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Characterizing drought in California: new drought indices and scenario-testing in support of resource management

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Abstract

Introduction: California's recent drought (2012–2016) has implications throughout the state for natural resource management and adaptation planning and has generated many discussions about drought characterization and recovery. This study characterizes drought conditions with two indices describing deficits in natural water supply and increases in landscape stress developed on the basis of water balance modeling, at a fine spatial scale to assess the variation in conditions across the entire state, and provides an in-depth evaluation for the Russian River basin in northern California to address local resource management by developing extreme drought scenarios for consideration in planning and adaptation.

Methods: We employed the USGS Basin Characterization Model to characterize drought on the basis of water supply (a measure of recharge plus runoff) and landscape stress (climatic water deficit). These were applied to the state and to the Russian River basin where antecedent soil moisture conditions were evaluated and extreme drought scenarios were developed and run through a water management and reservoir operations model to further explore impacts on water management.

Results: Drought indices indicated that as of the end of water year 2016 when reservoirs were full, additional water supply and landscape replenishment of up to three average years of precipitation in some locations was needed to return to normal conditions. Antecedent soil conditions in the Russian River were determined to contribute to very different water supply results for different years and were necessary to understand to anticipate proper watershed response to climate. Extreme drought scenarios manifested very different kinds of drought and recovery and characterization helps to guide the management response to drought.

Conclusions: These scenarios and indices illustrate how droughts differ with regard to water supply and landscape stress and how long warm droughts recover much more slowly than short very dry droughts due to the depletion of water in the soil and unsaturated zone that require filling before runoff can occur. Recognition of ongoing conditions and likelihood of recovery provides tools and information for a range of resource managers to cope with drought conditions.

Keywords: California drought, Russian River, Water supply, Basin Characterization Model

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Introduction

Recent droughts in the western USA have emphasized the need to understand long-term impacts, the accumulation of drought impacts, and the recovery to normal conditions. Climate change studies project an increase in frequency and extent of future droughts (Polade et al. 2014; Dai 2013). The recent unprecedented drought in California has been longer and warmer than other droughts in the state over the last millennium (Griffin and Anchukaitis 2014). The precipitation lagged by one to two normal years from 2012 through 2016 across the state, and air temperatures repeatedly reached record-breaking levels. In particular, on the basis of monthly climate data (Daly et al. 2008), temperatures in winter–spring (Nov–Apr) 2014 were the warmest to date (over the past 120 years), about 2 °C warmer than the 1951–2000 normal, and temperatures during 2015 beat that new record handily, by another 0.8 °C. The winter 2016 season was also 1.2 °C warmer than normal, with February 2016 by itself matching the warmest on record, 3.3 °C warmer than normal. These conditions also led to major reductions in snowpack, with 1 April 2015 only 5% of normal. Snowpack is an important natural reservoir that many of the state's water supply systems rely upon to carry water from the cool, wet and potentially flood prone, winter seasons into the later parts of the year when temperatures and water demands are high. Over the 5-year drought, 2012–2016, drought conditions impacted surface water supplies, increased agricultural demand, and increased groundwater extraction (resulting in land subsidence). These factors inspired the development of legislation to regulate groundwater resources for the first time in the state (California's Sustainable Groundwater Management Act of 2014). Drought conditions also put excessive stresses on the landscape, particularly forests with little snowpack, and resulted in massive forest die-off (Asner et al. 2016) and severe wildfire seasons (van Mantgem et al. 2013). Rangelands had little forage and drinking water for cattle resulting in ranching being the most impacted agricultural sector (Potter 2015). The range of hydrologic conditions across rangelands and watersheds in California is very large, dictated by very local differences in climate, energy loading, vegetation, soils, and underlying geology. Water supply, forest desiccation, and agricultural demand differ in response to drought across the landscape and in different basins. The resulting impacts then also differ for different sectors, public water supply, fisheries, agriculture, health and safety, ranching, forest management, and wildfire. The utility of a national drought monitor (US Drought Monitor; http://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?CA) provides a broad indication of conditions but does not address the different kinds of drought explicitly nor how they differ across the landscape.

Complications arise with definitions of drought because drought is contextually defined for specific user communities (Harpold et al. 2017). Common definitions for drought include partitioning into four types of drought, meteorological, hydrological, agricultural, and socioeconomic (Rasmussen et al. 1993). The Palmer Drought Severity Index (PDSI) combines precipitation and air temperature and has been used extensively to characterize the first two types of drought. Palmer indices have been used in conjunction with many objective inputs to construct the US Drought Monitor that is adjusted manually by experts to reflect real world conditions. The weekly results reflect a consensus product but are not reproducible. An additional limitation with the Drought Monitor is that it tries to show drought at several temporal scales and not explicitly for any of them. There is also snow drought, which can be further categorized into dry and warm snow drought, each with very different kinds of impacts (Harpold et al. 2017).

With the reams of publications on drought, there have not been indices described that explicitly address natural water supply and landscape drought independently, allowing for improved assessments of resources and drought recovery. To that end, we have developed two new indices that describe deficits in water supply and increases in landscape stress. These indices reflect the combination of climate and energy loading, by including the constraints imposed by soil moisture water holding capacity and actual evapotranspiration, and differing rates of drainage due to variations in bedrock permeability. These two indices characterize drought in hydrologic terms and are represented across the landscape at a fine spatial scale.

Managing resources, infrastructure, and available information by using forecasts selectively to optimize available resources under varying levels of risk requires a picture of how conditions differ across the landscape at a spatial scale describing the local range of conditions. Optimizing also requires separating out the short-term and longer term impacts. We intend to demonstrate that drought can be better characterized by augmenting climate metrics with an index of water supply, which is a combination of runoff and recharge, often an acute impact, and an index of landscape stress, which is more of an extended and cumulative condition. We will illustrate this across the state of California and then focus on a case study funded by the National Oceanographic and Atmospheric Agency (NOAA) to study drought for the National Integrated Drought Information System (NIDIS; https://www.drought.gov/drought/) in the Russian River basin, Sonoma and Mendocino counties located north of San Francisco. More specifically, in the Russian River, we examine drought indices, in addition to a comparison of historical droughts. We include a test of extreme drought scenarios and the implications for local management of water for public use and ecological health and sustainability. It has been suggested that western droughts begin gradually and end abruptly, often in a very wet month, accompanied by several atmospheric river events (Dettinger 2013). We use these two indices as examples of differing kinds of droughts. Whereas immediate water supply may be replenished over a few wet months as reservoirs return to capacity, water supply in a basin also relies on tributaries and the replenishment of the groundwater, which may be delayed far longer following reservoir recovery. Landscapes in extended droughts with warmer than usual conditions may also take much longer to recover.

