Post-fire Vegetation and Hydrologic Recovery in a Mediterranean Climate

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Abstract

Accurate field data are required to predict elevated runoff and sediment transport to aid post-fire planning. This is especially significant at the small catchment scale, where these runoff processes occur disproportionately, occurring at a higher magnitude and higher frequency. Sources of elevated runoff include soil hydrophobicity, in-channel sediment loading through dry ravel, extensive rill networks, and exposed bare soil. Recovery of these processes are related to vegetation conditions before, during, and after fire. This can be quantified using satellite-based vegetation indices to understand the recovery of the burned area and resulting hydrologic response. The main objective was to demonstrate potential for ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) evaporation measurements in post-fire hydrology by linking to hydrologic signatures (flashiness index and runoff-ratio) to highlight changes and improve vegetation assessments after fire. A case study of the 2018 Holy Fire is presented using a control catchment and a burned catchment. Results show that areas containing higher proportions of montane hardwood and montane hardwood conifers burned at high soil burn severity, a result of the normal to moderately dry period (2012-2016, 2018) that decreased annual evapotranspiration and increased water stress leading up to fire. For 1-year post-fire, ECOSTRESS measured the highest variation between burned and control during the peak dry months (3 to 4 mm/day), which explained the comparatively higher dry-season flows observed for the burned catchment. Summer field visit also showed vegetation regrowth that consisted of mostly annual grasses following a moderately wet year. Preliminary results were adequate; however, not enough time has passed for the system to fully recover, and thus, we present a Google Earth Engine application to help track recovery.

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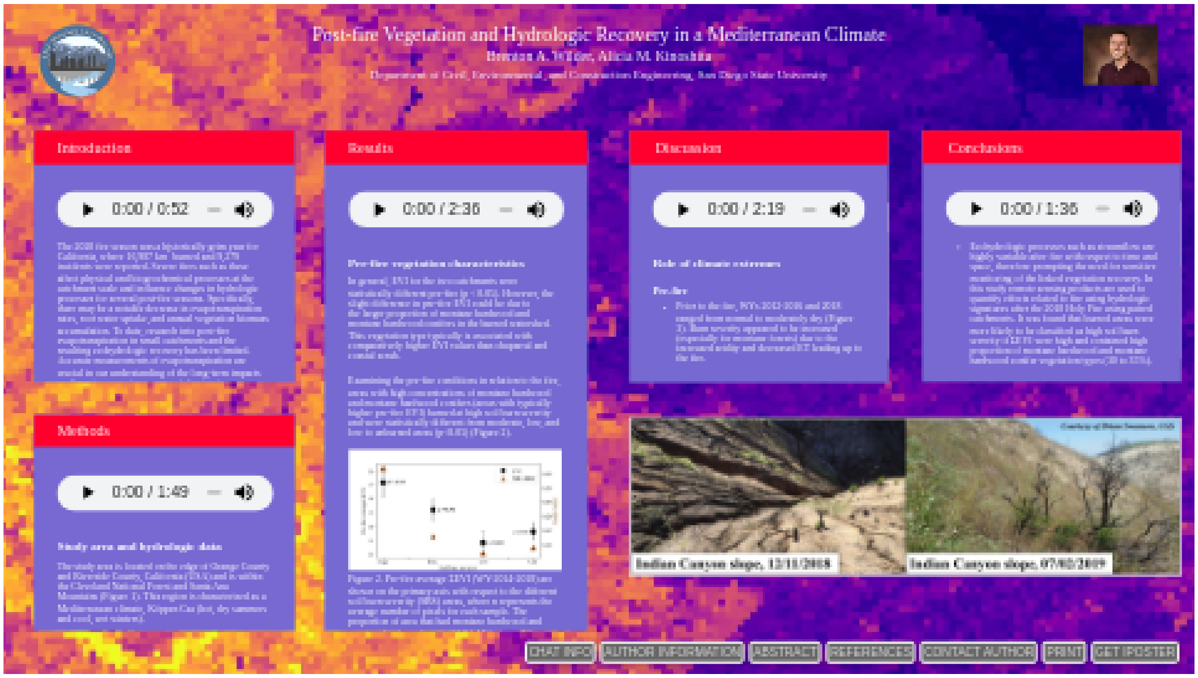

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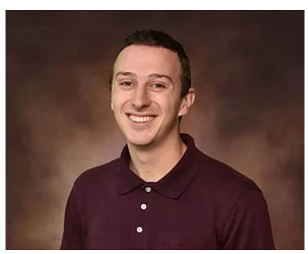


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INTRODUCTION

The 2020 fire season was a historically grim year for California, where 16,987 km^2 burned and 9,279 incidents were reported. Severe fires such as these affect physical and biogeochemical processes at the catchment scale and influence changes in hydrologic processes for several post-fire seasons. Specifically, there may be a notable decrease in evapotranspiration rates, root water uptake, and annual vegetation biomass accumulation. To date, research into post-fire evapotranspiration in small catchments and the resulting ecohydrologic recovery has been limited. Accurate measurements of evapotranspiration are crucial in our understanding of the long-term impacts on downstream water resources infrastructure, ecosystems, and communities after fire. This research builds upon previous studies by collecting evapotranspiration to assess disturbance from fire in small catchments. We used vegetation biomass indices, vegetation type, evapotranspiration, soil burn severity, and local rainfall-runoff data to quantify changes in streamflow using hydrologic signatures at the annual timescale. Thus, this work will:

1) Investigate changes in ecohydrologic processes like streamflow at the small catchment scale.

2) Improve vegetation assessments after fire.

