FINAL REPORT
Hydrology and Fire in the Sierra Nevada: A Possible Win-Win
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Scott Stephens
ESPM Department, UC Berkeley

John Battles
ESPM Department, UC Berkeley

Maggi Kelly
ESPM Department, UC Berkeley

Sally Thompson
Civil Engineering Department, UC Berkeley

Brandon Collins
ESPM Department, UC Berkeley
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Abstract:
The Illilouette Creek Basin (ICB) in Yosemite National Park has experienced 40 years of managed wildfire, reducing forest cover by 22%, and increasing meadow areas by 200% and shrublands by 24%. Statistical upscaling of 3300 soil moisture observations made since 2013 suggests that large increases in wetness occurred in sites where fire caused transitions from forests to dense meadows. The runoff ratio (ratio of annual runoff to precipitation) from the basin appears to be increasing or stable since 1973, compared to declines in runoff ratio for 3 nearby, unburned watersheds. Managed wildfire increased landscape heterogeneity, and likely improved forest resilience to disturbances, such as fire and drought. We conclude that there is strong evidence for a win-win concerning fire and hydrology in the Sierra Nevada with important connections to policy development in California and other western US states.

Objectives:

1. Establish a water balance under three different canopy conditions in the ICB in Yosemite National Park to better understand watershed response
2. Establish empirical evidence of possible differences in soil and stream water status as a function of post-fire vegetation type and fire history in the ICB
3. Acquire, classify and analyze remotely sensed (aerial photography) records of ICB to establish patterns and rates of vegetation change due to fire and due to post-fire succession to better understand forest resilience
4. Model ICB hydrologic response to fire using the RHESSys hydrology model to better understand the processes leading to the observed hydrology changes in the ICB

Background:

Forested mountain watersheds supply the majority of water to the western United States, and are fundamentally fire-prone ecosystems. Warming climates threaten water supply from these watersheds in several ways: snow-packs are likely to decrease and melt earlier in the year, while the forests that cover watersheds are likely to experience more frequent and severe fires which can damage infrastructure and diminish water quality. Management approaches that could simultaneously reduce fire risks while safeguarding water supplies are sorely needed. One such management approach is managed wildfire, which allows natural fires to burn without intervention, except under very specific, clearly defined conditions, such as if a fire poses a direct threat to buildings or air quality. Managed wildfire contrasts with the current approach of fire suppression, in which fires are extinguished upon detection. Fire suppression has been practiced for almost a century, and has changed forests in ways that have likely both increased fire risk and reduced water supply. This research took advantage of a unique watershed in the Sierra Nevada where fire suppression has been reversed, and managed wildfire implemented since the 1970s. This basin was studied to determine how vegetation cover, snow and soil moisture behavior, and water yields have responded to the changed fire regime.
Materials and Methods:

ICB is located within Yosemite National Park, which is situated in the central Sierra Nevada, California. The basin is over 14,000 ha with elevations ranging from 1400 to nearly 3000 m for the surrounding ridges. The climate is Mediterranean with cool, moist winters, and warm, generally dry summers. Average January minimum temperatures range from -2 to 5°C, while average July maximum temperatures range from 19 to 31°C (1992–2009, Crane Flat Remote Automated Weather Station—RAWS). Precipitation varies with elevation and is predominantly snow, with an annual average of 62 cm (1993–2008, Crane Flat RAWS).

The upper elevation mixed-conifer forests of the ICB are dominated by Jeffrey pine (Pinus jeffreyi), white fir (Abies concolor), red fir (Abies magnifica), and lodgepole pine (Pinus contorta var. murrayana), and are interspersed with meadows and shrublands. Shrublands are largely dominated by Arctostaphylos spp. and Ceanothus spp. Based on tree-ring reconstructions, the historical fire regime within Jeffrey pine-dominated stands predominantly consisted of frequent low- to moderate-severity fires. Collins and Stephens (2007) reported a mean fire interval of 6.3 years for the area and a fire rotation of 24.7 years from 1700 to 1900. The same study also found that the mean fire return interval and the fire rotation in the recent fire use period (1974–2005) did not differ noticeably from historical estimate (6.8 and 32.9 year, respectively).

