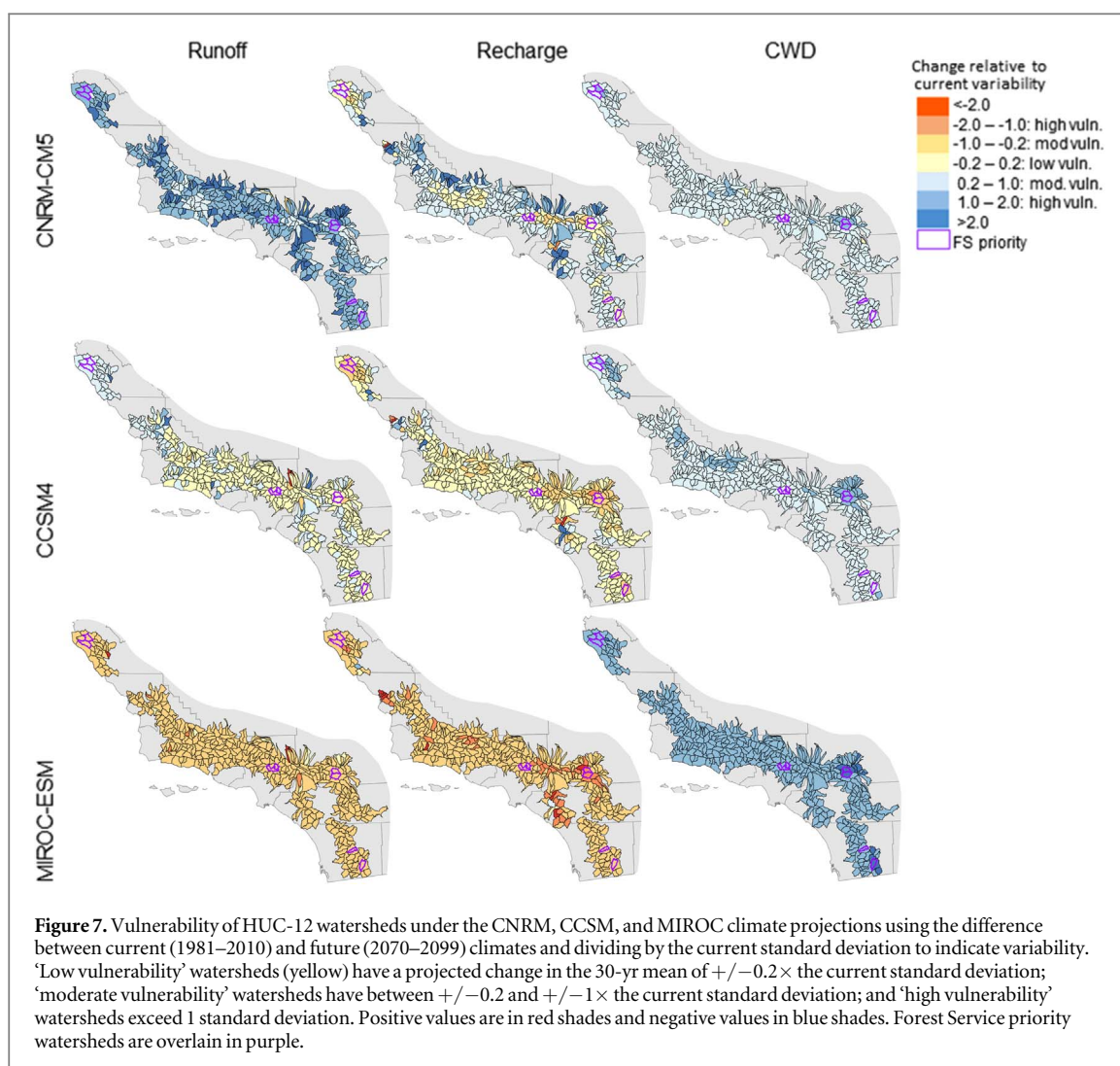
likely to become increasingly frequent in southern California—even if annual precipitation increases over time as projected by CNRM-CM5—especially in the southern and northern study area (figure 3). This is of particular concern in a region where local precipitation contributes substantially to groundwater recharge and water resources.

