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RESEARCH ARTICLE

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Characterizing the Influence of Fire on Hydrology in Southern California

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ABSTRACT: The chaparral-dominated national forests of southern California were in part established to provide water provision services to the surrounding urban populations and irrigation for agriculture. However, water provision in the form of groundwater recharge and surface runoff depends on the climatological conditions of any given year and also landscape-scale disturbances such as fire. Fire is increasing in frequency in southern California and understanding its impacts both immediately post-fire and as vegetation recovers, and the interactions between fire and hydrology, are key components to managing federal lands effectively. In this study we focus on nine fires in a study area that encompasses the four southern California national forests (Los Padres, Angeles, San Bernardino, and Cleveland) and use a water balance model to investigate the effects of water provision services post-fire at a regional scale. We found that runoff and recharge increased post-fire, with increases in recharge being greater with recovery times ranging from 2 to 4 y post-fire. Vegetation recovery occurred 2 y post-fire for all basins as indicated by remotely sensed imagery measuring vegetation greenness having returned to or exceeded pre-fire values for the basin. We found that runoff and recharge were more sensitive to the effects of climate than to length of time post-fire. Findings from these modeling tools allow users to anticipate the impact of fire on water provision services in the region and develop management strategies that help reduce the impacts of wildfire.

Index terms: chaparral shrublands, climate, groundwater recharge, hydrology, national forests, surface runoff, water resources, wildfire

INTRODUCTION

The national forests of southern California are dominated by chaparral ecosystems, which play a critical role in providing groundwater recharge and other ecosystem services. However, wildfire plays a central role in chaparral landscapes (Keeley et al. 2011; Safford et al. 2014) and even small hydrologic effects resulting from fire and fire recovery are felt throughout the water resources infrastructure of southern California (Meixner and Wohlgemuth 2003). Frequency of fire in southern California forests has steadily increased over time as a result of ignitions at the growing wildland–urban interface (Syphard et al. 2007; Safford and Van de Water 2014), as well as a result of warming due to climate change (Westerling et al. 2006). Understanding the implications of increased wildfire on hydrologic conditions and water supply is particularly important given the increasing demands for water resources to satisfy growing populations and agricultural intensification in southern California.

Wildfire has been found to increase storm runoff, peak discharge, and recharge (Neary et al. 2003; Cydzik and Hogue 2009; Coombs et al. 2013) due to the temporary reduction or elimination of transpiration as vegetation cover is removed and the reduction of infiltration due to hydrophobicity. The longevity of these effects, however, is uncertain with studies from southern California reporting a wide range of recovery periods from a couple of years to decades (Hibbert 1985; Meixner and Wohlgemuth 2003; Kinoshita and Hogue 2011). Factors influencing the temporal variability include burn intensity and post-fire weather (Warrick et al. 2012).

Additional uncertainty in hydrologic changes as a result of wildfire is reflected in the development of soil hydrophobicity or water repellency. On the basis of numerous studies that are largely inconclusive regarding the impacts at a basin scale (e.g., Prosser and Williams 1998; Woods et al. 2007), we address this issue with an example that reflects a potential use of modeling to test the implications of hydrophobicity. However, we believe that, due to the extremely large spatial variability and lack of contiguous patches of hydrophobicity following wildfire, the impact of hydrophobicity does not warrant additional consideration when analyzing hydrologic responses to fire at basin scales over the southern California region. We focus instead on the wildfire impacts on hydrology due to the removal of vegetation.

The value of hydrologic provision (either groundwater recharge or surface runoff) can be described in terms of the various components of water balance. Summer air temperature has increased since the 1970s by nearly 2 °C over much of southern California, and while an increase in air temperature can increase the rate at which plants transpire and deplete soil moisture, the additional storage space in the soil can store more winter rainfall, increasing recharge and reducing runoff. Water that becomes recharge will either penetrate to the groundwater aquifer or help to maintain baseflows through the dry season. In contrast, runoff occurs mostly in the wet season (winter) and is more likely to leave the watershed, and in many cases in southern California, discharge into the Pacific Ocean. When vegetation is removed from the landscape by wildfire, the resulting lack of transpiration results in water remaining in the soil, increasing runoff. If a big precipitation year follows the fire year this could result in excess runoff that can carry extra sediment from burned areas, compromising water quality. While "water supply" can be considered a combination of both recharge and runoff, in this largely groundwater-dependent region, recharge may be a more valuable hydrologic provisioning service than runoff.

Watersheds in southern California's four national forests differ dramatically with regard to climate and coastal proximity, energy loading, underlying geologic material, soil type and storage, and vegetation, as well as fire history. As a result, the hydrologic response to wildfire is widely disparate across the national forests. The ability to evaluate the sensitivity of watersheds across the region in their hydrologic response to wildfire would improve water resource planning and help to prioritize management activities.

Water balance modeling has been conducted in numerous watershed studies in southern California, but with the exception of Bart (2014, 2016), who utilized a mixing model approach calibrated to paired burned and unburned watersheds, no regional-scale characterizations have been done that directly use spatially distributed water balance modeling to analyze wildfire impacts on hydrology. Bart's results indicate that recharge increased (baseflow recession rates decreased) following wildfire at a regional southern California scale from 38% to 66%, while at a watershed scale the results were much more variable.

In another semiarid Mediterranean-type climate region, water balance modeling in Spain indicates that both runoff and recharge increase post-fire (although recharge increases the most) and effects are more dramatic in dry years; in addition, the effects of fire on water provision are greater in locations with grass rather than trees or shrubs (Bellot et al. 2001). In southern California, the conversion of native shrubland to grasslands dominated by nonnative annuals is well documented (Syphard et al. 2018), and the influence of this vegetation conversion on hydrologic provision is confirmed by numerous studies (e.g., Bosch and Hewlett 1982; Minnich and Bahre 1995; Meixner and Wohlgemuth 2003). Water balance modeling can serve as a useful tool for evaluating hydrologic conditions coincident with wildfire, what wildfire may do to the post-fire hydrologic response (whether runoff increases and where), and how recharge processes may change over time as vegetation recovers.

As part of a region-wide assessment of ecosystem services across southern California's national forests funded by the US Department of Agriculture Forest Service, we evaluated the sensitivity of hydrologic processes to wildfire using data associated with 10 well-studied fires (Table 1). Our overarching objective was to increase our understanding of hydrologic regimes and the interaction of fire with these regimes in southern California's chaparral-dominated national forests. More specifically we sought to evaluate how recharge and runoff changed as a result of wildfire, what the hydrologic and vegetation recovery time was, and the interactions between climate and vegetation recovery. To achieve this, it was necessary to develop the modeling tools needed to characterize the hydrology in these forests, test the tools before and after historical fires, and examine the sensitivity of hydrology to fire and climate across the region.

We had three initial hypotheses: (1) wildfire would reduce plant evapotranspiration (ET) and increase recharge and runoff temporarily; (2) runoff would increase more than recharge because reduced ET keeps more water in the soils resulting in more runoff; (3) recovery of vegetation, ET, and pre-fire hydrologic conditions would take several years and differ among fire sites depending on post-fire weather. To explore these hypotheses, we first looked in detail at post-fire vegetation recovery after the Old fire and the relationship between vegetation recovery, normalized difference vegetation index (NDVI; an index of live green vegetation cover derived from remote sensing data), and precipitation. Second, we assessed hydrologic recovery using six fires in seven watersheds. Finally, we tested the sensitivity of post-fire vegetation recovery by looking in detail at three fires in the Santa Clara River watershed to provide insights to resource managers on the implications of vegetation loss on runoff and recharge.