Study area

The study area is the state of California, including all basins draining into the state, with a focus on the Russian River basin in the San Francisco North Bay counties (Fig. 1). California has a Mediterranean climate with wet winters and dry summers, with several mountain ranges that have annual snowpack. The Russian River watershed drains the Russian River, a southward-flowing, 177-km river that drains 3800 km^2 in Sonoma and Mendocino counties. Precipitation in the Russian River is distinctly seasonal, about 80% of the total occurs during the 5 months November through March. The bulk of the precipitation across this region occurs during moderately intense storms of several days duration. Most of these storms are generated as a result of atmospheric rivers (ARs; Ralph et al. 2013) that develop over the Pacific Ocean. The frequency of ARs has been increasing in recent years, and a more thorough understanding of their implications in the Russian River basin is currently under investigation.

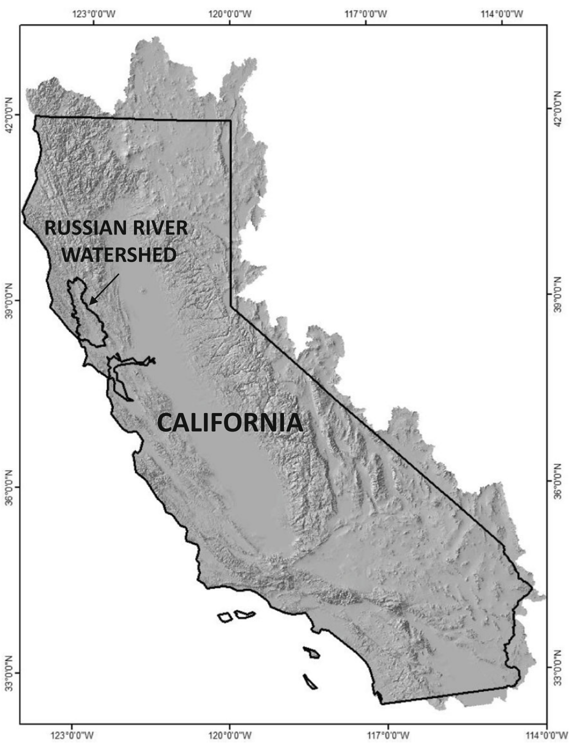

Fig. 1 Study area, indicating the state of California, the boundaries of watersheds draining into the state in gray shaded relief, and the Russian River watershed boundary

Background on Russian River water management

The principal use of water in the basin is for the irrigation of agricultural land, with evapotranspiration from the irrigated areas accounting for most of the water actually consumed (Rantz and Thompson 1967). The Russian River is also used for municipal, domestic, and industrial purposes, notably in the communities of Ukiah, Cloverdale, Healdsburg, Santa Rosa, and Sebastopol and including parts of Marin County. Sonoma County Water Agency (SCWA) is the largest single diverter and provides wholesale water to its contractors on Sonoma and Marin counties, which ultimately serves about 600,000 people. SCWA diverts water under its water rights permits from the Russian River using six collector wells located near Forestville, CA, just upstream of the Mark West Creek and Russian River confluence.

Several major water developments have been constructed that effect the Russian River basin. The Pacific Gas and Electric Co. (PG&E) constructed the Potter Valley Project (PVP) in 1908 that diverts Eel River water into the East Fork Russian River (East Fork) through a diversion tunnel and power plant, northeast of Ukiah. This diversion is now regulated by storage in Lake Mendocino, a flood-control and water conservation reservoir that is described below. From 1959 to 2006, PG&E diverted, on average, 151,000 acre-feet a year through the PVP in accordance to its Federal Energy Regulatory Commission (FERC) license. Following an amendment to FERC license in 2006, the diversion through the PVP to Lake Mendocino dropped to an average of 67,000 acre-feet a year.

There are two reservoirs in the Russian River watershed: Lake Mendocino and Lake Sonoma. Both are jointly owned by the SCWA, who operates for water supply, and United States Army Corps of Engineers (USACE) who operates for flood control. Lake Mendocino is the most upstream reservoir located on the East Fork of the Russian River. Its maximum water supply capacity is determined by a seasonal guide curve with the top of the pool reaching 111,000 acre-feet between May and October and down to 68,400 acre-feet from November through March. Lake Sonoma is located on Dry Creek and has a maximum water supply capacity of 245,000 acre-feet for the entire year. During the summer, SCWA releases water from Lake Mendocino and Lake Sonoma to maintain minimum flows in the Russian River as specified in SCWA's water rights permits and for downstream beneficial uses, such as the abovementioned municipal, domestic, industrial, and agricultural uses.

SCWA water rights permits are based on Decision 1610 (D1610) that was issued by the State Water Board in 1986. D1610 states that the minimum flows are determined by a hydrologic index based on cumulative inflow into Lake Pillsbury, a reservoir on the Eel River in Lake County. However, in 2008, a Biological Opinion (BiOp) for the Russian River issued by National Marine Fisheries Service determined that the minimum flow in D1610 creates velocities that are too high for some salmonid species. To mitigate for this adverse effect, the BiOp requires SCWA to petition for lowering the D1610 minimum flow requirements to improve habitat for coho salmon and steelhead trout, both protected under the federal Endangered Species Act. Also, the reduced diversions through the PVP starting in 2006 has led the D1610 hydrologic index, determined by Lake Pillsbury inflow, to set minimum flows that are too high for the amount of inflow in the Russian River watershed. This has led to low storage in Lake Mendocino in some years and emergency petitions to be filed for lower minimum flows.

Methods

Water balance modeling and drought indices

Metrics of water supply and landscape stress are developed using a California-wide grid-based water balance model, the Basin Characterization Model (BCM; Flint et al. 2013; Flint and Flint 2014) that calculates the monthly or daily water balance for each 270-m grid cell based on a rigorous energy balance and soil moisture depletion calculation. The water balance can be characterized by these different processes that then lead to losses of water by evaporation and sublimation, changes in soil water storage due to snowmelt, infiltration, and plant water use (transpiration) and runoff from the soil surface or recharge below the plant root zone (Fig. 2). There are multiple modeling approaches or tools that could alternately be used to calculate these variables, although the BCM is unique in its application of bedrock permeability to spatially distribute differences in recharge across the landscape. The spatial scale of 270 m implemented here does not suggest any level of certainty in the calculations, which rely heavily on mapped soil properties, but it has been suggested that water supply variables use planning watershed scales for interpretation, while climatic water deficit (CWD), relying on energy balance calculations, can be reflected more accurately at the hillslope scale (Flint et al. 2013).