To assess *sensitivity*, we calculated changes in runoff, recharge, and CWD. As might be expected, runoff and recharge increased in the warmer, wetter projection (CNRM-CM5) due to more available water. In addition, as the North Pacific storm track becomes increasingly active at lower latitudes there are more opportunities for intense precipitation events (Dan Cayan, pers. comm), which also results in runoff as the soil storage is readily overcome. These increases in larger than historical precipitation events also occur under the moderate projection (CCSM4) resulting in increases in water runoff in three of the four national

forests by 1.2× the current mean by end-of-century. However, warming increases evapotranspiration, reducing the total water available annually, as well as reducing snowpack and melt, which resulted in decreased recharge in all four national forests (0.9×) (tables 1, 2). Higher elevation areas were more sensitive to projected changes in runoff and recharge (e.g. the San Bernardino, San Jacinto, and San Gabriel mountains) as future precipitation will fall as rain rather than snow under warmer climates (negating beneficial delays in water delivery associated with snowmelt in the spring) and soils at higher elevations tend to be thinner, thereby reducing their capacity to store water through the long, dry summer.

Our third measure, focused on *vulnerability*, highlights the challenges associated with managing the Forest Service priority watersheds for the future as most will experience hydrological conditions well outside the range of the current variation. This analysis

Figure 7. Vulnerability of HUC-12 watersheds under the CNRM, CCSM, and MIROC climate projections using the difference between current (1981–2010) and future (2070–2099) climates and dividing by the current standard deviation to indicate variability. 'Low vulnerability' watersheds (yellow) have a projected change in the 30-yr mean of $+/-0.2\times$ the current standard deviation; 'moderate vulnerability' watersheds have between $+/-0.2$ and $+/-1\times$ the current standard deviation; and 'high vulnerability' watersheds exceed 1 standard deviation. Positive values are in red shades and negative values in blue shades. Forest Service priority watersheds are overlain in purple.
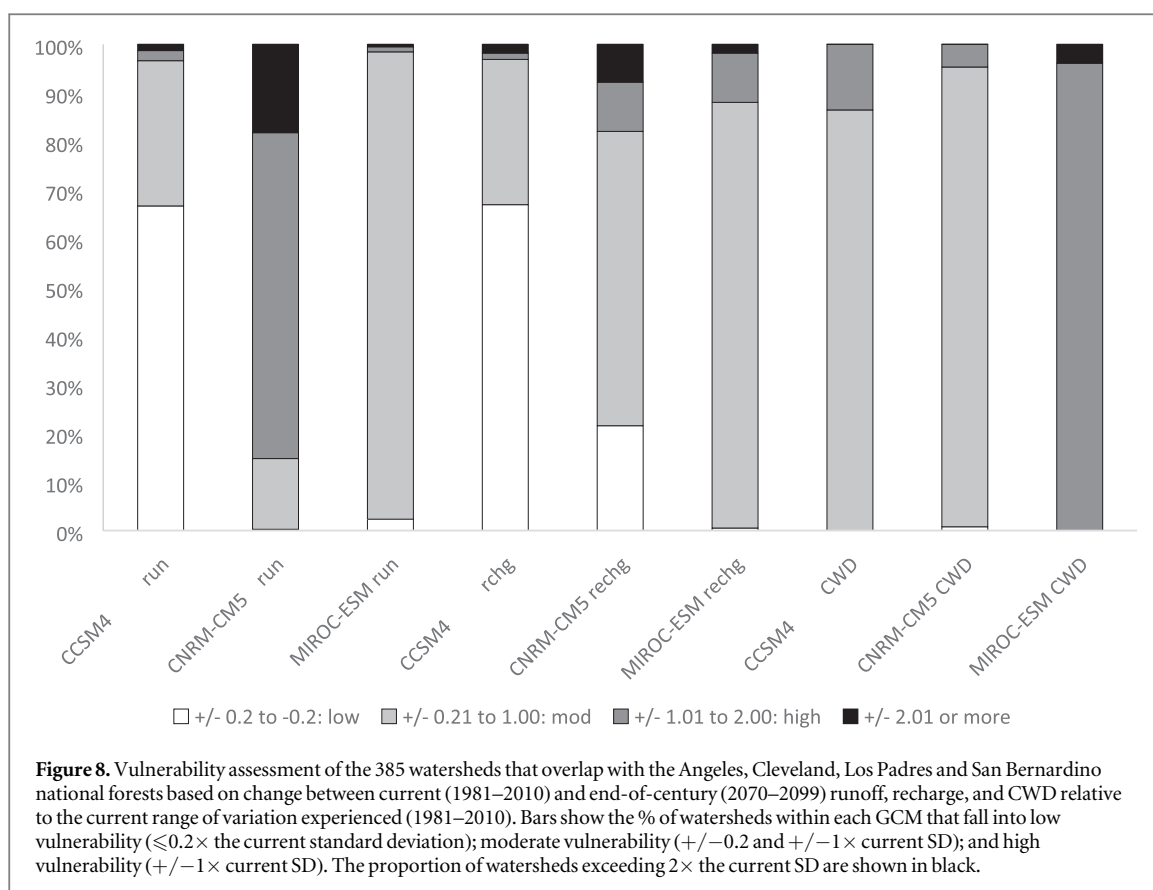
could be expanded to include an assessment of future variability to provide further insights. Increased runoff risks include more flooding, erosion, and downstream sediment transport (Dettinger *et al* 2011), while increased water in streams would affect stream morphology (although it would also lower stream temperatures, and provide better habitat for aquatic species, at least during the rainy season).