Aerial photographs, taken in 1969-70, were used to produce a detailed vegetation map across the ICB. Given that these aerial photographs pre-date the implementation of the natural fire program, this map will serve as a baseline to assess fire-driven vegetation change. Previous work from the area demonstrated a long-fire free period (~100 years) prior to the 1974 because of fire exclusion (Collins and Stephens 2007), suggesting that vegetation has been relatively stable in the preceding decades. We examined vegetation composition and structure within vegetation patches, along with patch sizes and proportions of different vegetation types across the landscape.

Analysis from the aerial photographs and field reconnaissance was used to identify the extent of mesic or wetland communities in the ICB over time and which of these areas were dominated by late seral forests before fire. Field measurement of surface soil water content were done in June or July when anticipated snow melt has mostly ended and the differences between wet and dry locations will be maximized. Analysis of soil moisture content data was done to determine what, if any, ability wetland or mesic vegetation has to predict hydrologic status. Mapping results was used in a broader GIS analysis to explore the effects of topography, fire history, and topography plus fire history as controls on the occurrence of vegetation transition to wetland and mesic communities.

We proposed to measure climate and soil moisture under three contrasting conditions: conifer forest with a closed canopy (representing a control condition), burned forest that are regenerating with xeric vegetation, and burned forest stands that are regenerating with wetland vegetation. At each site we installed time-delay-reflectrometers (TDR’s) to measure the soil volumetric water content. TDR’s were installed at five depths: top 5 cm, 20-50 cm, 50-80 cm, 80-110 cm and 110-140 cm, effectively spanning the root zone. One weather station was installed for each vegetation stage (closed canopy, xeric and wetland regeneration) to monitor ambient temperature, precipitation, and humidity. We visited each site three times during each winter to sample snowpack density and estimate snow water
equivalents. We used the data obtained from these measurements to evaluate if increases in mesic areas are driven by reductions in 1) snowfall interception and sublimation or 2) rainfall interception and transpiration, at hillslope scales by computing the water balance for each site and comparing the water balance dynamics between the different vegetation-fire combinations.

To investigate if hydrological changes are from the reintroduction of a functional fire regime versus other factors (such as climate change), we examined a set of control watersheds of similar size, vegetation, and topography but with very different recent fire histories. A GIS analysis has determined that 3 such watersheds exist near the ICB. All of these sites have a long hydrological record but have experienced very little fire (almost none) compared to the ICB. A similar runoff coefficient analysis was done in these control watersheds to determine if a significant difference exists without the reintroduction of a fire regime.

Fire in the ICB during Fall 2017 posed a potential threat to our established weather stations. Ahead of the moving fire-front, the research team (with support from the National Park Service) removed above-ground components of the weather stations, and buried all electrical cabling from the below-ground measurements. The Empire Fire burned through the basin in October 2017. Reconnaissance visits to the ICB in November 2017 indicated that the equipment was unharmed, and weather stations were re-installed in their original locations to continue data collection.

Results and Discussion

(1) Establish the water balance under three different canopy conditions in the Illilouette Creek Basin

The ICB provides an example of a successful return to a natural fire regime after decades of fire suppression. This transition was achieved without significant negative effects, and has resulted in reduced fire risk, greater forest resilience to both fire and drought, greater landscape diversity in vegetation and hydrologic terms, and potentially an increase or stabilization of water yields. The resulting landscape is closer to the pre-European settlement ecosystems to which Sierra Nevada species are presumably best adapted.

Despite the reductions in snowpack accumulation in our forested site, the water inputs to the soil surface were similar there to the other sites (shrubland and wetland), indicating that warmer temperatures and melt processes, rather than differences in canopy interception and sublimation snow losses were mostly responsible for the shallower snowpack at that site.

Results suggest that significant differences in snowpack dynamics arise between sites with different canopy cover. Notably, snowpack is persistently smaller and less persistent in the forest site than in the shrub and wetland sites (Figures 1 and 2). This is associated with persistently warmer temperatures within the forested canopy. Snowpack is deepest and most persistent in the wetland site, potentially due to cold air drainage at that location. There is strong evidence that the restored fire regime is producing positive results regarding the hydrology of this ICB. We published the following paper to report these results

Boisramé, G., Thompson, S., Collins, B., & Stephens, S. 2016. Managed wildfire effects on forest

Figure 1: Snowpack observations under three contrasting forest types in the Illilouette Creek Basin, 2015-2017.