To account for the majority of water supply uses, from surface water runoff to baseflow and groundwater, water supply for this study is characterized as the combination of runoff plus recharge. Runoff is water that leaves the grid cell because the soil profile is saturated, and recharge is water that makes it below the root zone where it can infiltrate at a rate equivalent to shallow bedrock permeability. These processes and calculated variables vary across the landscape on the basis of variations in soil properties and bedrock, timing and quantity of precipitation and snowmelt, and energy balance calculations that include topographic shading and cloudiness, driven by air temperature. Together, recharge and runoff describe the combination of streamflow, late season baseflows, and groundwater recharge that make up the total sustainable, available water supply.

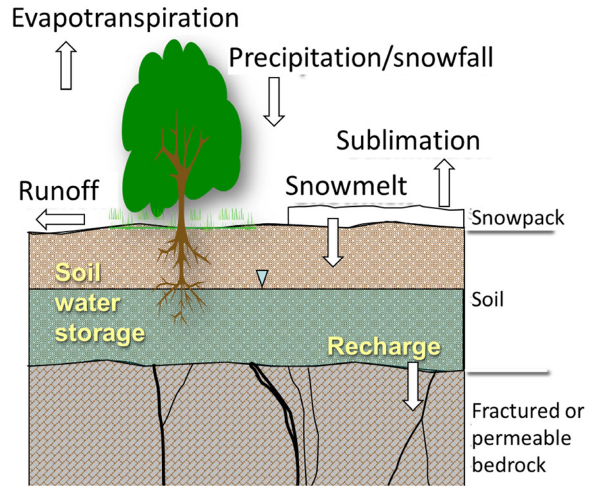

Fig. 2 Schematic of the water balance calculated by the Basin Characterization Model where precipitation = evapotranspiration + runoff + sublimation + recharge + change in soil water content and indicating flow paths of the different components

Landscape stress is characterized on the basis of the calculation of climatic water deficit (CWD) first coined by Stephenson (1998) as the evaporative demand that exceeds available water and calculated as potential minus actual evapotranspiration. In Mediterranean climates with most of the precipitation occurring in the winter months when demand is low, runoff is lost from the landscape, and thus, CWD primarily describes the extent of the dry season, larger in years with high temperatures or early snowmelt. CWD describes the seasonal accumulation of deficit that corresponds to agricultural demand for irrigation to maintain evapotranspiration at potential, rising with increased air temperature. It represents the depletion of environmental moisture, including subsurface depletion of soils with deeply rooted plants, especially in extended dry periods, and drying out of live fuel moisture, thus correlating well with forest stress, die-off, and wildfire (van Mantgem et al. 2013; Anderegg et al. 2015; Das et al. 2013).

The water balance was calculated using the BCM for the state of California at a monthly time step for 1910–2016, and average water supply as recharge plus runoff and CWD were computed for 1981–2010 to represent average baseline historical conditions. In addition, the difference between average baseline water supply and CWD was calculated for each of water years 2012–2016. The difference values were aggregated and divided by 5 years to estimate the number of years the water supply deficit and landscape stress had accumulated as a result of the drought and how many years of average climatic conditions would be necessary for the system to recover to normal hydrologic conditions.

The BCM was used to calculate the daily water balance for the Russian River basin for 1910–2015, and recharge and runoff were used to develop estimates of unimpaired flows for subbasins with streamflow gages, following methods described in Flint et al. (2015). These unimpaired flows were used in the Sonoma County Water Agency's water management model to simulate reservoir operations for dams at Lake Mendocino and Lake Sonoma to evaluate water supply management strategies.

Extreme drought scenarios

Characterizing and understanding different kinds of droughts, their associated impacts, and how they are considered to have ended serves to provide information for managers to develop adaptation strategies, forecast short- and long-term management needs, and inform the public. To assist local resource managers to prepare for drought, in 2015, we developed a suite of extreme drought scenarios in conjunction with stakeholder interaction for a variety of sectors in the basin, including water management, fisheries, health and safety, conservation and biodiversity, and forest management. It was concluded that the most useful examples would be to append historical droughts to the ongoing drought to evaluate the impacts of extended and extreme droughts on the infrastructure. The rationale for this approach was to represent potential future extreme conditions by incorporating a range of past conditions that people had lived through and dealt with and add these to current conditions of landscape and water supply stress to see how management strategies could cope with exacerbated conditions they had not dealt with before. We chose to use the acute 2-year drought of 1976/1977 that drained the reservoir at Lake Mendocino and prompted serious drought planning, as well as the drought of the 1930s, a drought that, although less acute in terms of reduced precipitation, was warmer and extended for multiple years from approximately 1928 through 1936. Including post-drought recovery years, the devised extreme drought scenarios extended from October 2011–June 2015 + July 1976–December 1985 for case 1 and October 2011–June 2015 + July 1928–December 1937 for case 2. The historical drought periods were corrected to have the mean air temperature coincide with the mean air temperature of water years 2012–2015. The adjustments were 1.8 °C for the case 1 analysis and − 0.8 °C for the case 2 analysis.

The climate for each case was run through the BCM, and results were used as unimpaired flow input to the Russian River ResSim (RR ResSim; Klipsch and Hurst 2007) model for the drought scenarios. The RR ResSim model was developed with the USACE HEC ResSim software package and is used for as a planning tool by SCWA. The model is able to simulate reservoir storage, release, and flows at designated junctions in the Russian River watershed for different reservoir operation and climatic scenarios. In this model, the operation of the system followed D1610 rules with the minimum instream flows set to the BiOp recommended flows.