This is further complicated by projections for three additional extreme precipitation events per year in California by the end of the century (Gao *et al* 2017) that will make episodic runoff more extreme as the volume of water exceeds the capacity of the soil to store it. Alternately, projected decreases in recharge in priority watersheds would result in lower baseflows, reducing river and creek flow during the dry season, and delivering less water to the aquifer and consequently reducing available groundwater, e.g. for agricultural or household use. To add to climate concerns, under the moderate and hotter-drier GCMs all eight priority watersheds are projected to endure droughts as severe as the 2015 event over the next century. In particular, for priority watersheds on the Cleveland and Los Padres national forests, drought was projected

in one-half and one-third of all years, respectively, between now and end-of-century. Even the warmer, wetter GCM projects more severe drought years for most of the priority watersheds.

Information on the relative vulnerability of priority watersheds to assess potential future influences of climate and hydrological change is important to incorporate as it may determine the attainment and sustainability of desired conditions and allocation of management resources.

The designation of priority watersheds was determined based on a variety of factors, including the presence of federally listed species or existing partnerships with other organizations (Potyondym and Geier 2011), even so, some watersheds have a higher capacity to adapt to climate-driven changes owing to landscape features that support natural patterns of hydrology, such as high habitat connectivity, higher natural vegetation integrity, topographic complexity, and long elevational gradients (Brauman *et al* 2007). Areas with lower CWD will have relatively more moisture for plant growth, theoretically decreasing overall vegetation flammability and shortening the fire season, but potentially growing more fuel between fires. Healthy

Figure 8. Vulnerability assessment of the 385 watersheds that overlap with the Angeles, Cleveland, Los Padres and San Bernardino national forests based on change between current (1981–2010) and end-of-century (2070–2099) runoff, recharge, and CWD relative to the current range of variation experienced (1981–2010). Bars show the % of watersheds within each GCM that fall into low vulnerability ($\leqslant 0.2\times$ the current standard deviation); moderate vulnerability ($+/-0.2$ and $+/-1\times$ current SD); and high vulnerability ($+/-1\times$ current SD). The proportion of watersheds exceeding $2\times$ the current SD are shown in black.

cover of vegetation is important in watersheds projected to experience increased runoff as: erosion rates are much lower where the soil is covered and live roots help tie it to the bedrock (Jenerette *et al* 2018, Wohlgemuth and Lilley 2018); and native shrubland and forest cover intercept more moisture and help promote precipitation infiltration (DeBano 1981). However, ensuring native shrub cover is becoming increasingly challenging as high fire frequencies in southern California are causing the conversion of native shrubland to annual non-native grasses (Keeley and Safford 2016; Safford *et al* 2018).