This research is funded by Joint Fire Science Program Graduate Research Innovation Award (#19-1-01-55) and uses data from a previous study:

METHODS

Study area and hydrologic data

The study area is located on the edge of Orange County and Riverside County, California (USA) and is within the Cleveland National Forest and Santa Ana Mountains (Figure 1). This region is characterized as a Mediterranean climate, Köppen Csa (hot, dry summers and cool, wet winters).

On August 6, 2018, a human-ignited fire burned approximately 94 km^2. The soil burn severity classifications for this fire were comprised of 14.3% high, 70.7% moderate, 7.7% low, and 7.3% low to unburned.

To analyze the effects of this fire, two catchments, Santiago (control) and Coldwater (burned), were selected. Daily streamflow data for both catchments were collected from United States Geological Survey (USGS), and daily precipitation data were acquired from Orange County Public Works. Both catchments were similar in size, elevation, topography, and vegetation type, consisting of mostly chaparral, coastal scrub, and montane forest. Streamflow results were transformed to improve visualization of the baseflows of the ephemeral catchments using a Box-Cox transformation:

$$Q_T = \frac{(Q+1)^{\lambda}-1}{\lambda}$$

where $\lambda = 0.3$

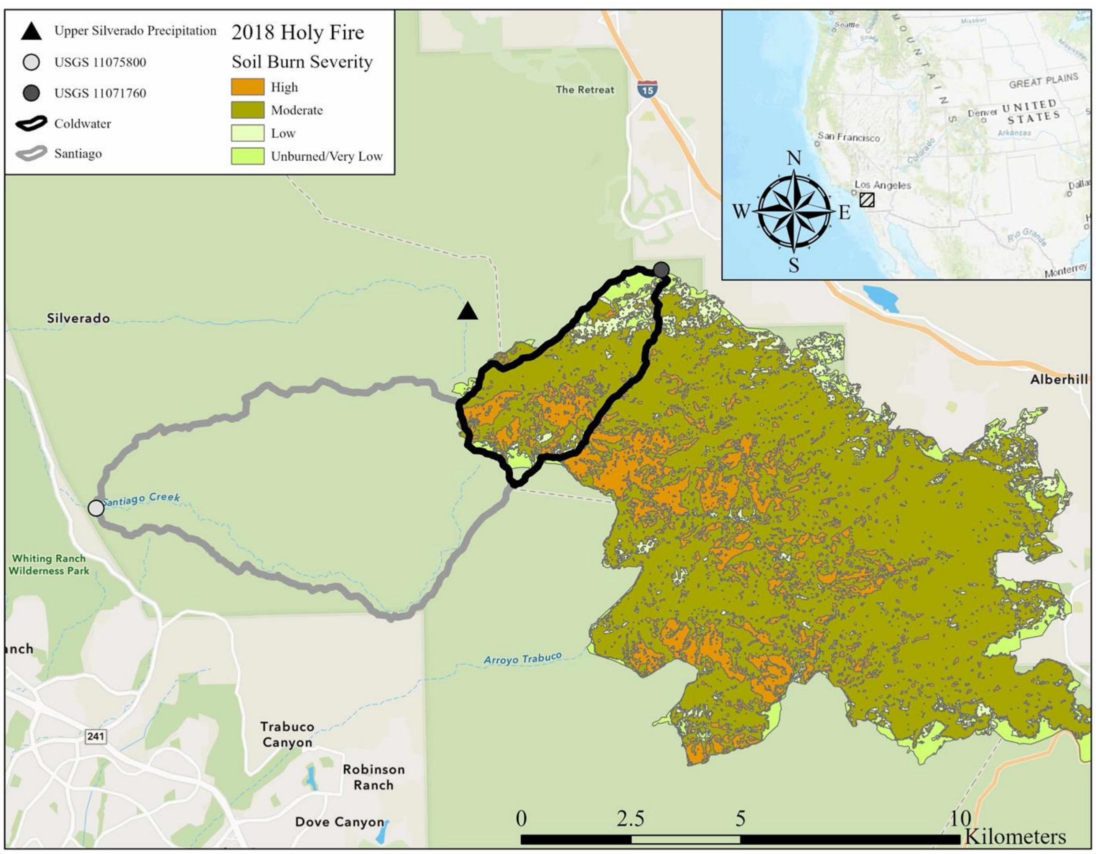


Figure 1. Location of Santiago (control) and Coldwater (burned) catchments and the 2018 Holy Fire; streamflow and precipita tion gages are denoted.

Remote sensing data and analysis

Remote Sensing data and analysis

- CAL FIRE Fveg (30-m)
- U.S. Forest Service soil burn severity (30-m)
- Landsat 8 EVI (30-m, 8 days)
- SSEBop ET (1-km, monthly)
- ECOSTRESS daily ET (70-m, 1-5 days)

Google Earth Engine (GEE) is a cloud based platform for spatial analysis. GEE was used to analyze spatial trends and create time series charts for the remote sensing data.

Standardized Precipitation Index

A standardized precipitation index (SPI) was used to note any climate anomalies or patterns in the study area for water year (WY) 1991 to 2020 using the following equation:

$$SPI_y = \frac{P_y - \bar{P}}{\bar{\sigma}}$$

where y denotes the year of interest, P_y is the

annual precipitation for a year, and P-bar and sigma-bar are the long-term average and standard deviation, respectively. SPI values greater than 2.0 were classified as extremely wet, values between 1.5 to 1.99 were classified as very wet, values between 1.0 to 1.49 were classified as moderately wet, values between -0.99 to 0.99 were classified as near normal, values between -1.0 to -1.49 were classified as moderately dry, values between -1.5 to -1.99 were classified as severely dry, and values less than -2.0 were classified as extremely dry.

Hydrologic Signatures

Hydrologic signatures at the annual timescale were calculated using the runoff-ratio (RO) and Richards-Baker (R-B) flashiness index to quantify changes in landcover and evapotranspiration after fire. The runoff-ratios were calculated for each WY using the following equation:

$$RO = \frac{Q_y}{P_y}$$

where year denotes the year of interest, P_y is the annual precipitation for a year, and Q_y is the annual streamflow for the year. The R-B indices were calculated for each WY using the following equation:

$$R - B\ \ Index = \frac{\Sigma|q_i - q_{i-1}|}{\Sigma q_i}$$

where q is the measured daily streamflow in, i.

Further, differences in evapotranspiration at the seasonal timescale were computed by using a 90-day rolling average line fitting algorithm to assess trends between the control and burned catchments using the Python package pandas.

RESULTS

Pre-fire vegetation characteristics

In general, EVI for the two catchments were statistically different pre-fire ($p < 0.05$). However, the slight difference in pre-fire EVI could be due to the larger proportion of montane hardwood and montane hardwood conifers in the burned watershed. This vegetation type typically is associated with comparatively higher EVI values than chaparral and coastal scrub.

Examining the pre-fire conditions in relation to the fire, areas with high concentrations of montane hardwood and montane hardwood conifers (areas with typically higher pre-fire EVI) burned at high soil burn severity and were statistically different from moderate, low, and low to unburned areas ($p<0.05$) (Figure 2).

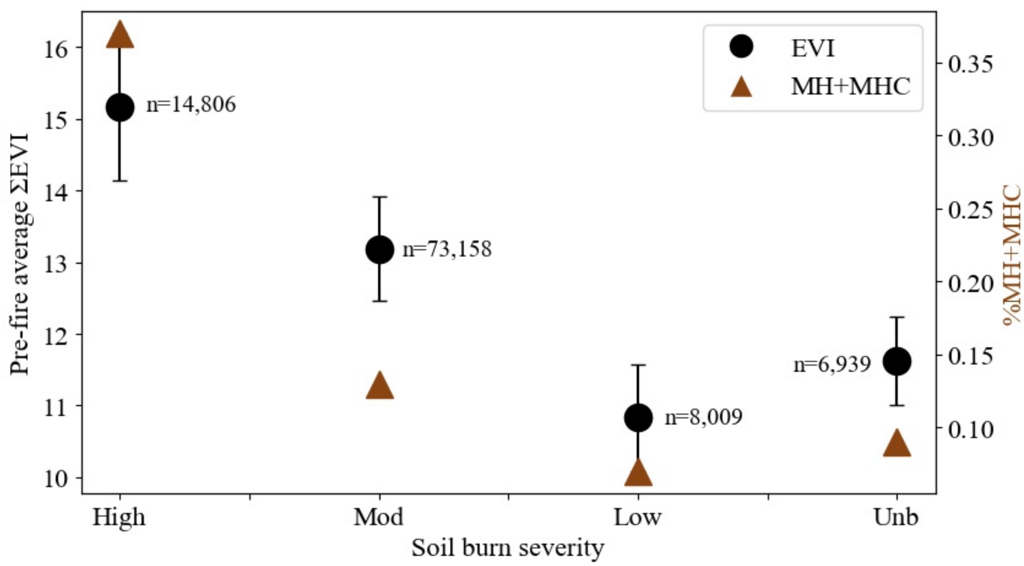


Figure 2. Pre-fire average ΣEVI (WY-2014-2018) are shown on the primary axis with respect to the different soil burn severity (SBS) areas, where n represents the average number of pixels for each sample. The proportion of area that had montane hardwood and montane hardwood conifer (MH+MHC) are shown as brown triangles

Pre-fire climate relationship

Timeseries of SSEBop evapotranspiration measurements and SPI analysis demonstrate the connection between drought variations and vegetation health for the entire area affected by the 2018 Holy Fire (Figure 3). Annual evapotranspiration for this area were found to have the three lowest values on record in the years prior to the fire, ranging from 610 to 625 mm. Other than the 2018 Holy Fire, this area experienced no other fires or land cover change during this period (1991-2018).

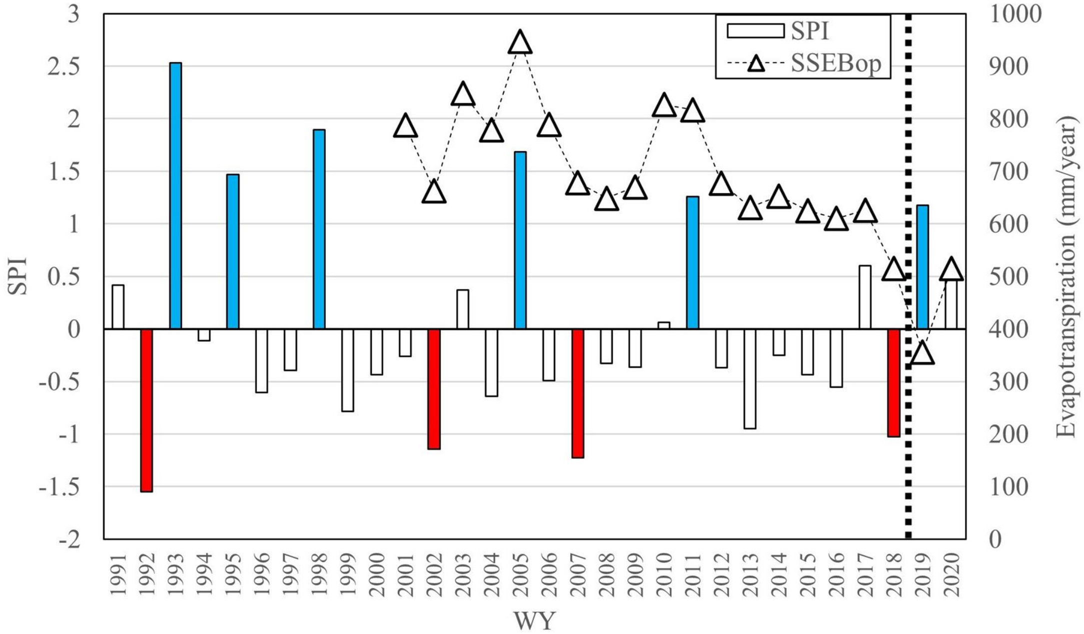


Figure 3. Standardized Precipitation Index (SPI) for Upper Silverado station (WY 1991-2020) are shown on the primary axis, where blue and red colors represent wet and dry classifications, respectively. SSEBop annual evapotranspiration measurements (WY 2001-2020) for the 2018 Holy Fire burn area are shown on the secondary axis. The dotted black line represents the 2018 Holy Fire burn occurring in August 2018 (near the end of WY 2018).

Pre-fire seasonal changes in ET

SSEBop was used to analyze wet and dry periods for the 2018 Holy Fire (Figure 4). This region typically peaked in monthly evapotranspiration between June through July, with values ranging from 74 to 151 mm/month for the pre-fire period. Most notably, one month prior to the fire in July of WY 2018, evapotranspiration had the lowest value during the pre-fire record (2001-2018) for the month of July.

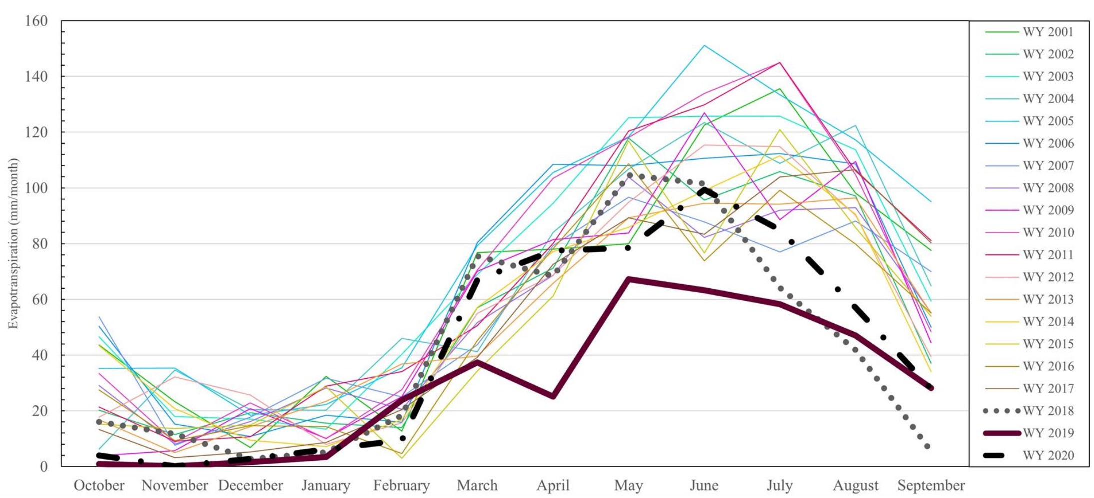


Figure 4. SSEBop monthly evapotranspiration at 1-km spatial resolution plotted for the 2018 Holy Fire burn area from WY 2001 to 2020

Post-fire hydrology

Immediately following the fire in WY 2019, a moderately wet year occurred (Figure 3). This season also included several intense storms, where 60-minute rainfall intensities ranged from 14-21 mm/hr, 30-minute rainfall intensities ranged from 18-28 mm/hr, and 15-minute rainfall intensities ranged from 23-40 mm/hr. This moderately wet year translated to large resurgence in evapotranspiration the following year during WY 2020 (Figure 4).

During the post-fire period, higher dry-season baseflows increased the runoff-ratio for the burned catchment (Figure 5; Table 1). Also, the R-B index was higher for the first year after fire, indicating more variation between daily flows or increased precipitation during that year. Also, smaller storm totals resulted in higher proportional runoff events for the burned catchment compared to the control. For example, the November 28, 2019 storm produced runoff that was larger by a factor of 12 for the burned catchment. Conversely, during a larger storm event beginning on April 6, 2020, the peak streamflow of Coldwater and Santiago were similar.

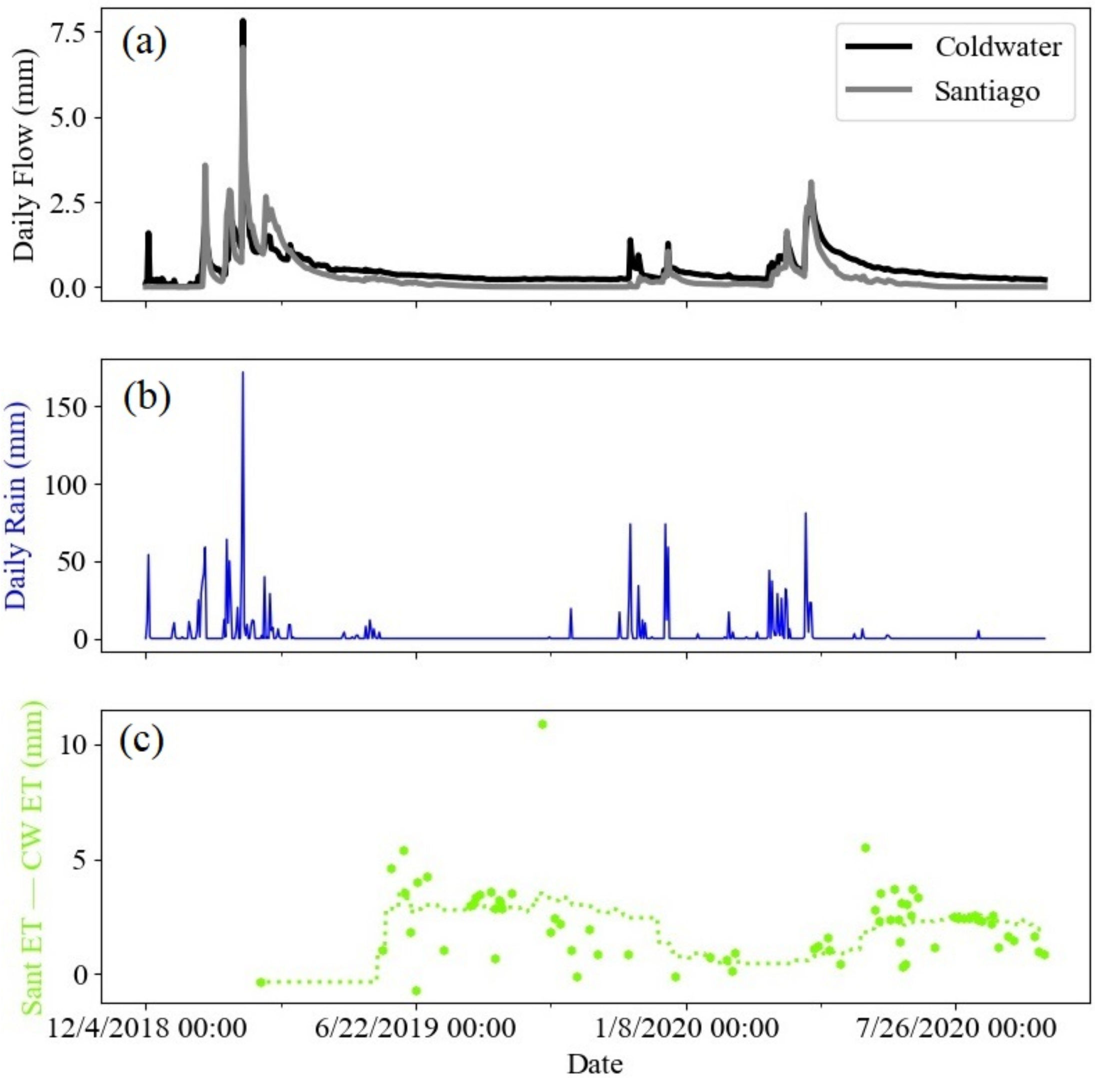


Figure 5. Coldwater (CW) and Santiago (Sant) daily streamflow (a), daily rainfall (b), and difference in daily evapotranspiration (ET) from WY2019-2020 (c). Difference in ECOSTRESS evapotranspiration is calculated as Sant ET minus CW ET. The dashed green line represents a 90-day rolling average.

Table 1. Hydrologic signatures calculated for WY 2014-2020 for Coldwater and Santiago. Rainfall-runoff data are based off daily data from OC Public Works Upper Silverado Station. EVI is shown using Landsat 8 data and ET_{Annual} is shown using SSEBop evapotranspiration data.

	Coldwater (burned)			Santiago (control)		
WY	RO (mm/mm)	R-B Index (mm/mm)	ΣEVI (ET_{Annual} in mm)**	RO (mm/mm)	R-B Index (mm/mm)	ΣEVI (ET_{Annual} in mm)
2014	N/a	N/a	12.6 (627)	0.01	0.56	12.3 (290)
2015	N/a	N/a	13.6 (635)	0.01	0.81	13.8 (319)
2016	N/a	N/a	13.9 (615)	0.03	0.54	13.8 (353)
2017	N/a	N/a	14.7 (633)	0.16	0.52	14.2 (406)
2018	N/a	N/a	11.7 (563)	0.01	0.67	12.4 (336)
2019*	0.30	1.68	7.3 (589)	0.28	0.91	14.3 (589)
2020	0.30	0.52	11.5 (607)	0.13	0.54	14.9 (504)

Rainfall runoff data for WY 2019 was incomplete due to streamgage installation on Dec 4, 2018

*****Due to the small scale, ET_{Annual} for Coldwater may present error due to sub-pixel contamination in post-fire***

Post-fire vegetation recovery

ECOSTRESS evapotranspiration varied between the two catchments depending on the season (Figure 5c). Evapotranspiration differences between the two catchments were highly sinusoidal after the fire, with the largest difference in magnitude between the dry months (July-September). This is supported by field images, which showed that the steep, decomposed granite slopes have weak vegetation recovery during the dry months (Figure 6).

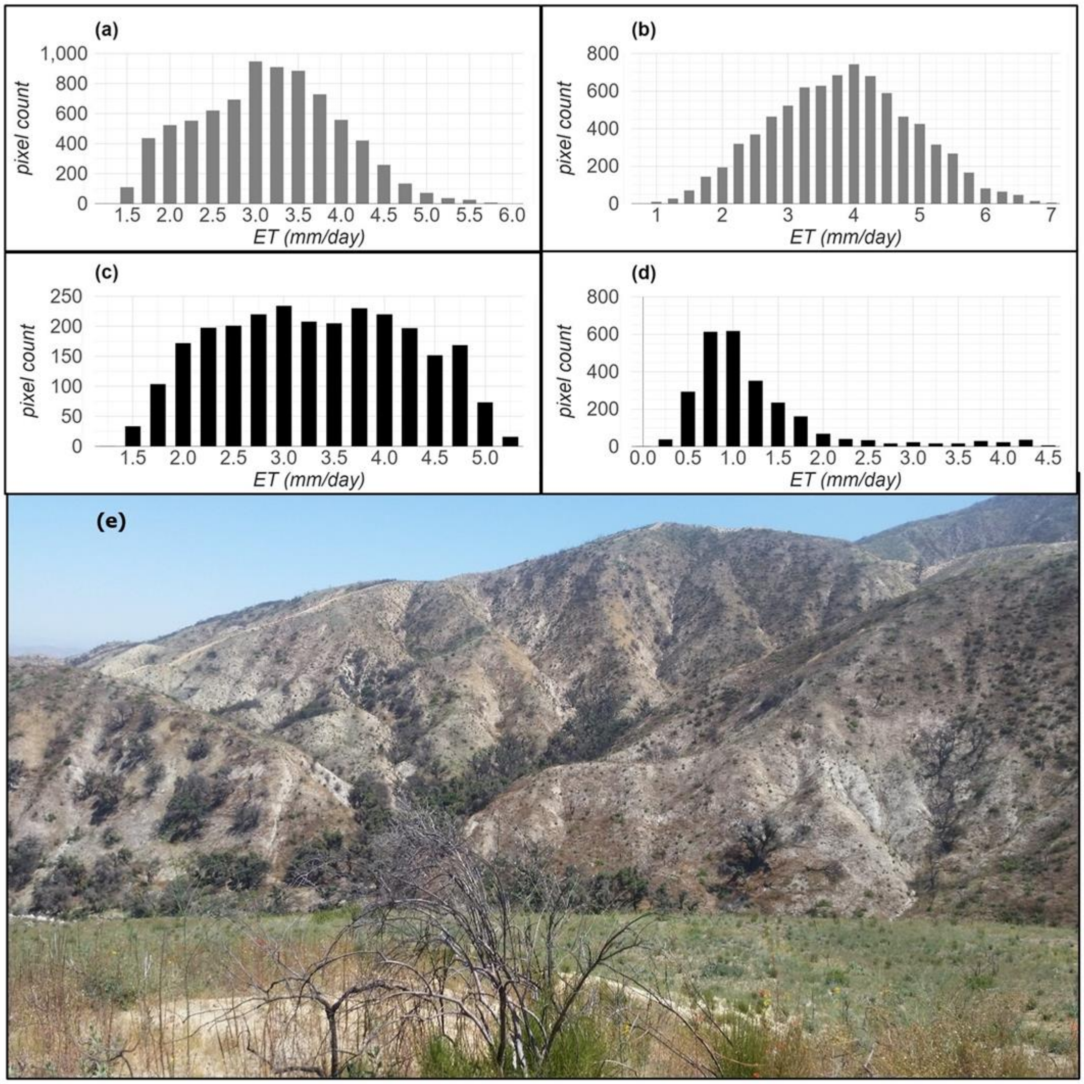


Figure 6. ECOSTRESS evapotranspiration (ET) pre-fire histograms on August 2, 2018 (a,c) and post-fire histograms on August 17, 2019 (b,d), where black represents Coldwater and grey represents Santiago. All four histograms were statistically different ($p < 0.05$). Field images taken near Coldwater Canyon in July 2019, nearly 1-year post-fire (e) courtesy of B. Swanson from California Geological Survey.

DISCUSSION

Role of climate extremes

Pre-fire

- Prior to the fire, WYs 2012-2016 and 2018 ranged from normal to moderately dry (Figure 3). Burn severity appeared to be increased (especially for montane forests) due to the increased aridity and decreased ET leading up to the fire.

- ECOSTRESS was launched in late Summer 2018, thus, we were not able to investigate water stress before the fire using this product.

Post-fire

- High intensity, short duration storms translated to larger flooding and hyperconcentrated flows in burned areas during the first post-fire wet season.

- The first post-fire year was moderately wet and included several intense rainfall storms. These extreme weather patterns will continue to become more common, as rainfall intensities are predicted to increase proportionately with global warming.

Post-fire hydrologic signatures

- R-B Index for Coldwater was higher than any value recorded by Santiago for the period WY 2014-2020. The RB-index decreased for the 2nd year after fire and returned to control levels similar to those measured at Santiago. This highlights the decrease in flashy floods for the 2nd year after fire for the burned catchment. This is similar to Guilinger et al. (2020), who documented rapid reestablishment of vegetation during the wet period of 2019. This also agrees with the SSEBop monthly ET, which showed a rapid resurgence during the following year in 2020 (Figure 4).

- RO for Coldwater were the same for both WY 2019 and 2020, highlighting the dramatic increase in dry season low flows after fire. The Coldwater and Santiago runoff-ratios appear to be similar for WY 2019, which could be due to the high amount of rainfall that was received during WY 2019, resulting in more saturation excess runoff and muting the effects from fire. In general, the increase in dry season flows highlight the decrease in deep root vegetation pathways to stop through-flow.

- Seasonal variations at the small catchment scale are well captured with ECOSTRESS dataset and can offer insight to post-fire streamflow processes (Figure 5). The largest difference in daily ET occurred during the dry periods. Santiago daily evapotranspiration were greater in magnitude by roughly 3-4 mm/day for the 1st year post-fire and 2-3 mm/day for the 2nd year post-fire. This contributes to the increased baseflow observed during the dry season flows.

The main advantage of ECOSTRESS (70-m) over SSEBop (1-km) is the increased spatial resolution. A pre-fire composite image and a 2-year post-fire composite image show differences in the upper reach hillslopes and riparian network (Figure 7).

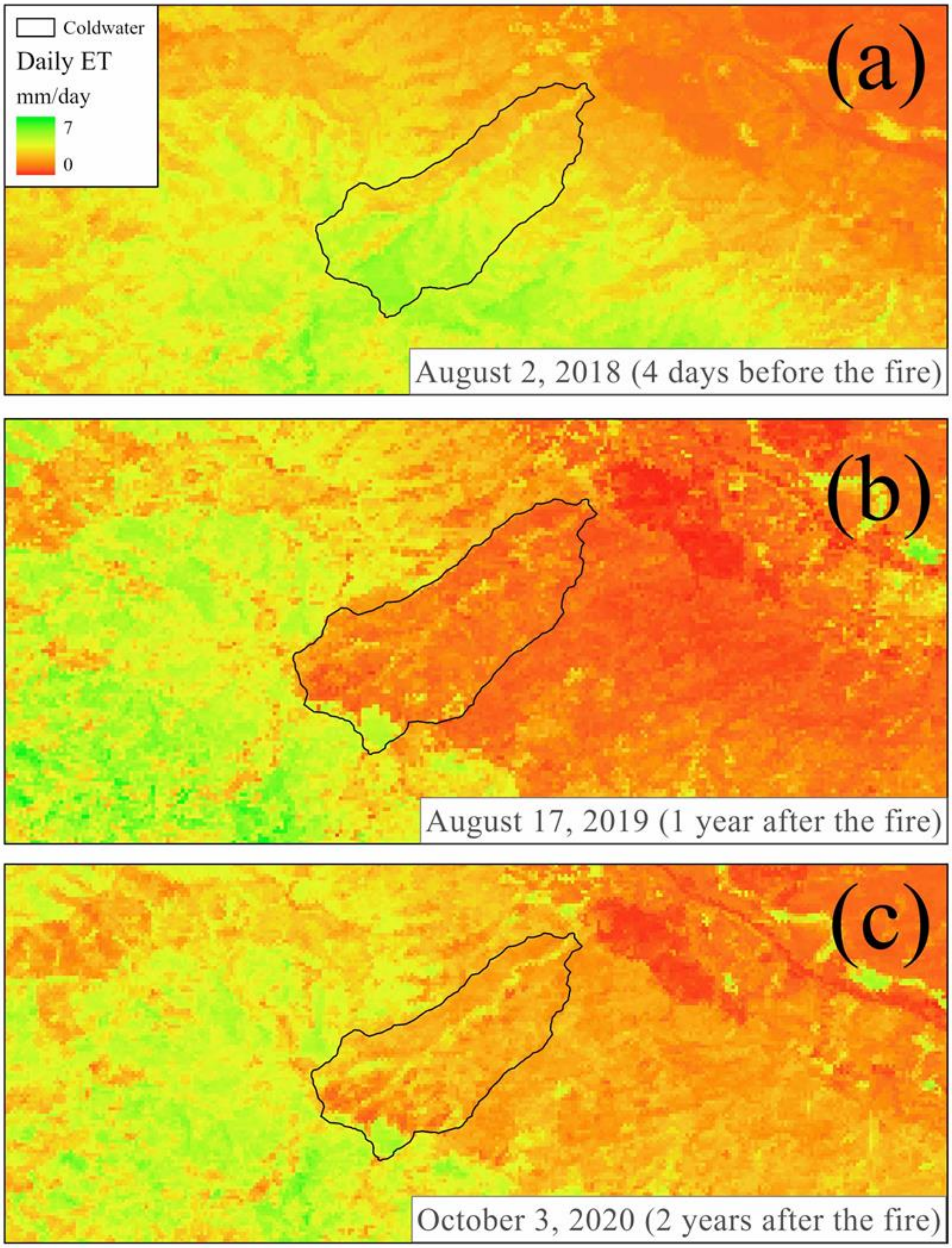


Figure 7. ECOSTRESS evapotranspiration images shown for Coldwater (burned) catchment for pre-fire (a) , 1-year post-fire (b), and 2-years post-fire (c). Composite images were created by taking the median value for each pixel for the sample period and can be found in the online application (Earth Engine (https://bwilder95.users.earthengine.app/view/holy-fire-vegetation-recovery)).

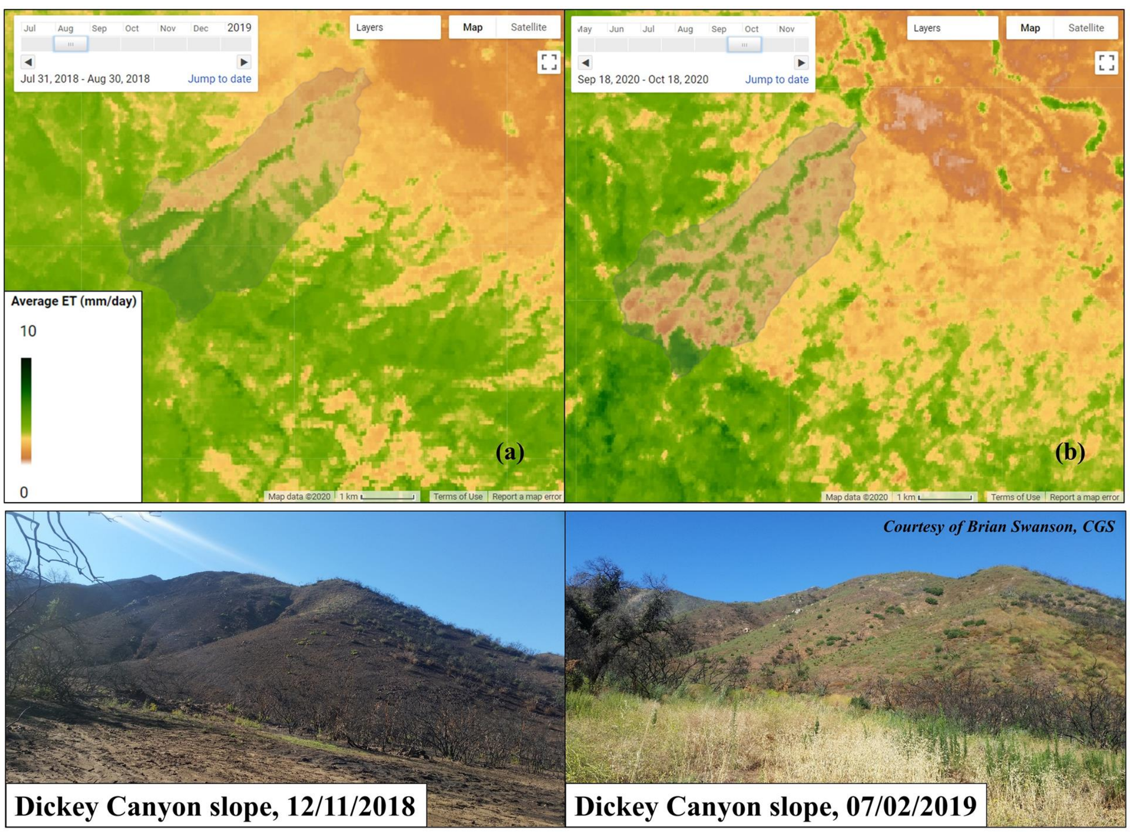
CONCLUSIONS

- Ecohydrologic processes such as streamflow are highly variable after fire with respect to time and space, therefore prompting the need for sensitive monitoring of the linked vegetation recovery. In this study remote sensing products are used to quantify effects related to fire using hydrologic signatures after the 2018 Holy Fire using paired catchments. It was found that burned areas were more likely to be classified as high soil burn severity if ΣEVI were high and contained high proportion of montane hardwood and montane hardwood conifer vegetation types (30 to 35%).

- Using SSEBop monthly evapotranspiration and SPI, we confirmed that there was high water stress in this region. Unfortunately, measurements of ECOSTRESS were not available for the pre-fire period, however, this dataset may be useful for future applications in fire management for locating specific areas that have high water stress.

- ECOSTRESS evapotranspiration measurements were in high agreement with field visits to the burned site 1-year after fire, regrowth consisted of mostly annual grasses on decomposed granite slopes.

- We conclude that ECOSTRESS daily evapotranspiration product is effective in monitoring ecohydrologic recovery for small catchments after fire; however, the question remains as to how long it will take for these hydrologic signatures to normalize, and so, we provide a simple Google Earth Engine application that will be updated regularly to help track recovery.




Indian Canyon slope, 12/11/2018

Indian Canyon slope, 07/02/2019

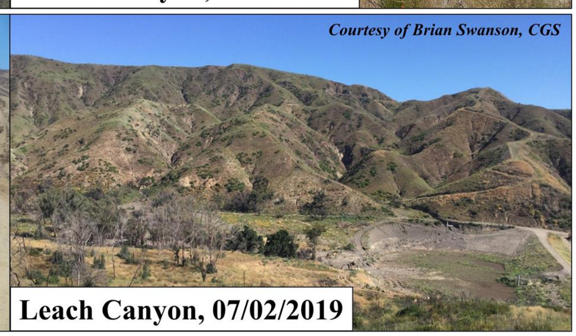

Indian Canyon, 12/11/2018

Indian Canyon, 07/02/2019

Indian Canyon, 12/11/2018


Indian Canyon, 07/02/2019


Leach Canyon, 12/11/2018



Leach Canyon, 07/02/2019

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ABSTRACT

Accurate field data are required to predict elevated runoff and sediment transport to aid post-fire planning. This is especially significant at the small catchment scale, where these runoff processes occur disproportionately, occurring at a higher magnitude and higher frequency. Sources of elevated runoff include soil hydrophobicity, in-channel sediment loading through dry ravel, extensive rill networks, and exposed bare soil. Recovery of these processes are related to vegetation conditions before, during, and after fire. This can be quantified using satellite-based vegetation indices to understand the recovery of the burned area and resulting hydrologic response. The main objective was to demonstrate potential for ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) evaporation measurements in post-fire hydrology by linking to hydrologic signatures (flashiness index and runoff-ratio) to highlight changes and improve vegetation assessments after fire. A case study of the 2018 Holy Fire is presented using a control catchment and a burned catchment. Results show that areas containing higher proportions of montane hardwood and montane hardwood conifers burned at high soil burn severity, a result of the normal to moderately dry period (2012-2016, 2018) that decreased annual evapotranspiration and increased water stress leading up to fire. For 1-year post-fire, ECOSTRESS measured the highest variation between burned and control during the peak dry months (3 to 4 mm/day), which explained the comparatively higher dry-season flows observed for the burned catchment. Summer field visit also showed vegetation regrowth that consisted of mostly annual grasses following a moderately wet year. Preliminary results were adequate; however, not enough time has passed for the system to fully recover, and thus, we present a Google Earth Engine application to help track recovery.

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