Results

California drought

While reservoirs were nearly empty in 2015, with some recovery in northern basins in 2016, and dramatic water use conservation measures put into place, the accompanying landscape stress induced forest conditions resulting in massive die-off (Asner et al. 2016) and intensified wildfire (Diffenbaugh et al. 2015; AghaKouchak et al. 2014). The impacts of the 2012–2016 drought were evaluated using the drought indices developed from the BCM, which provided a spatial representation of where the impacts were felt the most for both metrics. These indicated that some locations required nearly 5 years of normal conditions to recover from the drought. The spatial distribution of the average annual water supply, as indicated by recharge plus runoff, and the landscape stress, as indicated by CWD, is shown in Fig. 3a, c. The total amount of water supply and CWD are each accumulated for the five water years 2012–2016 and divided by five to assess the number of years of average conditions it would take to replenish the water supply and return it back to average conditions or to have the landscape conditions return to normal (Fig. 3b, d). As of the end of WY2016, which was a relatively normal water year, water supply ranged from about a half a year deficit in the north coast to greater than 3 years of water supply deficit or "missing water" in the south coast (Fig. 3b). The landscape shows less of a dramatic stress overall but with more heterogeneity resulting from combinations of factors besides the climate, including soil storage, bedrock permeability, and topographic shading. Figure 3d highlights mountains that had little snowpack (dry snow drought, Harpold et al. 2017) during the drought as resulting in the highest stress to overcome, particularly the southern Sierra Nevada. But many other locations also show drought, including the north coast and Trinity Mountains, the Cascades, and the southern Coast Ranges and Transverse Ranges (Fig. 3d). There are differences between the relative impacts of these two maps,

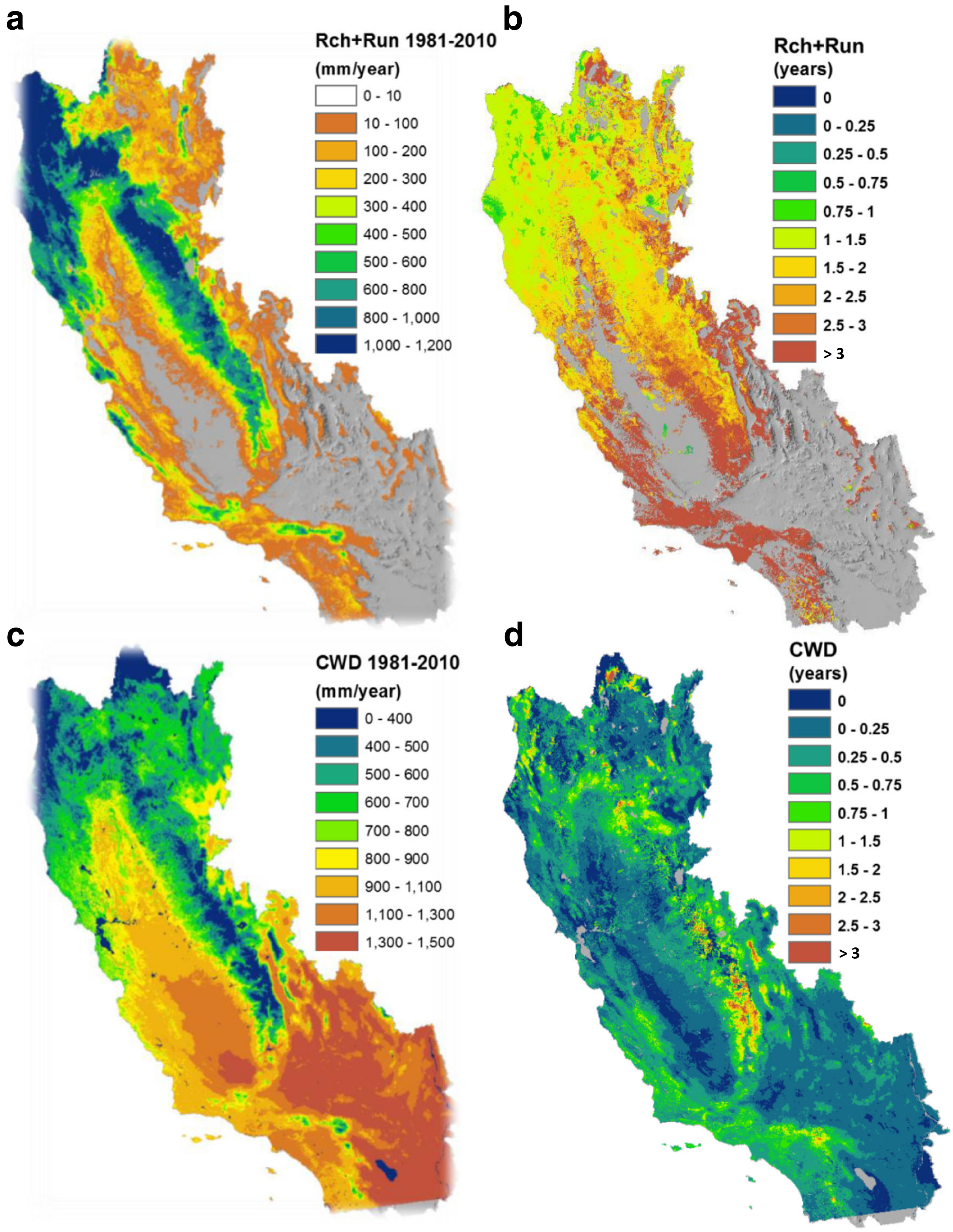

Fig. 3 Calculations of statewide drought metrics of water supply (recharge plus runoff) for **a** average annual conditions and **b** years of missing water supply accumulated for drought water years 2012–2016 and landscape drought (climatic water deficit) for **c** average annual conditions and **d** years of accumulated landscape stress for drought water years 2012–2016. Gray in **a** and **b** signifies that there is no average annual recharge or runoff for 1981–2010

where some locations that have relatively little “missing” water supply may have higher CWD; thus, some locations with full reservoirs may have higher irrigation demands or forest die-off. There is a large variability in drought indices across the state, and in order to evaluate the underlying mechanisms that lead to various kinds of drought, we focus on a watershed that has a relatively homogeneous climate in comparison to the whole state.

Russian River focus study

The drought in the Russian River basin echoes the statewide drought, starting with water year 2012, the 11th driest year in the northern part of the basin occupied by the water supply reservoir Lake Mendocino since 1950. Water year 2013 did little to fill reservoirs and was warmer than 2012. The time period between January of 2013 and January of 2014 received the lowest amount of precipitation in a 13-month period over the region since 1907 and is the lowest for the Lake Mendocino watershed since 1949. This dry spell was relieved when a series of atmospheric rivers made landfall between February 7 and 10, 2014, producing about 6 in. of precipitation in 4 days. The long period of dry, hot conditions, however, parched the landscape, increased the evapotranspiration, and depleted soil moisture and the shallow unsaturated zone, resulting in little runoff to the reservoir. Soil moisture measured 14% in Healdsburg, and total simulated Lake Mendocino watershed soil moisture was the lowest since 1900 at 2413 acre-feet.