Our modeling-based study considered a wide spectrum of potential futures, and the implications of projected climatic and hydrological change on the region's watersheds clearly depend largely on the sign and magnitude of future precipitation change. This complicates management response, however, certain trends and patterns hold true across the three projections we employed and we suggest that managers can already use these to begin to plan for the future. In terms of drought, more frequent occurrence of severe droughts is a universal projection of the GCMs we used. This echoes other work by Diffenbaugh *et al* (2015) who find California's droughts are more likely if precipitation deficits co-occur with warm conditions (Diffenbaugh *et al* 2015), a confluence that has increased in recent decades most likely owing to anthropogenic warming. Likewise, AghaKouchak *et al* (2014) explain California's 2014 drought as the

interaction of low precipitation and extreme high temperatures, while Yoon *et al* (2015) project intense drought and excessive flooding will both increase by 50% by the end of the century, associated with a strengthened relation to El Niño and Southern Oscillation (ENSO). Also, projections of higher variability in precipitation, higher rain:snow ratios at higher elevations, and increased probability of episodic, intense rainstorms contributes to other work such as that by Berg and Hall (2015) who find extremely dry wet seasons are 1.5–2× more common from mid- to end-of-century, with a tripling of wet season extremes compared to that experienced historically. Other important variables, such as fire activity and human demographics, were not modeled in our study, but managers can use recent trends to extrapolate their ecosystem effects into the near future.

Conclusion

In this contribution, we identified precipitation and temperature sources of ecosystem exposure in watersheds at least partly managed by the US Forest Service; we measured the sensitivity of three ecohydrological variables—runoff, recharge, and CWD—to these changes; and we quantified watershed vulnerability in priority watersheds by comparing the projected end-of-century change in these variables to the current range of variation.

Southern California's public lands are highly threatened and extensively degraded, but they provide critical ecosystem services to millions of people (Underwood *et al* 2018). As such, understanding spatial variation in water provision and CWD and how it will vary in the face of climate change is critical. Our analyses suggest an era of new hydrological conditions for many, if not most southern California watersheds by the end of the century, representing a huge challenge to water resource management in the region (Dettinger *et al* 2011). This conclusion reflects those from other studies, for example, AghaKouchak *et al* (2014) who find winter water shortages are of critical concern for decision makers as this is the season to build up water supplies for the rest of the year.

Spatial data on hydrological services and their vulnerability can assist in climate-smart planning on public lands, but the uncertainty of future climate projections is likely to leave many watershed managers stopped in their tracks. At the same time, the rapidity of current global warming means that in most places inaction is not a viable option. We recommend that, wherever possible, managers work with partners to adopt a more experimental, 'learn-as-you-go' framework in their management efforts. For example, up-front scenario planning can be employed on those landscapes that have high ecological or socio-economic importance, such as the Forest Service priority watersheds. In areas of lower political sensitivity or conservation value, different (credible) hypotheses of future change can be used to develop differing management approaches that may be carried out on different parts of the landscape and compared as climatic and other conditions change (Safford *et al* 2012, 2018). In short, management action to address the impacts of climate change on water resources, and their knock-on effect on water supply for surrounding populations, should not be postponed until there is sufficient information or until the problem arrives (Lee 1999). Implementing activities in short-time steps is one way to overcome the challenges associated with the variability and uncertainty of the climate projections (see table 1). These management activities can be explored systematically, with a focus on experimentation and organized learning while doing. By trying things, making mistakes, and experiencing unexpected outcomes this will ultimately lead to more effective management and achievement of water resources goals as the future unfolds.