Study Area Description

The study area is composed of the four national forests in southern California and adjacent watershed units at the HUC-12 spatial scale (hydrologic unit code, Watershed Boundary Dataset, US Geological Survey): the Los Padres in the north, extending from Monterey County into Ventura County; the Angeles in Los Angeles County, encompassing the San Gabriel Mountains; the San Bernardino, in San Bernardino and Riverside counties; and the Cleveland, which extends through San Diego County to the Mexican border (Figure 1). The study area covered 35,158 km^2. The region has a distinct Mediterranean-type climate with mild, wet winters and hot, dry summers. Most rainfall is generated by frontal systems from the Pacific Ocean. The geology of the region consists of igneous and metamorphic rocks in the inland areas and primarily sedimentary rocks in the coastal ranges. Shrublands are the dominant vegetation within the national forests, although grasslands, chaparral, oak woodlands, mixed conifers, and coastal sage scrub are also common.

METHODS

Datasets

The fire dataset was compiled as a comprehensive fire perimeter GIS layer by CAL FIRE, USDA Forest Service Region

Table 1. Description of fires and corresponding watersheds with stream gages, properties, hydrologic and climatic conditions, and years to apparent post-fire recovery. (*Continued across*)

Basin ID	Gage name	Forest	Gage ID	Fire name	Fire alarm date	Area of water-shed burned	Slope of burned area, average and range	Vegetation type
Calibration fires						(%)	(%)	
1	Big Sur River nr Big Sur	Los Padres N	11143000	Basin Complex	21-Jun-08	100	29 (0.5–85)	mixed chaparral
2	Sisquoc R nr Sisquoc		11138500	Zaca	4-Jul-07	40	22 (0.2–75)	mixed chaparral, montane hardwood
3	Santa Cruz C nr Santa Ynez	Los Padres S	11124500	Zaca	4-Jul-07	65	22 (0.2–75)	mixed chaparral
4	Mission Cr at Rocky Nook Park at Santa Barbara	Los Padres S	11119745	Jesusita	5-May-09	80	22 (2–55)	mixed chaparral
5	E Twin Cr nr Arrowhead Springs	Angeles	11058500	Old	25-Oct-02	100	7 (0–84)	mixed chaparral, montane hardwood conifer, Jeffrey pine
6	Santa Ysabel Cr nr Ramona	Cleveland S	11025500	Witch	21-Oct-07	55	15 (0.1–73)	mixed chaparral, montane hardwood
7	Santiago Cr at Modjeska	Cleveland N	11075800	Santiago	21-Oct-07	70	14 (0.3–63)	montane hardwood, mixed chaparral
Sensitivity analysis fires								
	Santa Clara River watershed	Los Padres S		Copper	5-Jun-02	5.7	13 (5–43)	*Sensitivity analysis fires*
				Piru	31-Oct-03	6.2	29 (4–67)	mixed chaparral, coastal
				Ranch	20-Oct-07	1.9	20 (2–68)	mixed chaparral, coastal

5, Bureau of Land Management, National Park Service, and counties in California (frap.fire.ca.gov). Streamflow data were obtained from the US Geological Survey National Water Information System. Remotely sensed NDVI data were obtained from the US Geological Survey remote sensing phenology website (phenology.cr.usgs.gov/get_data_250w.php) and time-integrated over the duration of each growing season to assess the recovery periods of the vegetation within selected fire perimeters. For each of the seven fires used for comparing post-fire vegetation with climate parameters and the three Santa Clara River watershed fires we report the amount of watershed burned, the soil organic matter and soil moisture condition (from SSURGO; NRCS 2006), geology (from Jennings 1977), mean climatic water deficit (CWD; 1981–2010), and mean precipitation (2001–2013) (Table 1). CWD is calculated as potential minus actual evapotranspiration; it represents the evaporative demand that exceeds available water and correlates with landscape stress, fire risk, and irrigation demand. Climate data used in the water balance model operation are PRISM monthly, 800-m transient data (Daly et al. 2008), spatially downscaled to 270 m for application to the regional water balance model (Flint and Flint 2012).

Model Description

A regional water balance model, the Basin Characterization Model (BCM; Flint et al. 2013) was used to explore changes in hydrologic response as a result of wildfire for the study area. The BCM is a grid-based platform that combines data on precipitation and air temperature along with topography, energy balance, soils, and geology to simulate the unimpaired responses of hydrology to changes in climate or land use. This model is unique in its ability to partition available water into recharge and runoff on the basis of spatially distributed bedrock permeability, and to be run for very large regions, providing the opportunity for regional comparisons of hydrologic response to disturbance or climate (Flint et al. 2013). Flint et al. (2013) describe the development, calibration, and validation of the model using 159 basins across California, including 22 basins in the southern California region. For this project, calibrations were done for all basins that were examined pre- and post-fire. The BCM was modified to allow for the reduction of evapotranspiration to simulate the effects of wildfire removing different percentages of vegetation. The water balance is calculated for each grid cell, and if evapotranspiration is reduced, the soil profile retains more water, resulting in more runoff from the soil surface. Recharge and runoff combined reflect water supply

Table 1. (*Continued from left*)

Basin ID	Soil organic matter	Soil moisture storage	Geologic type	Mean climatic water deficit	Mean precipitation 2001–2013	Hydrologic recovery	Vegetation recovery
	(%)	(mm)		(mm/yr)	(mm/yr)	(years)	(years)
1	1	28	granite, metamorphic	816	1177	3	2
2	0.5	43	sandstone, shale	926	750	2	2
3	0.5	43	sandstone, shale	926	777	4	2
4	2	42	sandstone, shale	1006	666	3	2
5	0.5	48	granite	1014	609	3	2
6	0.7	80	granite, gabbro	972	488	4	2
7	1.2	33	sandstone, shale, metavolcanic	1050	520	3	2
	1	65	sandstone, shale,	1064	455	–	–
	1.3	57	sandstone, shale, valley fill	1011	461	–	–
	0.8	67	sandstone, shale, siltstone	1116	548	–	–

as a whole, but considered separately, the ecosystem services they provide are different. Runoff occurs primarily in the winter or following springtime snowmelt, generally flows to streams or reservoirs, and is negligible in the summertime. Recharge penetrates below plant roots and may recharge the groundwater aquifer or return to the surface as baseflow that extends streamflow longer into the dry summer season to sustain late-season flows. The ability of the BCM to differentiate between these processes is useful for evaluating results and the implications of fire impacts on hydrologic mechanisms. Results of calculations from the BCM are in the form of maps with a value (mm) for each grid cell for each output variable. The recharge and runoff outputs can be post-processed by summing the monthly output values for each grid cell upstream of a stream gage to calculate watershed discharge for comparison to streamflow hydrographs. Post-processing includes a surface water component composed of runoff and a shallow- and deep-flow component composed of recharge, which are combined with exponential equations to match peaks, recessions, and summer baseflows of the measured hydrographs. When calibrated to historical records of streamflow, changing model inputs to reduce evapotranspiration due to changes in vegetation resulting from wildfire will predict, for a given watershed and climate, how streamflow will respond to wildfire.

There is ample literature on post-fire hydrophobicity—water repellency that develops due to heating of soil organic matter (Imeson et al. 1992; DeBano 2000; Doerr et al. 2000). The spatial heterogeneity within the fire footprint and temporal fluctuations in recovery are large (Hubbert and Oriol 2005; Shakesby and Doerr 2006). There are few data on the persistence of hydrophobicity post-fire (MacDonald and Huffman 2004), there is continuing uncertainty about the causes (Larsen et al. 2009), and there is little evidence for statistical correlation between fire intensity and degree or duration of hydrophobicity (Huffman et al. 2001). Without explicit knowledge of the extent of hydrophobicity any given fire produces, or of how long it lasts, we account for the effect by reducing the soil porosity to 90% of the original mapped porosity to simulate hydrophobic conditions in the year following the Old fire. However, the results proved negligible and inconclusive, and therefore for remaining analyses of the basins across the region we assumed no post-fire hydrophobicity in the model.