These antecedent watershed conditions were evaluated using measured reservoir inflows and climate and watershed conditions analyzed using the Basin Characterization Model (Flint et al. 2013). Between Feb 5th and Feb 12th, the total precipitation was 6.82 in. over the Lake Mendocino watershed, totaling approximately 37,900 acre-feet, but Lake Mendocino storage only increased by 3823 acre-feet (~ 10% of the total precipitation), 3% of that was from direct rainfall and 7% from runoff. Of the remaining precipitation, 44% was simulated as replenishing dry soil, another 39% went to fill the unsaturated zone, and 7% was lost to evapotranspiration. For comparison, during an event between January 13 and 20, 2010, when 6.5 in. fell over Lake Mendocino, Lake Mendocino storage increased by 13,327 acre-feet (about three times as much as in 2014). The soil water content at Healdsburg was 43%, and modeled soil moisture for the Lake Mendocino watershed was 3971 acre-feet, 64% higher than that for February 6, 2014.

These different watershed conditions contributed to very different water supply results and exemplify the need to understand antecedent watershed conditions for planning management actions for water supply. "Paying back" the watershed is necessary following drought conditions to anticipate proper watershed response to climate and develop useful water management strategies.

The recovery necessary following the water year, 2016, can be considered with the "missing water" analysis from the BCM that further characterizes the drought in the Russian River basin. Figure 4 is Fig. 3b, d zoomed in to the Russian River basin and indicates that water supply in the basin by the end of water year 2016 would require between 1 and 3 years of normal conditions to recover. Locations in the southern parts of the basin will require more than the northern portion. These accumulated watershed conditions were present even though both water supply reservoirs were at capacity, indicating that stresses in the tributaries were persisting, with implications for fisheries and late summer flows, and local groundwater declines were likely. The deficit in CWD ranges from a few months to over a year, with the valley bottoms nearly recovered and the higher elevations with

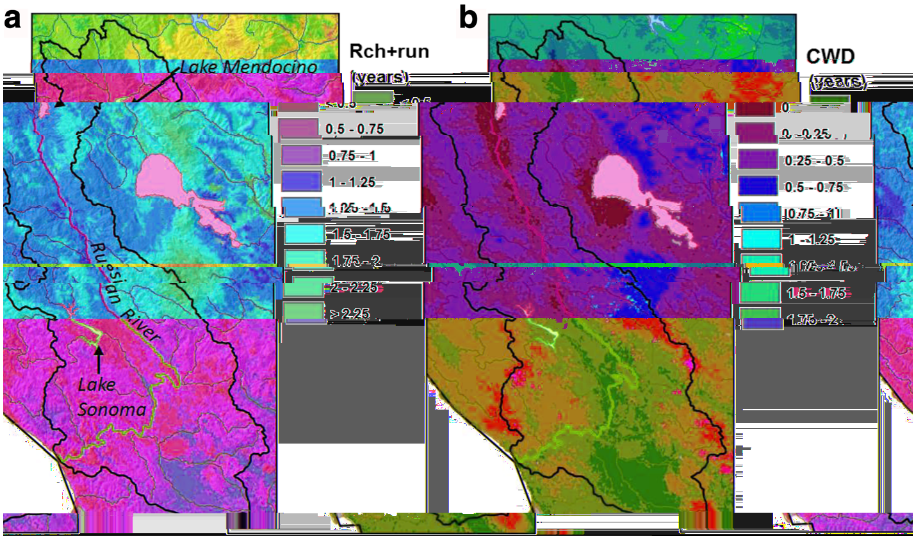

Fig. 4 Calculations of Russian River watershed drought metrics of **a** water supply (recharge plus runoff) for years of missing water supply accumulated for drought water years 2012–2016 and **b** landscape drought (climatic water deficit) for years of accumulated landscape stress for drought water years 2012–2016

the shallowest soils, primarily the forested areas, with the greatest deficit in CWD from which to recover.

The historical climate and hydrology of the Russian River basin provided both insight into the characterization of drought for the basin and a basis for the selection of historical time periods to append to the current drought to represent an extreme drought scenario. Annual anomalies in comparison to the long-term 1910–2016 are shown for precipitation, average air temperature, soil moisture, CWD (landscape stress index), recharge, and runoff (combined to be water supply index), averaged over the whole basin in Fig. 5. Drought periods are shown by vertical bars indicating the dust bowl days of the 30s, water years 1929–1936, 1976/1977, 1986–1992, and 2012–2016 (Fig. 5). These droughts are characterized by the dominance or presence of different conditions. Although all of the droughts have higher than average air temperature and lower than average precipitation (Table 1), the extent of each of these impacts the basin differently. For example, the drought in the 30s shows an extended period of below normal precipitation, average 20% below normal for all 8 years, higher than average air temperatures with associated low soil storage and high CWD, and resulting in below average water supply (recharge plus runoff) of 31% for all 8 years (Table 1). The acute drought of 1976–1977 was short, with very low precipitation, 51% below normal, but only slightly warmer than the long term average. The low precipitation stressed the water supply system for the first time since Lake Mendocino was relied on as the primary water source, and prior to the installation of Lake Sonoma, and Lake Mendocino was nearly drained. CWD integrates the seasonal timing of precipitation, air temperature, and soil storage, and is highest for the recent 2012–2016 drought. This recent drought had the highest accumulated CWD of all the droughts but only moderate decline in water supply in comparison to the other droughts. However, although late season precipitation filled the two reservoirs by mid-2016 (Fig. 6), the extreme conditions over five long years had depleted soil storage and the shallow unsaturated zone to such an extent that water supply, calculated as recharge + runoff was still behind normal by 1 to 3 years by the end of water year 2016. CWD ranged from 0 in the deep river valley to 1–2 years behind normal in the higher elevations.