Acknowledgments

ORCID iDs

Emma C Underwood ⓘ https://orcid.org/0000-0003-1879-9247

References

Ackerly D D, Cornwell W K, Weiss S B, Flint L E and Flint A L 2015 A geographic mosaic of climate change impacts on terrestrial vegetation: which areas are most at risk? *PLoS One* **10** e0130629

AghaKouchak A, Cheng L, Mazdiyasni O and Farahmand A 2014 Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought *Geophys. Res. Lett.* **41** 8847–52

Anderegg W R, Flint A L, Huang C Y, Flint L E, Berry J A, Davis F and Field C B 2015 Tree mortality predicted from drought-induced vascular damage *Nat. Geosci.* **8** 367–71

Berg N and Hall A 2015 Increased interannual precipitation extremes over California under climate change *J. Clim.* **28** 6324–34

Brauman K A, Daily G C, Duarte T C and Mooney H A 2007 The nature and value of ecosystem services: an overview highlighting hydrologic services *Annu. Rev. Environ. Resour.* **32** 67–98

Bristow K L and Campbell G S 1984 On the relationship between incoming solar radiation and daily maximum and minimum temperature *Agric. Forest Meteorol.* **31** 159–66

CalWater 1999 California interagency watershed map of 1999 (CalWater version 2.2.1) (prepared by the Natural Resources Conservation Service California Interagency Watershed Mapping Committee)

Cayan D R, Mauer E P, Dettinger M D, Tyree M and Hayhoe K 2008 Climate change scenarios for the California region *Clim. Change* **87** S21–42

DeBano L F 1981 Water repellent soils: a state-of-the-art *General Technical Report* PSW-GTR-46 USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA

Dettinger M D, Ralph F M, Das T, Neiman P J and Cayan D R 2011 Atmospheric rivers, floods and the water resources of California *Water* **3** 445–78

Diffenbaugh N S, Swain D L and Touma D 2015 Anthropogenic warming has increased drought risk in California *Proc. Natl Acad. Sci. USA* **112** 3931–6

Drexler J Z, Knifong D, Tuil J, Flint L E and Flint A L 2013 Fens as whole-ecosystem gauges of groundwater recharge under climate change *J. Hydrol.* **481** 22–34

Flint L E and Flint A L 2012 Simulation of climate change in San Francisco Bay Basins, California: case studies in the Russian River Valley and Santa Cruz Mountains *U.S. Geological Survey Scientific Investigations Report* 2012–5132 p 55

Flint L E and Flint A L 2014 California Basin Characterization model: a dataset of historical and future hydrologic response to climate change. U.S. Geological Survey Data Release

Flint L E, Flint A L, Thorne J H and Boynton R 2013 Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance *Ecol. Process.* **2** 25

Flint L E, Flint A L, Thorne J H, Weiss S B, Boynton R and Curtis J A 2015 Basin Characterization Model of the Great Basin: a dataset of historical and future hydrologic response to climate change (https://ca.water.usgs.gov/projects/reg_hydro/projects/dataset.html)

Gao X, Schlosser C A, O'Gorman P A, Monier E and Entekhabi D 2017 Twenty-first-century changes in US regional heavy precipitation frequency based on resolved atmospheric patterns *J. Clim.* **30** 2501–21

Hanson R T, Flint L E, Flint A L, Dettinger M D, Faunt C C, Cayan D and Schmid W 2012 A method for physically based model analysis of conjunctive use in response to potential climate changes *Water Resour. Res.* **48** W00L08

Hayhoe K *et al* 2004 Emissions pathways, climate change, and impacts on California *Proc. Natl Acad. Sci.* **101** 12422–7

IPCC 2014 *Climate Change: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects* (*Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*) ed C B Field (Cambridge: Cambridge University Press)

Jenerette G D, Park I W, Andrews H M and Eberwein J R 2018 Biogeochemical cycling of carbon and nitrogen in chaparral dominated ecosystems *Valuing Chaparral: Ecological, Socio-economic, and Management Perspectives* ed E C Underwood *et al* (Berlin: Springer) pp 141–79

Keeley J E and Safford H D 2016 Fire as an ecosystem process *Ecosystems of California* ed H A Mooney *et al* (Berkeley, CA: University of California Press)

Lee K N 1999 Appraising adaptive management *Conserv. Ecol.* **3** 3

Lifeng L, Apps D, Arcand S, Xu H, Pan M and Hoerling M 2017 Contribution of temperature and precipitation anomalies to the California drought during 2012–2015 *Geophys. Res. Lett.* **44** 3184–92