A selection of six fires and seven watersheds was made on the basis of pre- and post-fire records of streamflow for model calibration and distribution across the range of national forests; these include the Basin

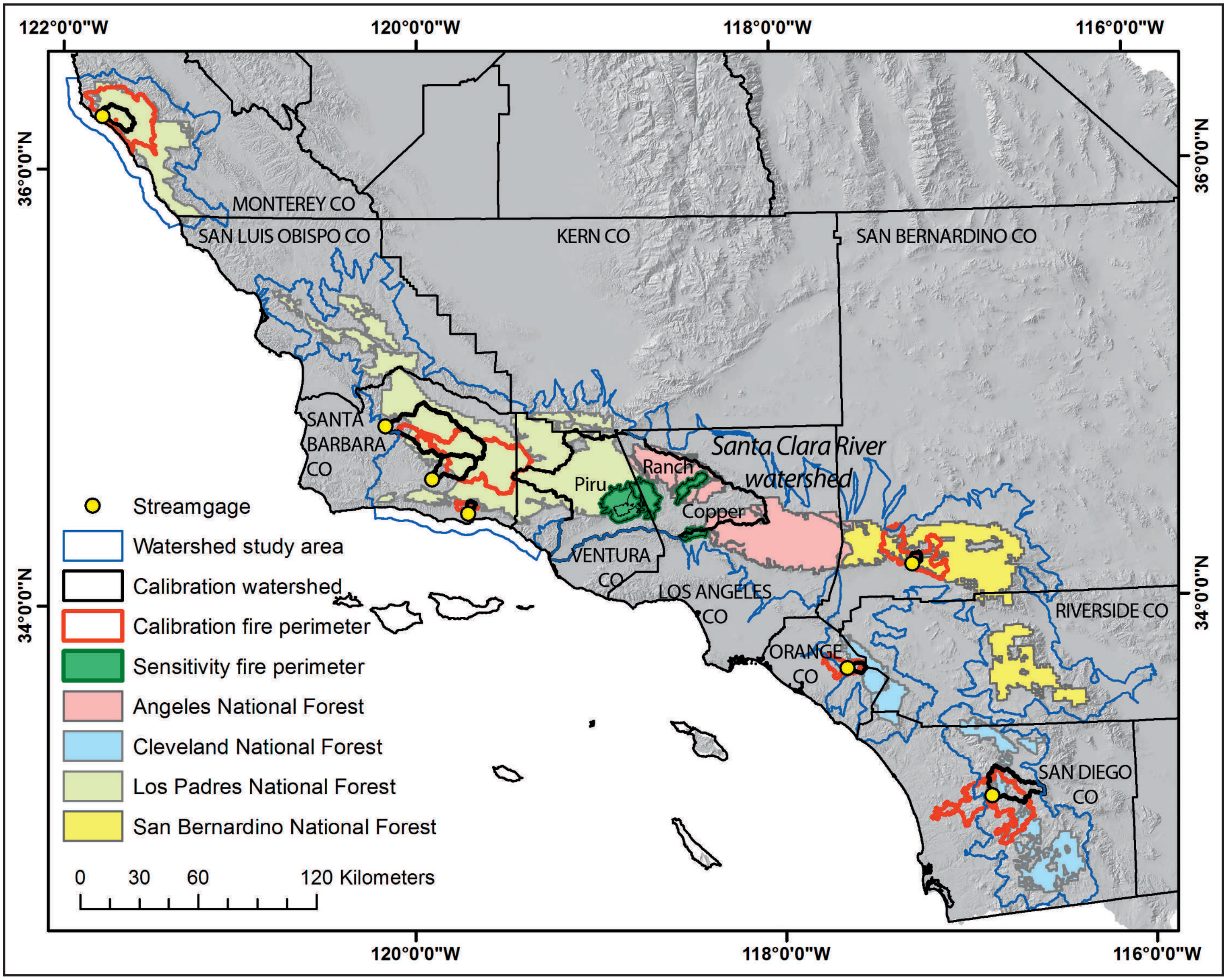

Figure 1. Map of study area indicating watershed study area, southern California national forests, calibration fire perimeters and watersheds, and fire perimeters in the Santa Clara River watershed used for sensitivity analyses. Streamgages are numbered from 1 in the northernmost basin to 7 in the southernmost basin and correspond to descriptions in Table 1.

Complex, Zaca (with two calibration watersheds), Jesusita, Old, Witch, and Santiago fires (Table 1). Additionally, three recent fires in the Santa Clara River watershed, where streamflow records were too poor for calibration, were used to evaluate the sensitivity of their hydrologic response (as recharge and runoff) to wildfire, assuming the year following the fire had no vegetation and then increased 20% in each subsequent year, and using the site-specific climate, to predict how recharge and runoff responded to fire. Model runs were at a monthly time step but all analyses on model results were done by water year (Oct–Sep), abbreviated WY2002, WY2004, etc. We describe and discuss findings for the Old fire in East Twin Creek watershed in detail and then summarize findings for the other five fires.

Estimation of vegetation recovery was attempted using the NDVI maps for 2001–2013 and correlating them with precipitation to assess the degree to which vegetation recovery is correlated to weather rather than length of time post-fire. Hydrologic recovery was estimated using the BCM calibrated to measured pre-fire hydrographs and running the model post-fire with and without vegetation.

RESULTS AND DISCUSSION

Climate in southern California is extremely variable, with a coefficient of variation exceeding all other mountainous regions in California. The long-term average precipitation for 1981–2010 in the region ranges from over 1100 mm/year in the Los Padres National Forest to less than 500 mm/year in the Cleveland National Forest. The water years looked at in this study, 2001–2013, were nearly all below the annual average for precipitation, with many of those years having warmer than historical maximum air temperatures (Figure 2) and with the last 2 y at the start of California's recent extreme drought. These weather trends set the stage for a large number of fires during these years and post-fire responses of runoff and recharge.

Estimating Vegetation Recovery Post-Fire Using NDVI

We used the NDVI imagery cumulated for the growing season over each water year (Oct–Sep) as a proxy for the amount of vegetation and recovery of vegetation following fire. When NDVI was very low following fire, we assumed loss of vegetation, and when NDVI increased over time, we assumed regrowth of vegetation and increase in evapotranspiration, without consideration of vegetation type or leaf area index. We use the term recovery to indicate when the post-fire evapotranspiration rates have returned to pre-fire conditions. As a case study we used the Old fire in East Twin Creek watershed (Basin ID 5), which burned in October 2002 and received about 22% of average annual precipitation the following year resulting in little post-fire vegetation recovery WY2004 (Figure 3). The WY2003 panel shows a coarse-scale view of the Old fire footprint, which shows as dark green due to the high temperatures and reflectivity of the burn, whereas the small panels all have green that indicate vegetation. About 90% of the East Twin Creek watershed burned. The smaller panels illustrate pre-fire (WY2002) and post-fire (WY2004–WY2010) conditions, indicating that most of the vegetation was still absent for the water year following the fire, as evidenced by the red color. However, WY2005, 2 y post-fire, had cooler average temperatures and received approximately 140% of average annual precipitation, which resulted in a flush of vegetation growth. The type of post-fire vegetation and whether it uses the same amount of water as pre-fire chaparral cannot be identified from this imagery, but anecdotally, in many places in the watershed immediately post-fire the chaparral was replaced by bracken fern, which is shallow-rooted and likely uses less water than chaparral. WY2006 still retains much of the vegetation signature in the NDVI, but with hot, dry WY2007 the vegetation signature looks much like WY2004. There was a little regrowth in WY2008, and then it is mostly constant for the next two somewhat less than average precipitation years.

To further isolate the interacting effects of climate with post-fire vegetation recovery, an analysis was done across all seven watersheds by correlating watershed precipitation with watershed NDVI values for pre-fire years, then evaluating how post-fire years compare (Figure 4). In all cases but one the second post-fire year had the highest NDVI. For one fire, the Zaca-Sisquoc, watershed NDVI peaked in the second post-fire year, second only to the wet 2011. The Old fire had the highest NDVI two water years post-fire in a high precipitation year, but recovery was not sustained due to four more dry, hot years. The four 2007 fires (Witch, Santiago, Zaca-Sisquoc, and Zaca-Santa Cruz) had the highest NDVI in 2009, even though the average precipitation was low (except for 2011, which was wet and cool). The Jesusita fire had the two-year vegetation flush in the wettest post-fire year, 2011, followed by two dry years. The Basin Complex fire had the highest NDVI also 2 y post-fire, and also in a dry year. While there is no statistical significance due to the high variability of year-to-year weather, these analyses suggest that post-fire recovery of vegetation as indicated by vegetation greenness in chaparral burned lands is likely on the order of 2 y, regardless of whether precipitation is high or low. Isolating the different contributions of precipitation, air temperature, and evapotranspiration on post-fire hydrology could be an illuminating analysis, requiring a much more local (fine-scale) modeling effort, and perhaps including field validation of the post-fire vegetation type to tease out the respective contributions of climate versus vegetation on post-fire streamflow. Other studies have shown variable vegetation recovery following fire, ranging from 10 y post-fire in Santa Barbara due to disruption by drought conditions (Hope et al. 2007) to 1 to >6 y over the Old fire perimeter for differing burn severities (Kinoshita and Hogue 2011).

Estimating Post-Fire Hydrologic Recovery across Watersheds

The hydrologic signature is much harder to discern than the vegetation response post-fire because of the flashy nature of southern California climate and hydrology, the long fire history, and the impairments to the water supply from urbanization and

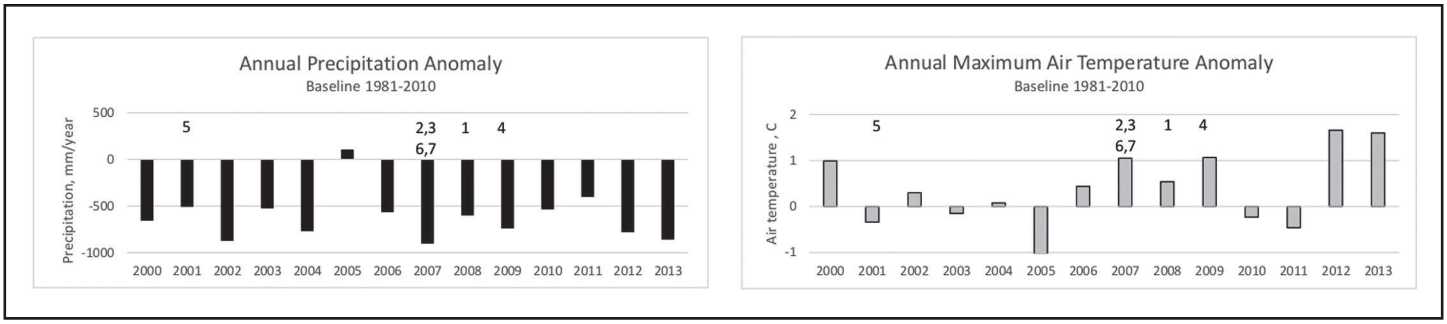

Figure 2. Average annual precipitation and maximum air temperature anomalies from 1981 to 2010 for the Santa Clara River basin for 2001–2013. Numbers above the bars correspond to the stream gages described in Table 1 and on Figure 1.

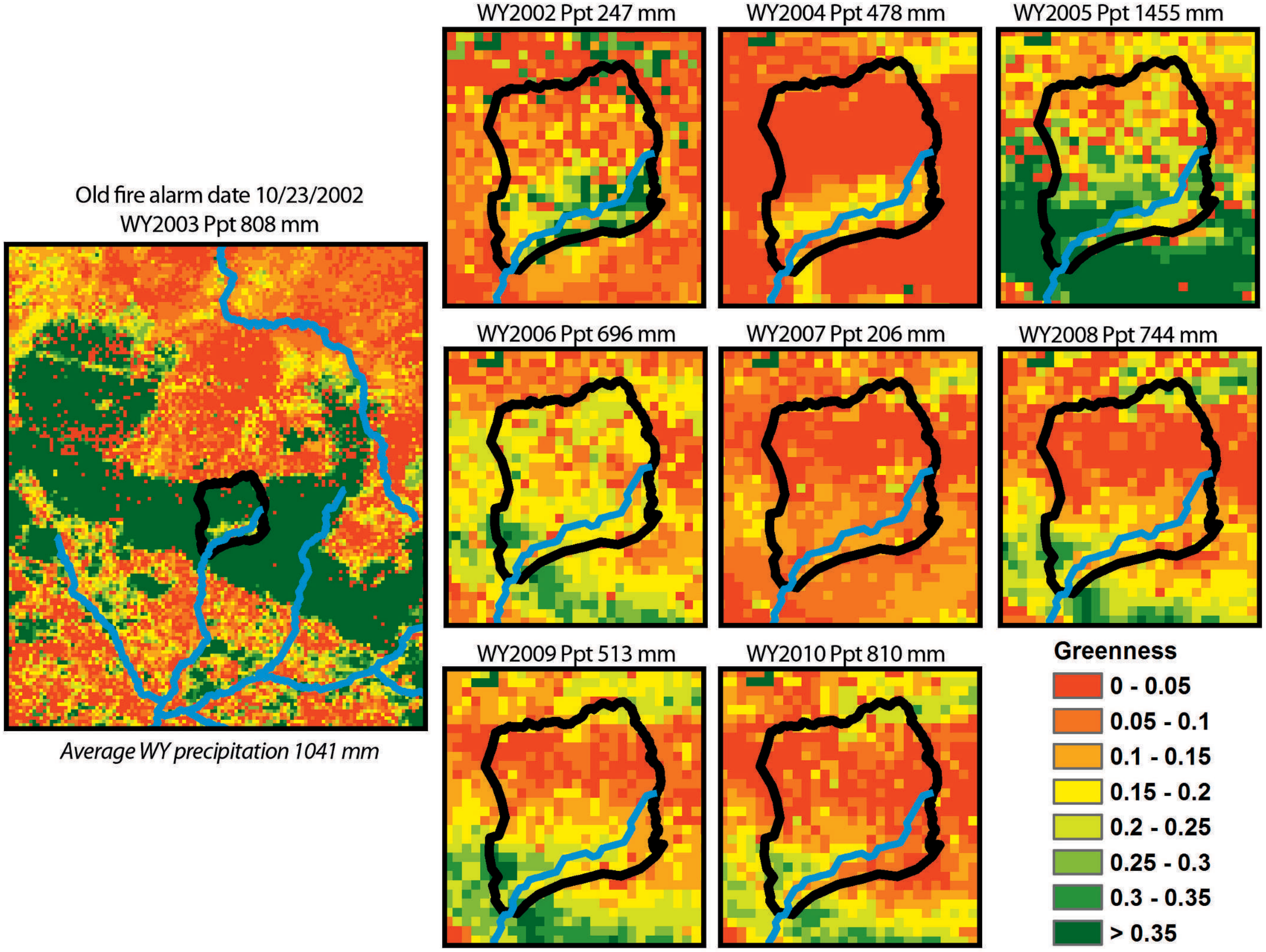

Figure 3. Normalized difference vegetation index (NDVI) for the East Twin Creek watershed showing the extent of the Old fire in the big panel and changes in vegetation before and after the fire in the small panels for water years 2002–2010. The black outline is the East Twin Creek watershed boundary. Water year precipitation is noted for each panel, and the year of the fire WY2003 shows green as the fire footprint due to high temperatures and reflectivity, whereas green in the small panels is vegetation.

other land uses, which also impact the ability to discern the basin characteristics most responsible for variation in wildfire occurrence, severity, and post-fire recovery across the region. One example of hydrologic response to fire is shown for East Twin Creek, where the fire apparently compromised the stream gage (Figure 5). BCM model runs of recharge and runoff were calibrated to pre-fire streamflow using the methods described above to match the hydrograph and the model was then run using post-fire weather data. Post-fire it is clear that the removal of vegetation (see Figure 3, panel WY2004) resulted in increased streamflow in WY2005 and WY2006, although there was an increase in vegetation corresponding to the 200% of normal precipitation. When vegetation ET is removed from the BCM for seven post-fire years, we were able to better match the wet year 2005 although not completely, likely due to post-fire hydrophobicity not represented by our model. When hydrophobicity was included in the post-fire water year 2005 the model better matched the peak flow in January but overestimated the first two small peaks in the fall. When post-fire vegetation was excluded, modeled streamflow matched the hydrograph for water years 2004–2006 but overestimated streamflow for later years. This suggests that the hydrologic signature returned to pre-fire conditions by at least 2007, and perhaps 2006.

In contrast to our findings, Cydzik and Hogue (2009) found that soil conditions and related runoff response had not recovered after three rainy seasons post-fire. They did note, however, that the curve number parameter, representing infiltration, in their hydrologic model of the Old fire had recovered by the end of year two, which may be due to recovery from hydrophobicity, although this apparent recovery did not extend to a reduction in runoff. Similarly, Kinoshita and Hogue (2011) commented that recovery rates for this fire were not sustained, and plant water consumption and flow paths were not back

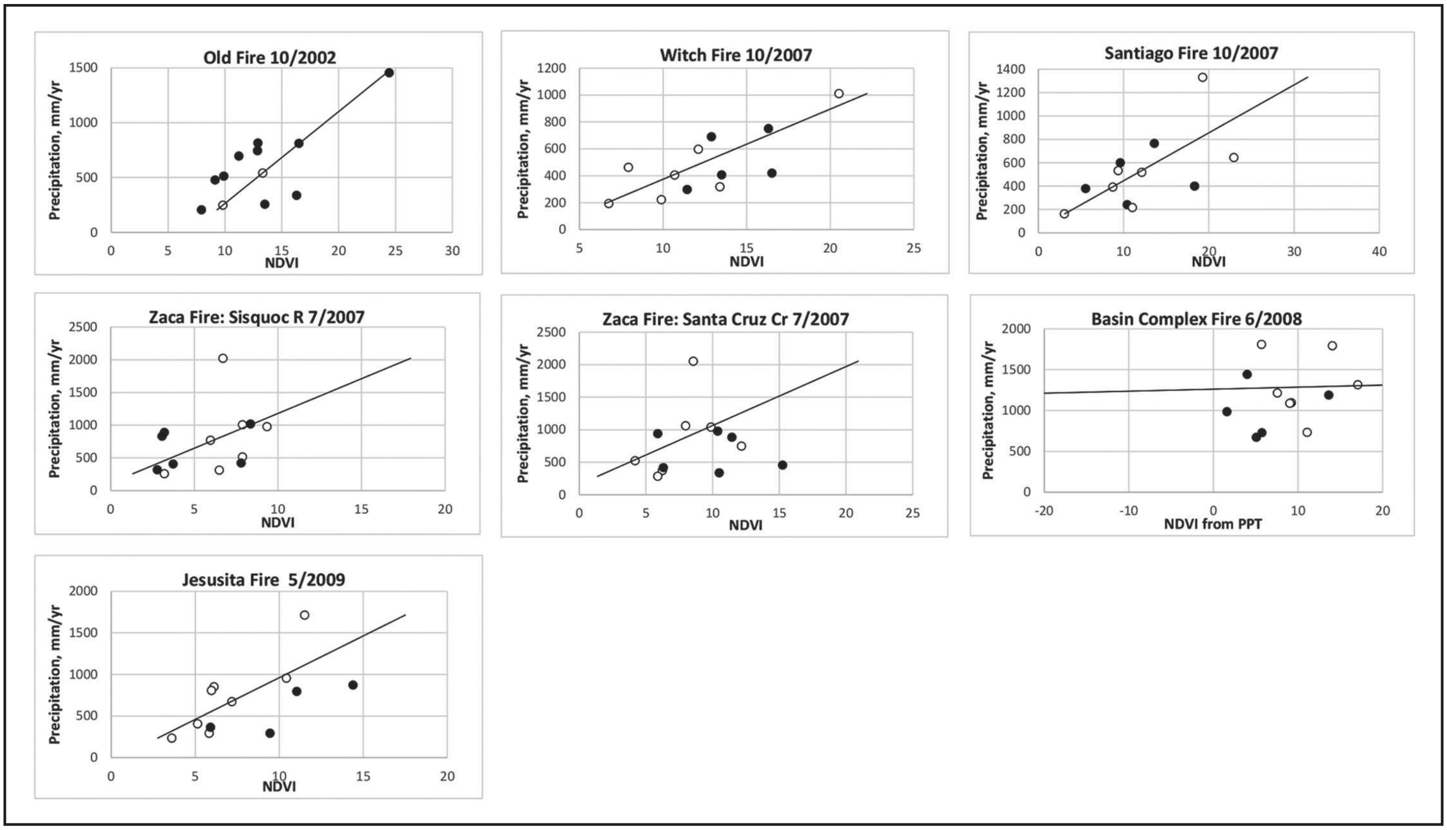

Figure 4. Normalized difference vegetation index (NDVI) vs. precipitation for seven basins indicating pre-fire conditions in blue and post-fire conditions in red (with post-fire years labeled). Black lines are the regression of pre-fire precipitation vs. NDVI.

to pre-fire behavior by the end of post-fire year seven. It is not clear in their analysis whether this is due to fire-related changes in the soils or vegetation, or is simply related to the extreme weather during this period. In contrast, our modeling suggests that post-fire weather may play a bigger role in this region than direct results of the fire after 2–3 y. The NDVI data and the streamflow data provided evidence that the hydrologic and vegetation signatures only partly describe influences from wildfire, but beyond 2–3 y in this watershed the runoff and recharge outputs more dominantly reflect climate.

Using the methods detailed for the Old fire in the East Twin Creek watershed we estimated the time for hydrologic recovery for each of the seven calibration watersheds (Table 1). As noted above, the estimated vegetation recovery time for all fires was 2 y; however, the time for hydrologic recovery until streamflow patterns reflect pre-fire levels varied, and indeed varied within different watersheds within the same fire perimeter. For example, the Zaca fire (2007) in the Sisquoc River watershed took 2 y to recover while the Santa Cruz Creek watershed following the same fire took 4 y to return to pre-fire streamflow patterns. As explained earlier, although both recharge and runoff should increase following fires due to lowered evapotranspiration, the recharge component should increase more relative to runoff, especially in dry years. There was no correlation among the other basin variables, such as soil characteristics, geology, or average annual climate or water deficit, to the evident hydrologic recovery following fire, which further supports the importance of transient weather on hydrology.

Assessing Sensitivity of Post-Fire Hydrologic Recovery to Climate and Changes in Vegetation

We explored the relative differences in runoff and recharge at the watershed scale using the Santa Clara River watershed across different years (2001–2013) and with six different levels of vegetation cover as a way to simulate vegetation recovery following fires of different fire intensities (Figure 6). For most years runoff was higher than recharge in this basin. In addition, both recharge and runoff decreased with each increasing level of vegetation cover, but recharge decreased more and at a higher rate, with the exception of water year 2005, a very wet year. The reduction in recharge with increasing vegetation cover is most notable when changing from 0% cover to 20% cover. This suggests that recharge is more sensitive to loss of vegetation than runoff, which is supported by the field data and other model results. In this example we assumed the weather and vegetation was consistent across the whole Santa Clara River watershed. However, the mechanisms are not so clear-cut when weather becomes a variable for different locations within a watershed.

To explore the sensitivity of hydrologic recovery to different amounts of vegetation regrowth post-fire when fires occurred in years with different subsequent weather,

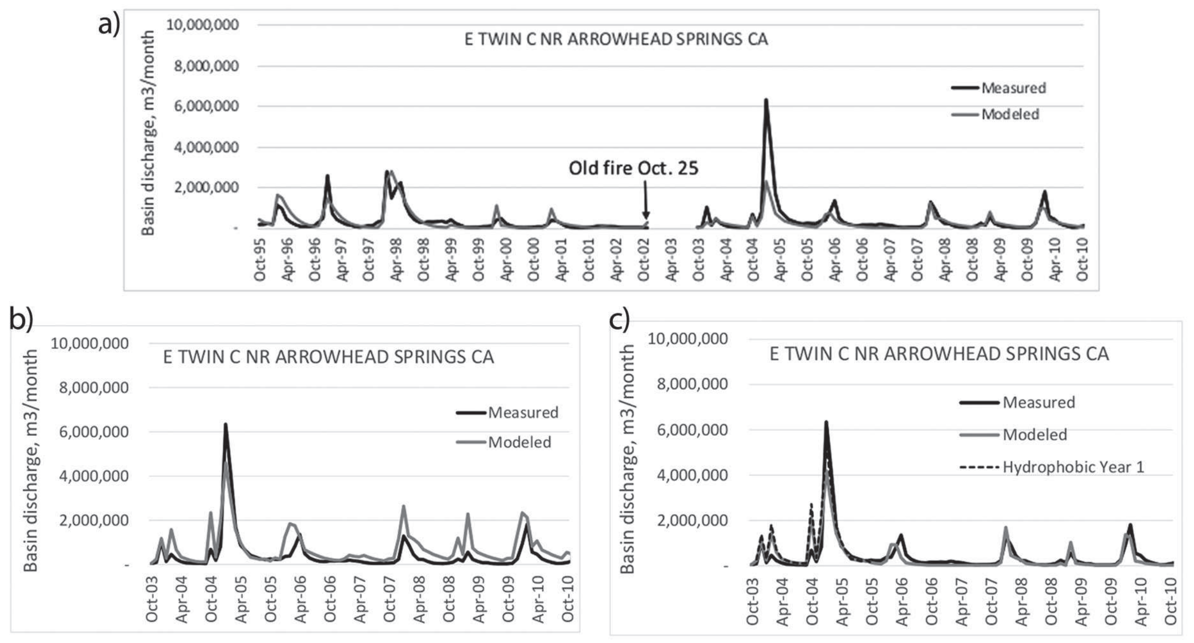

Figure 5. Measured streamflow for East Twin Creek and modeled basin discharge calibrated to pre-fire conditions and run with (a) post-fire climate, (b) post-fire climate with vegetation removed for eight years, and (c) post-fire climate with vegetation removed for the first three post-fire years.

we focused on the three recent fires in the Santa Clara River watershed. The three fires were in locations with slightly different weather and soil conditions and occurred in different years—the Copper in 2002, the Piru in 2003, and the Ranch in 2007 (Table 1). These were all very dry and warm years, but the weather in post-fire years differed from fire to fire. We compared runoff and recharge in simulations with 100% vegetation and only weather as a variable, then again assuming vegetation recovery over time (Figure 7a). Using these parameters, we can see how variable and sensitive to post-fire weather these three different fire locations are, even within a single watershed. We then examined the recharge and runoff while keeping the vegetation recovery over time consistent for all locations by assigning the post-fire water year with no vegetation, and the subsequent 5 y with 20% increases in vegetation each year (Figure 7b). If we assess changes in recharge and runoff on the basis solely of weather for 1 y pre-fire and 6 y post-fire, all three fire locations have more runoff than recharge for all but the driest years 2004 and 2009, with 2005, 2008, and 2011 the biggest precipitation years where runoff is much higher than recharge (Figure 7a). For all fires, baseline and 100% vegetation cover are the same for both (a) and (b). This is a simple sensitivity analysis, but maps of vegetation regrowth for subsequent post-fire years could be used to better reflect actual conditions. In the experiment where vegetation recovers at 20% cover per year the first two fires in 2002 and 2003 have increases in both recharge and runoff post-fire until the dry year 2007. For the Copper fire (2002) it was very dry, and there was no recharge or runoff in the baseline graph, whereas when all vegetation was removed for the fire year and the following year, recharge was much higher than runoff. It was not until the wet year 2005 that runoff was greater than recharge. This fire returned to pre-fire conditions in the dry year 2007 and the sixth year 2008. The Piru fire in 2003 had a big jump in recharge over runoff for the fire year, then 2005 arrived with more precipitation and runoff dominated, as in the Copper fire. The Ranch fire location had more baseline recharge and runoff than either of the other two locations in 2006, 2008, and 2009, so its location (even though overlapping the Piru fire) with different local soil and bedrock properties was more sensitive to weather. This location in the fire year, 2007, had a big spike of recharge with almost no runoff, then both were very high in 2008 with runoff not dominating until the wet year of 2011 with 60% vegetation cover. During the drought years of 2012 and 2013 there was little to no recharge or runoff. Again, the degree of recovery appears to have been more dependent on the weather than on the amount of evapotranspiration from vegetation.

The spatial differences between the three fire locations can be illustrated by simulating recharge and runoff with the weather of only WY2006 for baseline conditions with 100% vegetation and 20% vegetation (Figure 8). The range of properties (soil and bedrock permeability) and weather conditions across the Santa Clara River watershed was distinctly different for the three fire locations, resulting in a range of recharge and runoff during that year. Baseline conditions in this relatively warm and dry year indicate a range of recharge across the area, but not in runoff. Here the recharge is more sensitive to weather

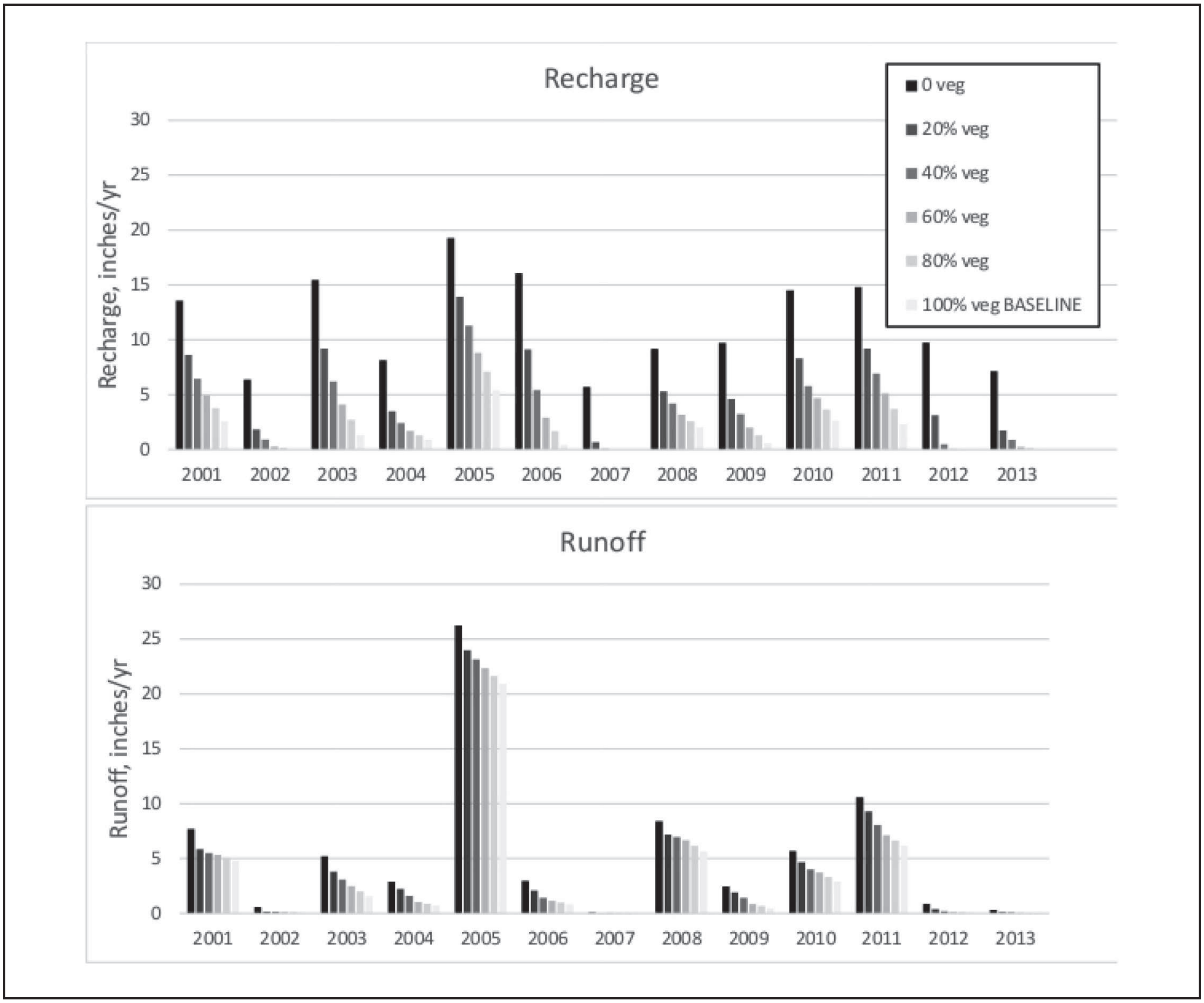

Figure 6. Sensitivity analyses for 13 y for recharge and runoff modeled with baseline vegetation conditions and five different levels of vegetation recovery for the Santa Clara River basin.

alone. The reduced vegetation simulated as a result of wildfire resulted in evenly distributed high recharge across the area and locally high runoff in some areas, indicating variable sensitivity of the influence of both wildfire and weather on runoff.

What is unknown in these comparisons using 20% estimates of vegetation recovery post-fire is whether returning vegetation has the same evapotranspiration rates and water use rates as pre-fire vegetation. Transpiration and water balance will vary, for example, if the vegetation returns post-fire as native shrubland or grassland dominated by nonnative annuals, which is increasingly occurring in high-fire-frequency areas (Syphard et al. 2018). NDVI only provides information on vegetation greenness, which can be from any vegetation types—whether with deep rooting systems or shallow ones. Post-wildfire successional or non-successional dynamics and the hydrologic implications are a set of issues that remain unresolved (Wine et al. 2018). However, our key finding is that the sensitivity of streamflow in southern California is less influenced by vegetation recovery than it is by climate.

CONCLUSIONS

The variability of weather and the flashiness of runoff in southern California watersheds provides a noisy and challenging dataset for analysis. We relied on various approaches to tease out the impacts of wildfire on hydrology in southern California national forests, including measured streamflow data and remotely sensed NDVI. We then used water balance modeling to perform sensitivity analyses to control some of the variables and develop a conceptualization of hydrological response after wildfire in the region.

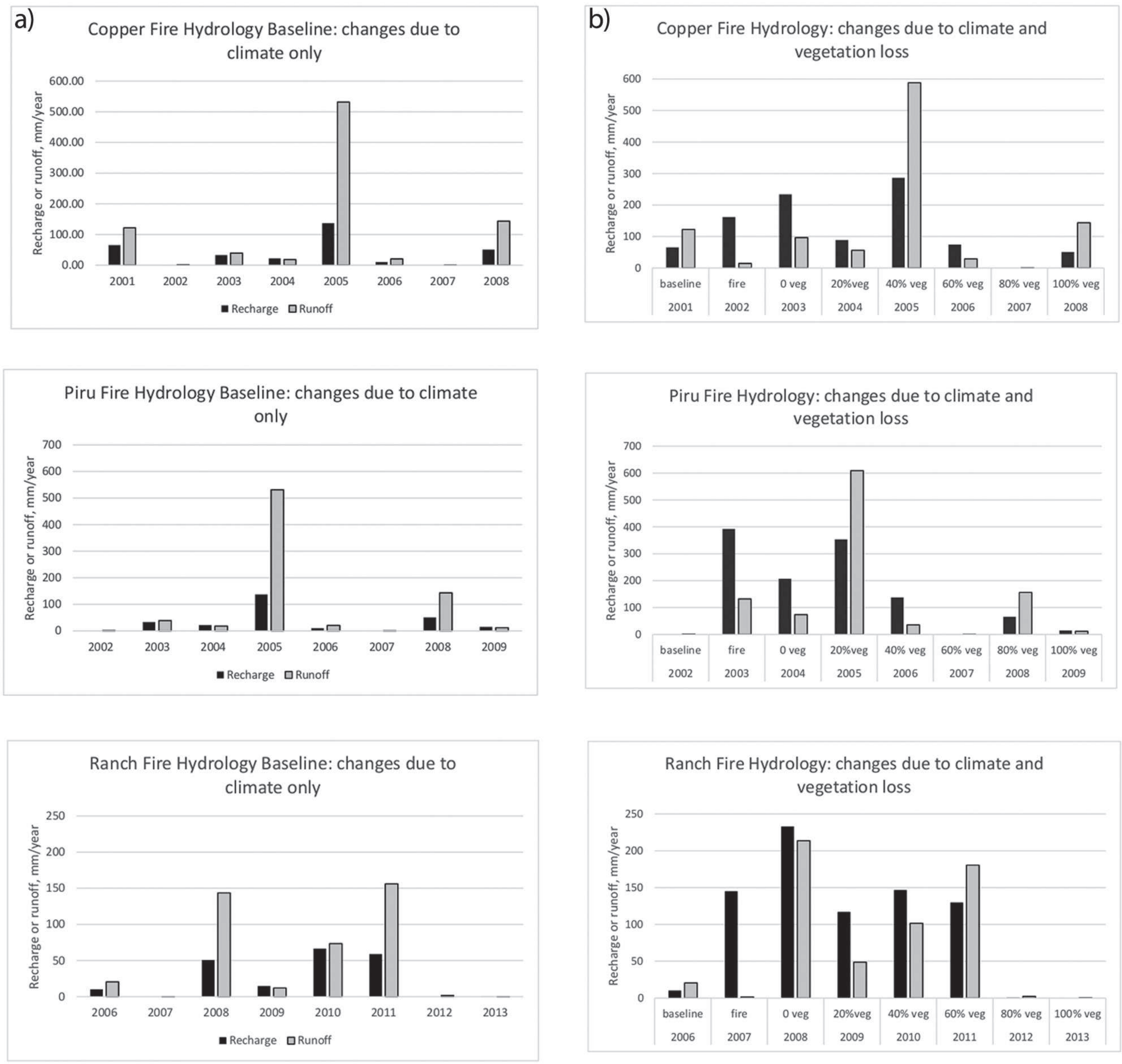

Figure 7. Recharge and runoff for three fires, water years 2002, 2003, and 2007 in the Santa Clara River basin, illustrating 1 y pre-fire and 6 y post-fire for each fire for (a) baseline climate conditions with no changes in vegetation due to fire, and (b) assuming all vegetation was removed due to the fire for the water year following the fire, 20% regrowth of vegetation in year two, 40% regrowth in year three, 60% in year four, 80% in year five, and 100% return of vegetation by year six.