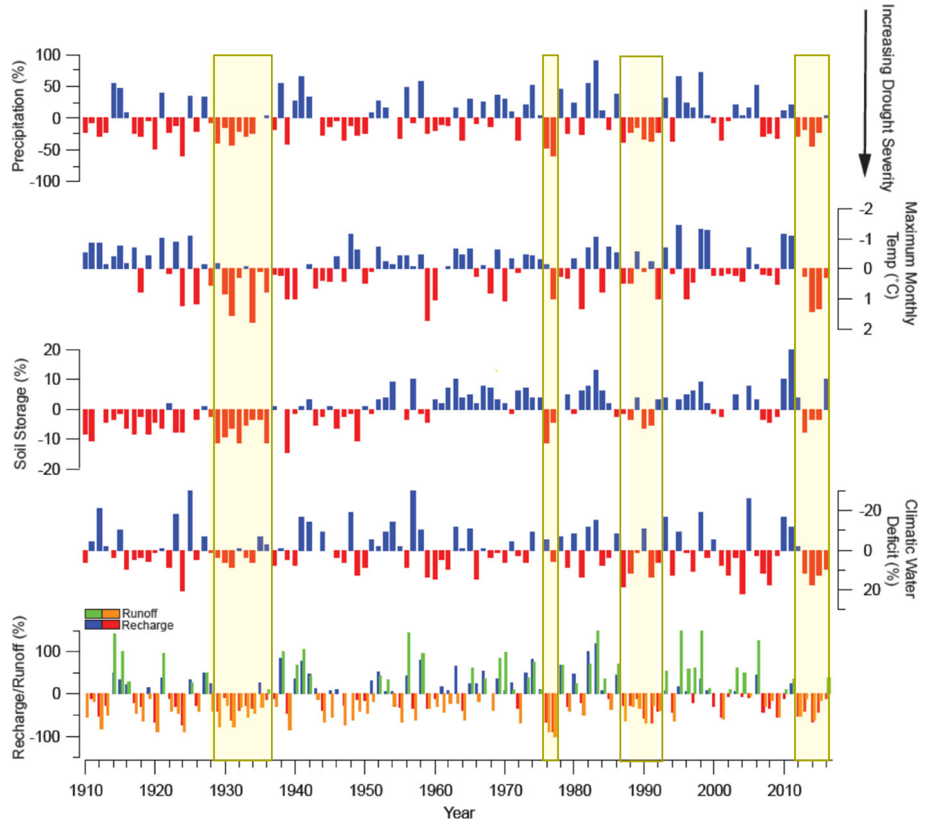

Fig. 5 Historical conditions in the Russian River basin represented as anomaly from the long-term mean for water years 1910–2016 for annual precipitation, average air temperature, soil moisture, climatic water deficit, and recharge and runoff. Drought periods are identified by yellow vertical bars

Table 1 Drought periods used for extreme drought scenarios and associated anomalies from the long-term mean (1910–2016) for climate and hydrologic variables

		Difference from long-term mean (1910–2016)				
Drought period	Number of years	Maximum air temperature	Precipitation	Soil water deficit	Climatic water deficit	Recharge plus runoff
(Water years)		°C	Percentage			
1929–1936	8	0.60	− 20	− 7	2	− 31
1976–1977	2	0.41	− 51	− 7	0	− 85
1986–1992	7	0.07	− 17	− 1	4	− 25
2012–2016	5	0.62	− 21	0	10	− 29

Extreme drought scenario

The development of the extreme drought scenario sought to extend the already extreme recent drought by starting in mid-2015 with two cases, case 1 by extending the recent drought with the 1976/1977 drought and case 2 with the 30s drought, to evaluate hydrologic results and water supply under both extended and acute conditions. Both cases were extended beyond the drought conditions to evaluate the conditions resulting in drought recovery, so each extreme drought scenario ran for 15 years total. The scenarios were run through SCWA's water management model assuming operations consistent with the SCWA's water rights permits and the requirements of the BiOP. In an effort to fully evaluate the vulnerability of current operational policies to the extreme drought scenarios, the modeling did not include any of the emergency operational changes exercised by the SCWA from 2013 to 2015 in order to reduce releases and conserve storage in Lake Mendocino. These emergency changes are not a part of standard policy and were pursued to prevent Lake Mendocino going dry. Reservoir storage levels were simulated for both cases and for both Lake Mendocino and Lake Sonoma (Fig. 7). Corresponding water year CWD and water supply (recharge plus runoff) are shown in Fig. 8 for Lake Mendocino. In case 1, Lake Mendocino empties in 2014 and then again in 1976 and 1977, with the very low water supply years and above average CWD, and then back to near capacity following the above normal precipitation and average CWD year of 1978 (Fig. 7). It should be noted that Lake Mendocino did not empty in 2014 (Fig. 6) due to the emergency operational changes pursued by the SCWA, as previously discussed. In case 2, despite the long warm drought of the 30s, Lake Mendocino never empties again. With slight increases in water supply over time and reductions in CWD by the mid-30s, Lake Mendocino gradually moves back to capacity. While not a direct correlation on a water year basis, some combination threshold of CWD and seasonality of water supply worked to keep water in Lake Mendocino in the 30s, whereas the acute years of 1976/1977 exceeded the threshold causing it to go dry. The recoveries from the two drought scenarios were very different. For the more acute 1976/1977 drought, 1978 was enough to recover the system. However, the low water supply years of the 30s never drained the reservoir, but the extended warm, relatively low precipitation years that dried out the landscape resulted in the reservoir not recovering until the late 30s with a couple of above normal water supply years coinciding with lower CWD. The results for Lake Sonoma, the larger of the two reservoirs in the basin, are similar, though it never went dry. Lake Sonoma storage levels plunged by the end of 1977, only to recover the next year, while case 2 gradually lowered the reservoir until the mid-30s when the couple of relatively good water years coincided with low CWD to increase storage levels. The lagged recovery of the appended 1930 droughts in case 2 is illustrated with

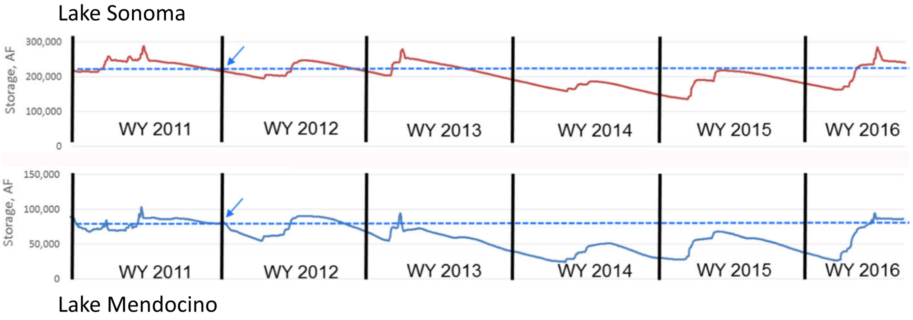

Fig. 6 Reservoir storage for water years 2011–2016 for Lake Sonoma and Lake Mendocino, with the dotted line indicating the storage at the end of the very wet water year 2011 for comparison