McCullough I M, Davis F W, Dingman J R, Flint L E, Flint A L, Serra-Diaz J M, Syphard A D, Moritz M A, Hannah L and Franklin J 2016 High and dry: high elevations disproportionately exposed to regional climate change in Mediterranean-climate landscapes *Landscape Ecol.* **31** 1063–75

Mearns L O *et al* 2013 Climate change projections of the North American Regional Climate Change Assessment Program (NARCCAP) *Clim. Change* **120** 965–75

Meehl G A *et al* 2007 Global climate projections *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon *et al* (Cambridge: Cambridge University Press) pp 747–845

Molinari N A, Underwood E C, Kim J B and Safford H D 2018 Climate change trends for chaparral *Valuing Chaparral: Ecological, Socio-Economic, and Management Perspectives* ed E C Underwood *et al* (Berlin: Springer)

Mooney H A 1977 The carbon cycle in Mediterranean-climate evergreen scrub communities *Presented at the Symp. on Environ. and Fuel Manage. Consequences of Fire in Mediterranean Ecosyst. (Palo Alto, CA)*

Potyondy J P and Geier T W 2011 Watershed condition classification technical guide *USDA Forest Service Report* FS-978

Priestley C H B and Taylor R J 1972 On the assessment of surface heat flux and evaporation using large-scale parameters *Mon. Weather Rev.* **100** 81–92

Safford H D, Underwood E C and Molinari N A 2018 Managing chaparral resources on public lands *Valuing Chaparral: Ecological, Socio-Economic, and Management Perspectives* ed E C Underwood *et al* (Berlin: Springer)

Safford H D, Wiens J A and Hayward G 2012 The growing importance of the past in managing ecosystems of the future *Historical Environmental Variation in Conservation and Natural Resource Management* ed J A Wiens *et al* (New York: Wiley)

Smith B, Burton I, Klein R J T and Wandel J 2000 An anatomy of adaptation to climate change and variability *Clim. Change* **45** 223–51

Stephenson N 1990 Climatic control of vegetation distribution: the role of the water balance *Am. Nat.* **135** 649–70

Swain D L 2015 A tale of two California droughts: lessons amidst record warmth and dryness in a region of complex physical and human geography *Geophys. Res. Lett.* **42** 9999–10003

Thorne J H, Flint L E, Flint A L and Boynton R 2015 The magnitude and spatial patterns of historical and future hydrologic change in California's watersheds *Ecosphere* **6** 1–30

Thornwaite C W and Mather J R 1955 The water balance *Publ. Climatol.* **8** 1–86

Underwood E C, Safford H D, Molinari N A and Keeley J E 2018 *Valuing Chaparral: Ecological, Socio-Economic, and Management Perspectives* (Berlin: Springer) p 467

van Mantgem P J, Nesmith J C B, Keifer M B, Knapp E E, Flint A L and Flint L E 2013 Climatic stress increases forest fire severity across the western United States *Ecol. Lett.* **16** 1151–6

Weidner E and Todd A 2011 From the Forest to the Faucet Drinking Water and Forests in the US. Methods paper (USDA Forest Service)

Williams S E, Shoo L P, Isaac J L, Hoffmann A A and Langham G 2008 Towards an integrated framework for assessing the vulnerability of species to climate change *PLoS Biol.* **6** e325

Wohlgemuth P M and Lilley K A 2018 Sediment delivery, flood control, and physical ecosystem services in southern California chaparral landscapes *Valuing Chaparral: Ecological, Socio-Economic, and Management Perspectives* ed E C Underwood *et al* (Berlin: Springer)

Yoon J-H, Simon Wang S-Y, Gillies R R, Kravitz B, Hipps L and Rasch P J 2015 Increasing water cycle extremes in California and in relation to ENSO cycle under global warming *Nat. Commun.* **6** 8657

Yu Z, Jiang P, Gautam M R, Zhang Y and Acharya K 2015 Changes of seasonal storm properties in California and Nevada from an ensemble of climate projections *J. Geophys. Res.* **120** 2676–88