Figure 2: Estimated water delivery to the soil surface for three different vegetation types in the ICB, 2015-2017.

(2) Establish empirical evidence of differences in soil water status as a function of post-fire vegetation type and fire history in two fire suppressed watersheds
Statistical models of the ICB indicate that vegetation can provide a useful proxy for soil moisture availability, and thus potentially its changes over time, provided that topographic and fire history effects can be controlled for. Vegetation was the most important predictor of variations in surface soil moisture; and surface soil moisture was related to both plant available water, and to measures of water availability in the surface 1m of soils. Thus, topographic and vegetation spatial information provided a scaling approach to link site based observations to basin-wide soil moisture regimes (Figure 3). Such an approach is widely applicable to watersheds with variable vegetation cover observable using remote sensing.

The most dramatic fire-related VWC increases shown by statistical models were associated with locations that were forested in 1970, experienced high severity fire, and were colonized by dense meadow. According to the model, most of these areas had elevated soil moisture compared to other forested areas even before burning, and became even wetter following the vegetation shift (Fig. 10). Based on this result and observations in the field, we believe that areas that transition from forest to dense meadow (rather than to a more xeric vegetation type) following fire have local topography and geology which facilitates high soil moisture storage in these areas. Such areas may even have been wetlands in the past, but in relatively dry years during fire suppressed periods trees were able to colonize (Norman and Taylor, 2005) and the high water demand of these trees further reduced the soil moisture. Once these trees and their high transpiration demand were removed, enough water was available for the soil to come closer to saturation, making the ground less favorable to tree seedling growth and more favorable for grasses and forbs.

Managed wildfire has wrought large changes in vegetation cover and structure in the ICB, and these have numerous documented benefits to resilience and ecological health (Boisramé et al., 2017; Collins and Stephens, 2007; Ponisio et al., 2016). While we do not find evidence of large hydrologic responses to these changes, the hydrologic shifts that have occurred are likely to be broadly positive, creating ecologically and hydrologically valuable wet summer habitat. Given the uncertainties associated with the statistical modeling approach taken here, further efforts to apply process models to, and ultimately improve hydrological monitoring of, basins experiencing vegetation change through managed wildfire regimes should remain a research priority for watershed management.

A paper was published that reported our results on this part of the study

Figure 3. Differences in soil water storage between fire suppressed and fire restored ICB, for the specific date of June 2015. Significant spatial variation in the effects of fire on soil moisture were found.

(3) Acquire, classify and analyze remotely sensed (aerial photography) records of the ICB to establish patterns and rates of vegetation change due to fire and due to post-fire succession.

The alleviation of fire suppression in the ICB reintroduced an agent of change to a landscape which had been artificially protected for 100 years. Landscape metrics do not appear to have stabilized or peaked, suggesting that the landscape is still recovering from the history of fire suppression or adapting to the new climate. We might expect the landscape to ultimately come into a dynamical equilibrium set by the fire regime and local climate, in which individual points on the landscape may change but the landscape composition and patch characteristics are approximately stationary (or vary within a natural envelope). However, the ICB does not yet appear to have reached such a state and possibly it never will. While it is unclear what the end point of the managed wildfire regime is likely to be in terms of landscape composition, especially in light of climate non-stationarity, it is clear that frequent, mixed severity wildfires in the ICB reintroduced heterogeneity to the landscape and increased the amount of non-forest land cover.

Clearly, there are many potential benefits to adopting wildland fire use (Stephens et al., 2016). There are nearly 10,000 km² of wilderness area in the Sierra Nevada within the same climate zone as the ICB, where wildland fire use could likely be implemented safely and successfully (Boisramé et al., 2016). Despite the long timescales that might be required to restore forests to a new natural state, in the ICB forty years were clearly sufficient to impose changes that could increase biodiversity, reduce plant water consumption, decrease the risks of extreme fire and enhance the resilience of forests.

This paper published our findings in this area


(4) Model ICB hydrologic response to fire using the RHESSys platform

We used the RHESSys model to examine the impact of forty years of restoration of a near-natural fire regime on the water balance of the previously fire-suppressed ICB. Our first model experiment reconstructs the Basin's fire history and examines changes in the water balance over time. This experiment shows that, compared to fire-suppressed conditions, fires have generally increased annual streamflow, soil water storage, and peak snowpack, while reducing transpiration and climatic water deficit at a basin scale. These changes tend to be most extreme during high precipitation years rather than low precipitation years (Figure 4).