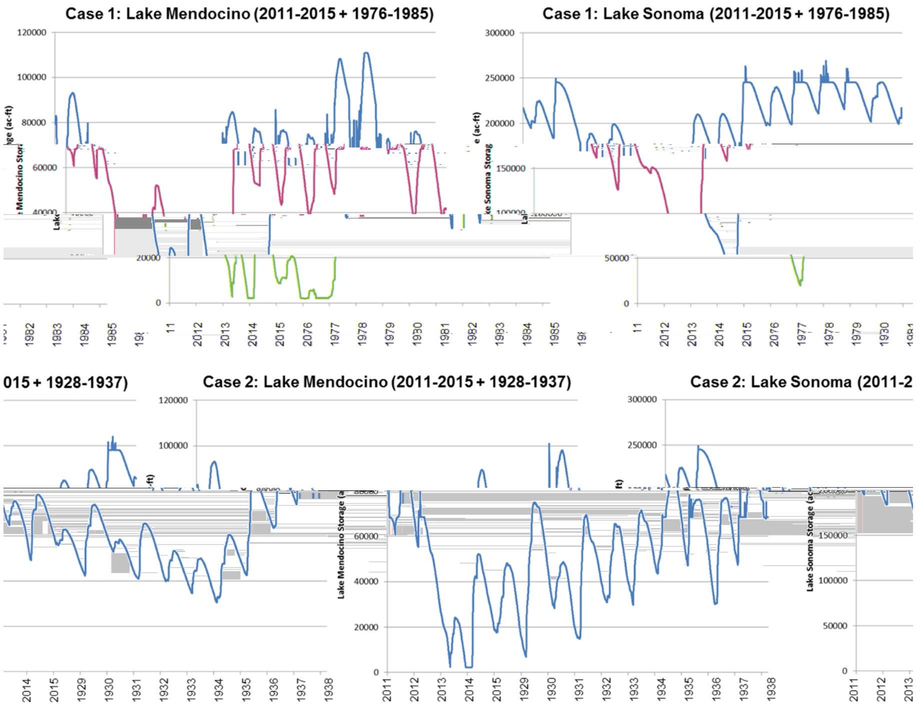

Fig. 7 Simulated reservoir storage for two extreme drought scenarios, case 1 (2011–2015 + 1976–1985) and case 2 (2011–2015 + 1976–1985) for Lake Mendocino and Lake Sonoma

both reservoirs, where the effects of extended drought conditions accumulate deficit in the soils and landscape and take several years to recover.

What kind of conditions lead to drought recovery in this example basin? As noted by Dettinger (2013), atmospheric rivers are often responsible for the abrupt end of droughts. This is the case for the 1976/1977 drought, where in a basin with an average of 14 large storms per water year (defined as the top 5% of daily total precipitation from 1910 to 2017), 1978 had 22 large storms, exceeding normal large storm conditions by 151%. This was not the case in the 30s, where it took 4 years, 1935, 1936, 1937, and 1938, where there were 20, 17, 11, and 26 storms, respectively, to effectively recover from a longer but less acute drought. The recent drought of 2012–2016 required more than just a year of large storms to recover as well. Although 2013 was just above normal with 16 large storms, 2012 was at 69% of normal, 2014 at 55%, 2015 at 69%, and 2016, 62% of normal yearly storms. By the end of water year 2016, as shown in Fig. 4, there was still from 1 to > 2 normal years of missing water supply. Water year 2017 was the wettest since 1998 and had 20 storms at 137% of normal storm conditions and 160% of annual long term precipitation but still not enough to replenish the missing water from the long, severe drought. Although not all storms are created equal and certainly, the hydrologic response of a basin differs with different timing of storms, this analysis supports the conclusion that droughts differ in their development, severity, and expression, and drought recovery differs accordingly, not always as a result of a year of heavy precipitation.

Discussion

The differences in how droughts are manifested are exemplified in the Russian River basin by a comparison of our two extreme drought scenarios. Following the recent 2012–2016 drought that many consider the worst drought in California's history, with the acute drought of 1976/1977, both reservoirs, large and small, were either emptied or nearly so, and in the next year following the drought, 1978, both reservoirs recovered. When a long warm drought of the 1930s followed the current drought, the reservoirs were only briefly or not at all depleted; however, it took much longer for recovery. A look at the more sensitive Lake Mendocino in Fig. 8 shows that in the first scenario, the watershed conditions were below normal for water supply for 9 of the 15 years, with an above normal CWD for 8 of 15 years. The second scenario, while not as extreme as 1976, was below normal water supply for 12 of the 15 years, while CWD was above normal for 9 of the 15 years. The utility of these scenarios is to test what it takes to stress each reservoir and recover each reservoir and assess what management strategies would have to be in place should

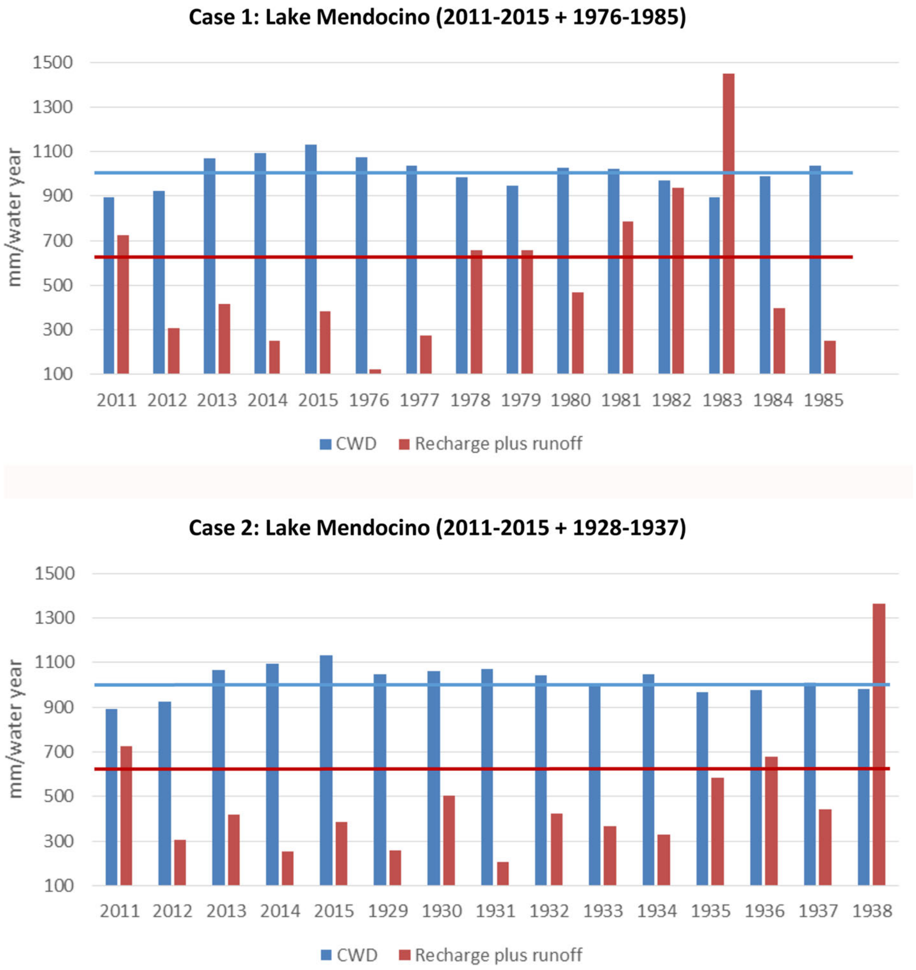

Fig. 8 Climatic water deficit and water supply (defined as recharge plus runoff) for the Lake Mendocino basin for each extreme drought scenario sequence of years. Horizontal lines indicate long-term average for each variable

these climatic conditions occur in the future. While Lake Sonoma shows some resiliency to these extreme scenarios, Lake Mendocino, with only 1 year capacity of water supply, is much more sensitive to seasonality of precipitation and extreme temperatures.

These examples amplify the need to consider the impacts of drought on the landscape in combination with measured water supply to evaluate recovery and how depleting the landscape in longer droughts requires “payback” before full recovery of water supply can occur. The longer term depletion of soil water and the shallow unsaturated zone in the watershed has a much more pervasive impact on the Lake Mendocino reservoir than the shorter acute drought. These extreme conditions and necessity to fill soils and shallow unsaturated zone before runoff could occur to fill reservoirs were evident in the driest year of 2014. In early February following 13 months of nearly no precipitation, Lake Mendocino was almost empty. Between February 6 and February 10, a series of ARs produced over 6 in. of precipitation, but only about 10% of the precipitation generated runoff as inflow into Lake Mendocino, 7% was lost to evapotranspiration, and the other 83% replenished the dry landscape, filling up dry soils, and draining to the dry shallow unsaturated zone that took three dry years, 2012–2014 to develop. This highlights the importance of antecedent conditions and the impacts of landscape drought on the hydrology and water supply of the region. While short, acute droughts like 1976/1977 may recover with an above-average year of precipitation, the recovery from long, severe drought may take much longer. Multiple big storms may only fill reservoirs, run off to the ocean, and still leave the basin in water supply deficit.

In the Russian River, there is no single definition of drought because of the diversity of sectors that are affected by low water availability and elevated air temperature, including urban and rural environments, recreation, agriculture, and ranching. These different drought conditions, and certainly those described by our two indices, may result in different management responses to cope with the impacts or to plan for future droughts.

Water managers in the Russian River basin considered the reservoir water supply crisis to have ended in 2016. While several factors contributed to this, including the amount and timing of precipitation (104% of normal, 30% of precipitation occurring after March 1st, coinciding with the increase in water supply storage), water supply in the Russian River is not solely about reservoir storage. Water supply also includes recharge throughout the basin and antecedent conditions that encourage runoff into all streams whenever it does rain, as well as the groundwater resources that are used for pumping. The competition for water among public supply, fisheries, and agriculture requires a basin-scale approach. The recharge and runoff for the Russian River basin by the end of water year 2016 ranged from 1 to 2.5 average years behind normal (Fig. 4), indicating that more water will be needed to fill the basin to result in normal streamflows that sustain baseflows and reduce the need for changes in reservoir releases to maintain environmental flows. The CWD by the end of water year 2016 ranged from recovered in the deep river valleys to 1.5 years behind average conditions in the mountain ranges where there is less soil storage to hold water through the summer season. While this does not seem drastic, these conditions specifically in water year 2014 combined to impact the ranching and rangeland communities, many of whom rely on rainfed, unirrigated pastures, with 54–55% in lost revenues in 2014 relative to the previous 5-year average (Mendocino County 2014). CWD describes the extent that the timing of rainfall can accumulate deficit though the growing season, with high temperatures exacerbating the demand for water, which was evident in losses to the wine industry.

Conclusions

Management of land and resources and planning for extreme conditions require an understanding of the spatially distributed impacts across the landscape, from upstream of reservoirs to forested hillslopes and from tributaries to plains, in order to inform all constituents and stakeholders. The state of California has developed a complicated system of water transport to move water from high rainfall locations to those typically in water deficit. The benefit of using two indices that reflect deficits in direct natural water supply as well as landscape stress that are based on unimpaired water balance calculations can help describe the interacting processes in watersheds that may require hydrologic payback to the landscape to ensure recovery of water supply and can also provide spatial information regarding basin recovery. These indices can inform regional planners regarding sensitivity of various watersheds or landscapes to extreme conditions, enable prioritization of resources for managing lands to reduce wildfire in locations vulnerable to high CWD, or increase forage for grazing. Both indices combine to provide local and regional managers a sense of how serious an ongoing drought is and the likelihood of rapid recovery. The indices can highlight sensitive locations, or those locations with high potential for recharge, that may be considered unsuitable for development. Sensitivity analyses, such as our extreme drought scenarios, that analyze potential future climate and frequency of droughts may differ across the state, and consideration of long term infrastructure can be assessed with more confidence when regional information is available, such as those available from these modeling tools.

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Availability of data and materials

Data supporting analyses and conclusions can be accessed in references, tables, and figures and at https://ca.water.usgs.gov/projects/reg_hydro/projects/russian_river_drought.html.

Authors' contributions

All authors helped to design the study and reviewed and revised the manuscript. LF was project chief, analyzed the data, and wrote the first draft of the paper, AF and JM processed data and JK and MR provided project guidance and expertise. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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