Undertaking such a detailed analysis of the impacts of climate and vegetation recovery provides important insights for resource managers trying to plan and adapt to changing climates and also to the impacts of fire, which is becoming an increasingly frequent disturbance on the landscape. The key take-home messages from this study are:

- The removal of vegetation cover (and therefore ET) post-fire results in increases in recharge and runoff, with recharge increasing more than runoff with loss of vegetation, except for the very wettest years.
- Apparent (NDVI) recovery of post-fire vegetation was 2 y for all watersheds despite the weather.
- Hydrologic recovery to pre-fire streamflow patterns ranged from 2 to 4 y for the seven basins analyzed, with no characteristics looked at in this study that explained the differences in recovery rate.
- Recharge and runoff were found to be as sensitive to large variations in weather as they were to fire after 2 or 3 y post-fire.

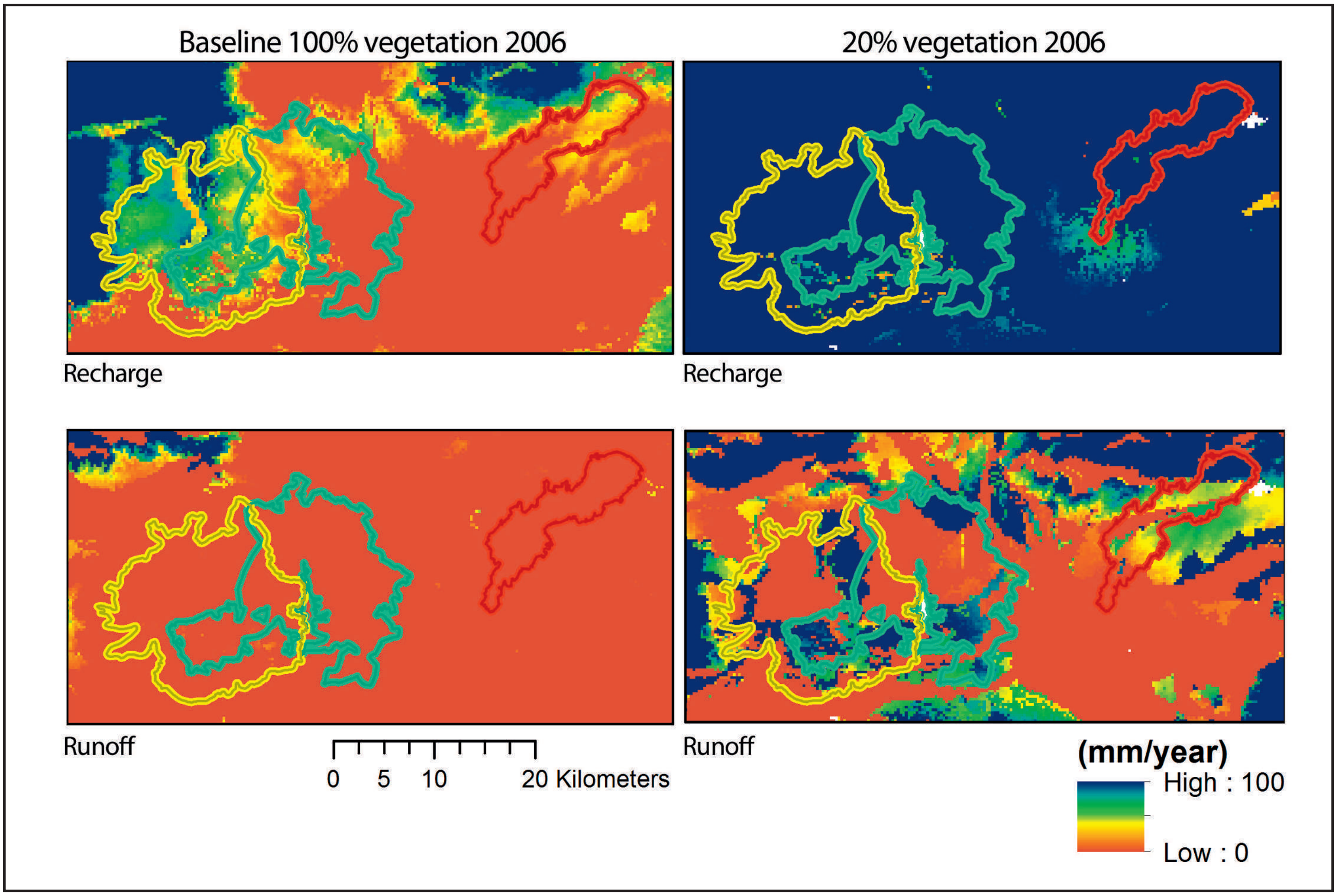

Figure 8. Recharge and runoff for three fire locations in the Santa Clara River basin for water year 2006, under baseline conditions of 100% vegetation and 20% vegetation.

- As an index of post-fire vegetation recovery, NDVI is highly dependent on annual precipitation but is unable to indicate the lifeform of recovering vegetation (e.g., whether grassland or shrubland).
- The greatest relative decrease in recharge post-fire during vegetation recovery was when vegetation cover changed from zero to 20% cover.

Returning to our three initial hypotheses, we (1) confirmed that plant ET is reduced post-fire and leads to increases in runoff and recharge; (2) determined that both runoff and recharge increase post-fire, with recharge being more sensitive to loss of vegetation than runoff, except in the wettest years; and (3) found post-fire vegetation recovers to full greenness after 2 y in all fires analyzed, in contrast to the several years that we had hypothesized, and hydrologic recovery to pre-fire streamflow patterns took from 2 to 4 y among the seven watersheds.

Uncertainties in the interpretations of results include vegetation type changes following fires and variation in impacts among variable fire intensities, including degree and duration of soil hydrophobicity.

All fires differ in conditions leading to fire, fire intensity, and post-fire weather, but model simulations reduce variables to a manageable, measurable few that can be used to more effectively predict the hydrologic impacts of wildfire. We are developing a modeling tool to allow users and natural resource managers in the region to predict their own post-fire scenarios by testing how different post-fire weather and vegetation conditions may influence hydrology in their watersheds. As watersheds respond differently to fire severity (different percentages of vegetation loss) and climate (model results across the full range of the highly variable weather experienced in 2001–2013), the tool will enable managers to evaluate different potential fire and weather combinations to predict the relative contributions of recharge and runoff to ecosystem services while taking into account spatial variation in these conditions. With better predictive tools land stewards are better able to prioritize and optimize management strategies that may serve to diminish some of the impacts of wildfire.

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