Many of the basin scale differences arise from spatially complex patterns of change. For example although there is minimal overall change in water storage in the basin, upper hillslopes overall seem to have dried, while lower valley areas wet up, with soil moisture differences as great as 20% VWC found in the model. While dry areas may have merely suppressed local transpiration, locally wet areas likely contribute to the modeled increases in streamflow.

A second model experiment compares a fire-altered landscape to a fire suppressed landscape over a range of weather inputs, showing that streamflow during spring snowmelt is more strongly affected by fire than summer low flows. The timing of streamflow may move earlier under the influence of fire, but under certain conditions spring snowpack depth increased (Figure 5). This modeling study indicates that restoring wildfire to a fire-suppressed landscape has the potential to increase downstream water availability, alter flow timing, and improve forest health. Results from this study are currently under review at Water Resources Research.

Figure 4: Trends in water balance components (Q – streamflow, E – evaporation, Transpiration and dS – annual change in water storage) for fire suppressed versus fire-impacted ICB obtained from RHESSys modeling. Results obtained with stationary vegetation and multiple climate years.
Figure 5: In relatively wet years (2015), fire increases the duration of snowpack and delays the timing of snowmelt in the basin. Under dry years (2011), however, snowpack melts earlier in the fire-impacted basin.

Conclusions and Implications for Management/Policy and Future Research:

This has been a very successful project. The ICB in Yosemite National Park has experienced 40 years of managed wildfire, reducing forest cover by 22%, and increasing meadow areas by 200% and shrublands by 24%. Statistical upscaling of 3300 soil moisture observations made since 2013 suggests that large increases in wetness occurred in sites where fire caused transitions from forests to dense meadows. The runoff ratio (ratio of annual runoff to precipitation) from the basin appears to be increasing or stable since 1973, compared to declines in runoff ratio for 3 nearby, unburned watersheds. Managed wildfire increased landscape heterogeneity, and likely improved forest resilience to disturbances, such as fire and drought. We conclude that there is strong evidence for a possible win-win concerning fire and hydrology in the Sierra Nevada with important connections to policy development in California.

Literature Cited:


Appendix A: Contact Information for Key Project Personnel

Scott Stephens, Professor of Fire Science, UCB, sstephens@berkeley.edu

Brandon Collins, Project Scientist UCB, bcollins@berkeley.edu

Sally Thompson, Professor of Ecohydrology, UCB, sally.thompson@berkeley.edu

John Battles, Professor of Forest Ecology, UCB, jbattles@berkeley.edu

Maggi Kelly, Professor of GIS and remote sensing, UCB, maggi@berkeley.edu

Jan van Wagendonk, Emeritus Research Scientists, USGS, jan_van_wagendonk@partner.nps.gov

Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products:

- Ten undergraduate student researchers, who were engaged in field work, data preparation and analysis, air photo classification and analysis, and hydrological modeling, supervised by postdoctoral scholars, PhD students, and professors
- One female PhD student who will finished in 2017
- One post-doc scholar from 2016-2018, left recently to take a permanent job

Stephens has presented information on this project to the California State Senate and California Assembly on 3 occasions in 2017 and 2018. In all cases policy makers were very interested in the connections of fire/forest management and mountain hydrology.

Outreach:

Research briefings presented to the California Fire Sciences Consortium: https://static1.squarespace.com/static/545a90ede4b026480c02c5c7/t/5977d9c1197aea7639a78cc7/1501026754171/Boisrame_2017_restoring_wildfire_improves_drought Resistance_Ecosystems_Final_RB.pdf

https://static1.squarespace.com/static/545a90ede4b026480c02c5c7/t/5977db95bf629a80c5628268/
Conference presentations:
Reclaiming the Sierra Conference on May, 2017
Yosemite Hydrology Forum presentation in 2015, 2016, 2017

Teaching:
UC Berkeley ESPM 181A, Fire ecology class, 2015 - present.
UC Berkeley Civil and Environmental Engineering, Graduate hydrology, 2017, 2018

Journal papers:
