Influence of Natural Fire Regime on a Watershed's Annual Flow and Flood Responses

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ABSTRACT

Fires are becoming more frequent and severe as a result of climate change and forest mismanagement. In face of the growing fire risk, one potential mitigation strategy is to restore a long-standing natural fire program or Wildland Fire Use (WFU). Although the hydrological effects of infrequent, large, severe fires have been well studied, a better understanding on the hydrologic effects of frequent, mixed severity fires is needed. This research was designed to characterize the relationship between disturbances within a WFU area and Illilouette Creek Basin's hydrological properties. I investigated the changes in annual flow and flood properties, the basin characteristics, and the relationship between the altered basin characteristics and hydrological properties Since the adoption of WFU, runoff ratio and base flow have increased by 28% and 69+%. Despite frequent disturbances from WFU, other annual flow and flood properties remained stable. Both univariate linear regression and principal component analysis indicate strong links (P-value<=0.05) between vegetation and fire variables and annual runoff ratio. The vegetation and fire variables have non-significant correlations with the variation in flood and other annual flow variables. Most of these hydrological variables are correlated with meteorological variables. The results support the hypothesis that WFU has changed UMW's runoff ratio through frequent fires and post-fire vegetation changes, but provide no evidence on whether WFU induced fires and vegetation changes has impacts on UMW's base flow, or other annual flow and flood variables.

KEYWORDS

Wildland Fire Use, streamflow, water yield, flood, Illilouette Creek Basin

INTRODUCTION

Fires are becoming more frequent and severe as a result of climate change and forest mismanagement. Increased temperature and earlier spring snowmelt have caused large forest wildfires to increase in frequency and duration in the western United States (Westerling et al. 2006). In addition, the long-term fire suppression program (FSP) over the past century and a half has exacerbated fire risks in some forest types, such as mixed conifer forests, by causing denser tree population and accumulation of significant amount of ground fuel (Parsons and DeBenedetti, 1979; Westerling et al, 2006) which catch on fire easily. As more accumulated ground fuels are burnt, the spread and temperature of the fire intensifies, causing more devastating effects on watersheds (e.g., more vegetation removal, bare soils). Changes in a watershed subsequently alter its hydrological properties, such as increasing overland flow, peak level, and total discharge (Baker Jr 1990). In the magnitude and context of large, high-severity forest fire (LHsF), these hydrological changes would bring more biotic and infrastructure damage through erosions than benefits of increasing water resources.

In face of the growing fire risk, one potential mitigation strategy is to restore a long-standing natural fire program or Wildland Fire Use (WFU). Early experimental sites that adopted WFU in the 1970s have fire characteristics that are unique from those of LHsF and prescribed fires. Illilouette Creek Basin (ICB) in Yosemite National Park and Sugarloaf Creek basin (SCB) in Sequoia & King Canyon National Park are two of few early experimental sites to adopt WFU (Wagtendonk 2007). In both sites, WFU fires were similar to historical (pre-fire suppression period) fire frequency and extent (Collins and Stephens 2007). Unlike LHsF that burn down most trees, many matured trees in both ICB and SCB that survived in the early, large WFU fires persists through current WFU fires (Collins and Stephens 2007). WFU fires in ICB also exhibited “self-limiting” characteristics, wherein a burned site in ICB has a nine year threshold against reburn (Collins et al. 2009). Thus, the perimeters of most WFU fires are constrained by boundaries of fires within the past nine years. These fire characteristics are favorable, because WFU fires behave like historical fires, are smaller and less severe than wildfires in fire-suppressed forest, and are easier to manage than prescribed fires. In addition to ecological benefits of fires (Stephens 2008), all federal land management agencies are now implementing WFU at many sites (Wagtendonk 2007).

Only 20% of California's land consists of national forests, but the national forests produce 45% of California's annual runoff (Sedell et al. 2000). Consequently, WFU in these forests may have a substantial influence on the state's water resources through several biotic and abiotic mechanisms. Based on hydrological research on LHsF and prescribed fires, WFU fires should change a watershed's biotic and abiotic characteristics, ultimately leading to changes in its hydrologic characteristics. Fires burn watershed vegetation, thus changing its hydrology through two biotic mechanisms: (1) fires decrease the canopy interception, allowing more precipitation to reach the ground (Klaassen et al. 1998); and (2) they reduce transpiration by removing vegetation, therefore less vegetation are available to absorb water during storm events (Brown et al. 2005). Fires also alter physical and chemical properties of the watershed's substrate: As ground cover, litter, duff, and debris are consumed by fire, runoff velocity increases while interception and storage decreases (Moody and Martin 2001); Fires can further alter the soil by creating a hydrophobic soil layer (DeBano. 2000), thus preventing soil from absorbing water. The primary mechanisms in which WFU may alter a watershed's hydrology is predictable based on previous studies on other fire types. However, the degree and proportion of changes among the biotic and abiotic characteristics varies, because WFU's fires, unlike prescribed fires and LHsF, constitute a regime of recurring frequent and low-moderate severity fires over time. Because of WFU's unique fire characteristics, and since old WFU sites are rare, no research has been published yet to reveal the hydrologic effects of implementing a WFU policy.

Among the old WFU experimental sites in California, ICB is the only site with long-term hydrologic records suitable for long-term hydrological study. This research was designed to characterize the relationship between disturbances within a WFU area and ICB's hydrological properties. Specifically, I investigated the changes in annual flow and flood properties by analyzing data from a USGS water gage, and NOAA weather stations. Through compiling and integrating Landsat satellite images, USDA Forest Service Region 5's forest fire records , and NOAA weather station records, I studied basin's characteristic, such as snowfall and temperature; vegetation greeness and wetness; and burn area and severity. Finally, I characterized the relationship between altered basin's characteristics and hydrological characteristics.

METHODS

Study area

The Upper Merced Watershed (UMW), with a drainage area of 181 square miles, is located within Yosemite National Park in California (Figure 1). The region has a Mediterranean climate with cool, moist winters, and warm, generally dry summers and most of its precipitation is deposited as snow between October and May (Lundquist and Loheide 2011). Vegetation in the basin varies with elevation: oak woodlands and chaparral shrublands dominate lower elevations (485 to 1,515 m); mixed conifer forests are prevalent in the mid-elevations (1,515 to 3,030 m); and subalpine forests dominate the high elevation (3,030 to 4,392 m) (Collins et al. 2007; Caprio et al. 2000; van Wagtendonk et al. 2004). Today, roughly 95% of the watershed is designated for WFU (Martin 2009).

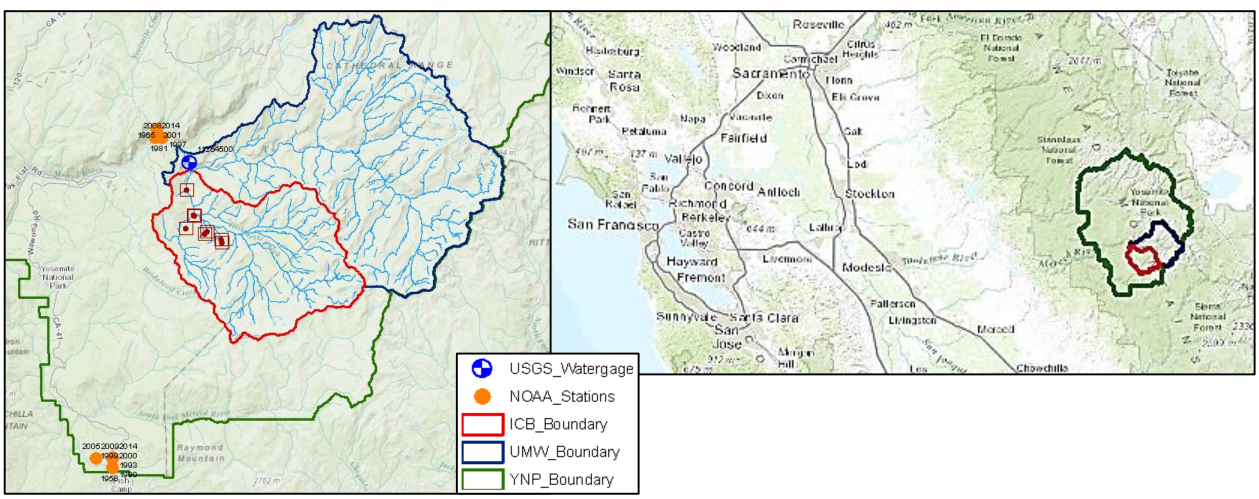


Figure 1: Study Area in Yosemite National Park. This maps shows the geographic location of the study area, weather station, and water gage.

The National Park Service experimented with WFU in ICB, a sub-basin of UMW. Since WFU began in 1973, prescribed burns have occurred 15 times, and wildland fire has occurred 59 times in UMW (CAL FIRE et al. 2014). Of those, three prescribed burns and 41 WFU have occurred in ICB and has dramatically transformed its vegetation. Although most disturbances occurred in ICB, this study focused on the UMW as a whole, because the nearest long-term hydrological gauge is located at Happy Isles in Yosemite National Park (USGS 11264500) near the drainage of UMW.

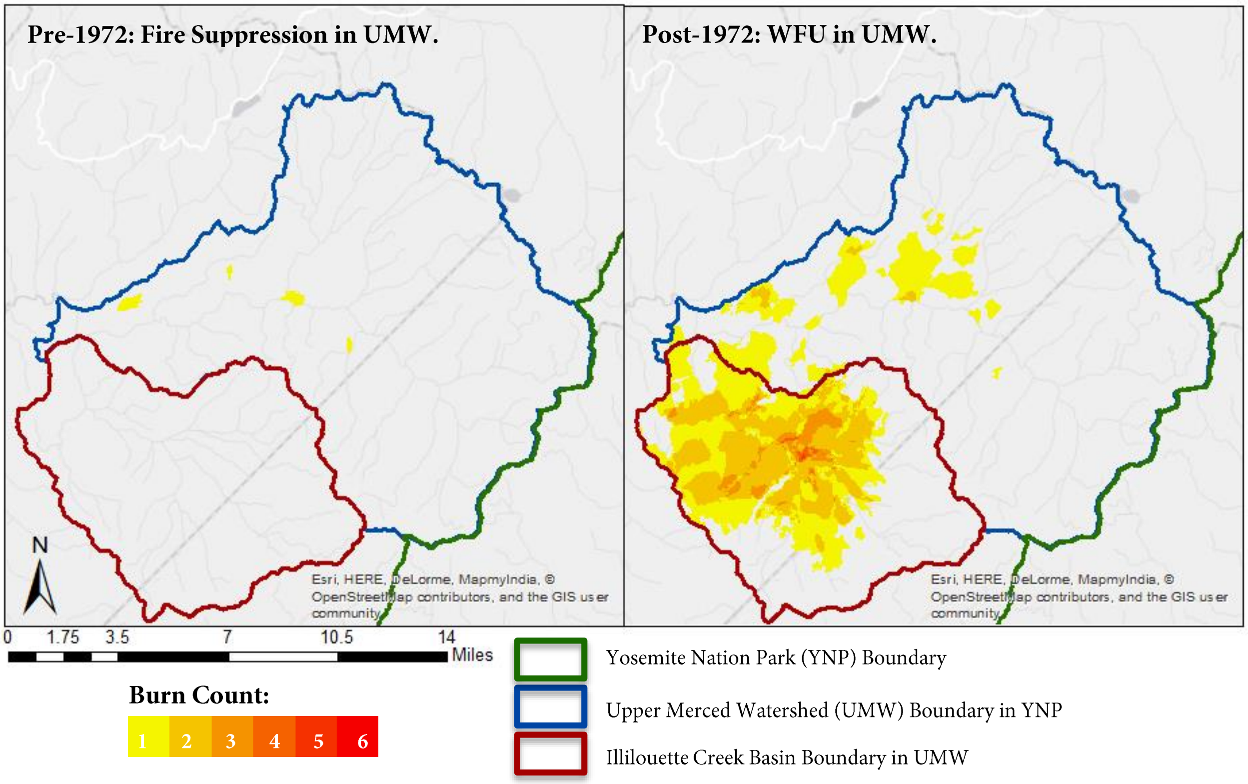


Figure 2: Fire occurrence in UMW. Since implementation of WFU in 1972, number of fire events dramatically increased. Some area in ICB burned as much as six times over the past four decades.

Data collection and processing

This research integrated four types of data, namely meteorological, remote sensing, historical fire, and hydrological. Data are all digital, and available for download online (Table 1).

Table 1: Data source.

Data Type	Dataset	Link
Meteorology	NOAA's Global Historical Climatology Network	http://www.ncdc.noaa.gov/cdo-web/search
Remote Sensing	Landsat TM Images Landsat TM Images Processed by LandTrendr	http://earthexplorer.usgs.gov/ http://landtrendr.bu.edu/?page_id=52
Historical Fire	Fire Perimeters	http://frap.cdf.ca.gov/data/frapgisdata-sw-fireperimeters_download.php
Hydrology	Daily Discharge and Water Temperature Data	http://waterdata.usgs.gov/nwis/dv?referred_module=sw&site_no=11264500

Meteorological data

I used historical climatic records from a weather station (GHCND: USC00049855) near UMW at the Headquarter of Yosemite National Park from the NOAA's Global Historical Climatology Network dataset. Although the weather station relocated slightly several times in elevation and/or coordinates, the data provide daily precipitation (mm), snowfall(mm) and maximum temperature (℃), with the earliest data dating back to January 12, 1905. I processed the data in MATLAB version 2011b (MathWorks 2011) to estimate the amount (mm) of precipitation and snowfall contributing to, and mean maximum temperature (℃) during, each flood event. To estimate rainfall from precipitation and snowfall data, I assumed the snow water equivalent of $0.1\,\frac{m^3 water}{m^3 snow}$. Finally, I summarized the data by year into annual rainfall, annual snowfall, ratio of annual rainfall to annual precipitation, average annual maximum temperature, average total rainfall during floods, average of mean maximum temperature during floods, and average total snowfall until floods since October.

Remote sensing data

Annual remote sensing data is fundamental in estimating vegetation condition and fire severity of previous years. The USGS stored the Landsat TM images at the EarthExplorer server, with the earliest images dateing back to 1984 with a spatial resolution of 30m. I used the already-processed annual tasseled-cap brightness, greenness, and wetness and NBR images (Kennedy et al. 2012) derived from the Landsat TM images for my study area. I used NBR, NDVI, Tasseled-Cap brightness, greenness, wetness and their annual differences to characterize vegetation condition. Using ArcMap version 10.2 (ESRI 2013), I calculated the annual mean of the frequency plot for each indices. The data were used later in the univariate regression model (URM) and principal component analyses (PCA).

Historical data

California's Department of Forestry and Fire Protection compiled and provided the historical fire perimeters (CAL FIRE et al. 2014). I used them to calculate the total area (m^2) of cumulative burnt, annual bunt and re-burnt forest and summarized the results by year for further analysis.

Hydrological data

I wrote multiple MATLAB scripts to calculate various flood and annual flow variables from the hydrological data. Since August 23, 1915, the USGS has recorded the daily mean discharge (CFS) at the drainage of UMW through a water gauge at Happy Isles. To measure changes in flood characteristics, I first defined the criteria for a flood event. Using the extreme value method (Gumbel 1941), I found the flow value of a 1-year flood. I defined any continuous flow above the 1-year flood flow threshold as a flood event. Then, I processed the hydrological data to measure six annual flood characteristics, namely frequency ($year^{-1}$), average total flow (m^3), average timing (days since October), average duration (days), average max magnitude (m^3/s), and average recession shape. Frequency is the number of flood events for each year. Average total flow is the average of flood events' total flow for each year. Average timing is the average of flood events' water-month for each year. Average duration (days) is the annual average of number of days that flow remains continuously above the flood threshold. Average max magnitude is the average of flood event's maximum flow for each year. Average recession shape is the average of flood event's coefficient from fitted exponential decay curve for each year. I also processed the hydrological data to measure four annual flow characteristics, namely annual runoff ratio, date of 50% annual flow (days since October), and base flow magnitudes (m^3/s) based on 30 days moving average and 7 days moving average of flow. Annual runoff ratio is calculated by dividing annual flow by annual precipitation. Date of 50% annual flow is the numbers of day it took for 50% of the annual flow to pass the water gage in each water-year. Base flow magnitudes are the minimum flow of the averaged flow data.

Statistical analyses

To test the assumptions that (a) annual flow and (b) flood characteristics have changed, and that (c) meteorological variables that contribute to flood events have not changed after 1972, I compared the pre-1972 data against post-1972 data using Box-and-Whisker Plots and calculated p-value from student t-tests.

To identify abiotic and biotic variables that have strong influences on UMW's annual flow and flood properties, I conducted linear regression to evaluate the linear relationship between each response (i.e. annual flow and flood variables) and predictors (e.g. remote sensing indices and historical fire variables). For each combination of dependent and independent variables, I determined the significance (p-value) of the model and R^2. Because some variables have a linear trend across time, I de-trended all annual variables with the linear trend and repeated the linear regression analyses.

In an attempt to create a variable that better predicts UMW's annual flow and flood properties, I selected significant predictors (both trended and de-trended p-value $\leq$ 0.05) for each response from previous linear regressions, and made new variables out the selected predictors through determining the principal components with principal component analyses (PCA). I conducted linear regressions to evaluate the linear relationship between each response (i.e. annual flow and flood variables) and new variable. For each combination of response and principal component, I determined the significance (p-value) of the model and R^2.

RESULTS

Longitudinal trends

Annual flow, flood, and meteorological variables of flood events exhibited a high level of variability. Of the three sets of variables, flood variables is the only complete set that does not show significant differences since adoption of WFU in 1972 (Table 2 - 7). Based on daily flow data since water-year 1916, the flood event threshold is 24.27 m^3/s.

Concerning annual flow variables, only the date of half annual flow does not show significant differences since adoption of WFU in 1972 (Table 2 - 3). Comparing to the mean of annual flow variables prior to 1972, both post-1972 data mean of annual runoff ratio and base flow magnitudes increased. Among all annual flow variables, Base flow magnitude, as measured by 30-day moving-window flow average, changed the most (88% increases). P-values from student's t-test rejected the null hypothesis that there is no detectable difference in annual runoff ratio and base flow magnitudes between the two periods (Table 2; Figure 3 – 4). Meanwhile, P-values from

Wilcoxon rank sum test only rejected the null hypothesis that there is no detectable difference in 7-day moving-window flow average base flow magnitude between the two periods (Table 3). Although both annual runoff ratio and 30-day moving-window flow average base flow magnitude do not meet conventional definition of non-parametric statistical significant changes (P-value $\leq$ 0.05), the P-value is small enough (P-value $\leq$ 0.1) that we should not rule out the possibility of WFU's influence over the two annual flow variables.

Table 2: Parametric Statistics Summary of annual flow variables. Degree of freedom = 96.

	Pre-1972		**Post-1972**			
Variables	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**% Difference in Mean**	**P-value**
Annual runoff ratio	7.22E-01	1.12E-01	9.22E-01	5.29E-01	27.71	6.66E-03
Date of 0.5 Annual flow	2.34E+02	1.13E+01	2.32E+02	1.35E+01	-1.01	3.47E-01
Base flow magnitude (m^3/s) (30-day moving-window flow average)	2.46E-01	1.73E-01	4.61E-01	7.45E-01	87.47	3.78E-02
Base flow magnitude (m^3/s) (7-day moving-window flow average)	1.72E-01	1.25E-01	2.91E-01	2.87E-01	68.97	6.50E-03

Table 3: Non-Parametric Statistics Summary of the annual flow variables.

	Normal Distribution (Lilliefors test)		
Variables	**Pre-1972**	**Post-1972**	**P-value (Wilcoxon rank sum test)**
Annual runoff ratio	False	True	9.19E-02
Date of 0.5 Annual flow	True	True	2.52E-01
Base flow magnitude (30-day moving-window flow average)	False	False	5.68E-02
Base flow magnitude (7-day moving-window flow average)	False	False	5.75E-03

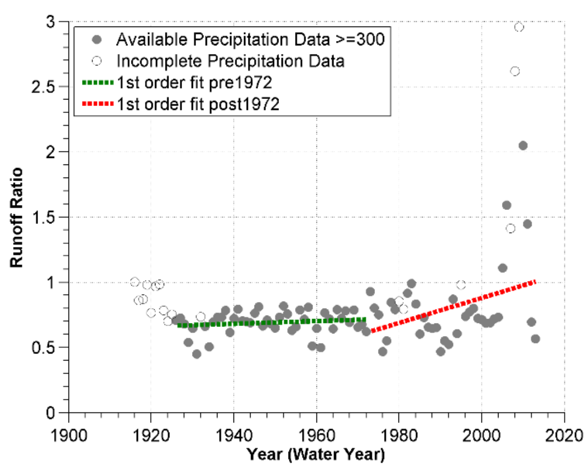


Figure 3: Time series of annual runoff ratio.

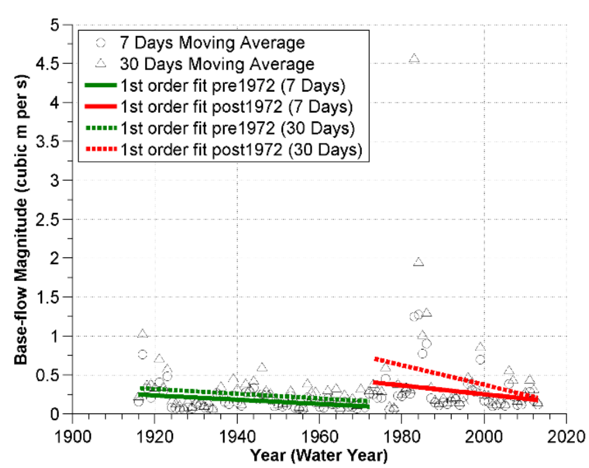


Figure 4: Time series of base flow magnitudes

Concerning flood variables, all six variables do not show significant differences since adoption of WFU in 1972 (Table 4 – 5). Among all flood variables, annual average duration of flood events changed the most (6% decreases). P-values from both student's t-test and Wilcoxon rank sum test rejected the null hypothesis that there is no detectable difference in all six flood variables between the two periods (Table 4 – 5). The P-values from both tests are large enough (P-value > 0.4) that give us confidence to rule out the possibility of WFU's influence over the flood variables.

Table 4: Summary of the year-long flood variables. Degree of freedom = 96.

	Pre-1972		**Post-1972**			
Variables	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**% Difference in Mean**	**P-value**
Frequency	3.74E+00	1.49E+00	3.88E+00	1.85E+00	3.78	6.77E-01
Average Total Flow	5.62E+07	4.44E+07	5.64E+07	4.33E+07	0.41	9.80E-01
Average Timing	7.08E+00	1.17E+00	6.90E+00	1.26E+00	-2.51	4.76E-01
Average Duration	1.47E+01	9.42E+00	1.38E+01	8.36E+00	-6.10	6.27E-01
Average Max Magnitude	4.70E+01	1.45E+01	4.82E+01	1.71E+01	2.44	7.21E-01
Average Recession Curve Coefficient	-1.79E-01	9.50E-02	-1.88E-01	1.05E-01	5.03	6.60E-01

Table 5: Non-Parametric Statistics Summary of the year-long flood variables.

	Normal Distribution (Lilliefors test)		
Variables	**Pre-1972**	**Post-1972**	**P-value (Wilcoxon rank sum test)**
Frequency	False	False	8.78E-01
Average Total Flow	False	False	9.89E-01
Average Timing	False	False	4.22E-01
Average Duration	False	False	6.50E-01
Average Max Magnitude	False	False	8.97E-01
Average Recession Curve Coefficient	False	False	7.19E-01

Concerning meteorological variables, only two of the seven variables show significant differences since adoption of WFU in 1972 (Table 6 – 7). Among all annual flow variables, ratio of annual rainfall to annual precipitation changed the most (55% decreases). P-values from both student's t-test and Wilcoxon rank sum test failed to reject the null hypothesis that there is no detectable difference in total annual snow and ratio of annual rainfall to annual precipitation between the two periods (Table 6 – 7; Figure 5 – 6).

Table 6: Summary of the year-long meteorological variables. Degree of freedom = 106.

Variables	Pre-1972 Mean	Pre-1972 Standard Deviation	Post-1972 Mean	Post-1972 Standard Deviation	% Difference in Mean	P-value
Annual Rainfall	6.79E+02	2.57E+02	7.39E+02	3.33E+02	8.97	2.88E-01
Total Annual Snow	2.11E+03	1.22E+03	9.48E+02	1.01E+03	-55.13	1.10E-06
Ratio of Annual Rainfall to Annual Precipitation	7.53E-01	1.40E-01	8.83E-01	9.94E-02	17.19	8.83E-07
Average Annual Maximum Temperature	2.02E+01	1.18E+00	2.00E+01	1.41E+00	-0.64	6.12E-01
Average Total Rainfall during Floods	2.44E+01	3.14E+01	2.08E+01	2.37E+01	-14.90	5.33E-01
Average of Mean Maximum Temperature during Floods	2.44E+01	2.56E+00	2.39E+01	3.74E+00	-1.87	4.76E-01
Average Total Snowfall until Floods since October	8.04E+02	2.42E+02	7.46E+02	3.03E+02	-7.20	2.96E-01

Table 7: Non-Parametric Statistics Summary of the year-long meteorological variables.

Variables	Normal Distribution (Lilliefors test) Pre-1972	Normal Distribution (Lilliefors test) Post-1972	P-value (Wilcoxon rank sum test)
Annual Rainfall	True	True	3.21E-01
Total Annual Snow	False	False	1.84E-07
Ratio of Annual Rainfall to Annual Precipitation	True	True	9.90E-07
Average Annual Maximum Temperature	True	True	5.51E-01
Average Total Rainfall during Floods	False	False	7.18E-01
Average of Mean Maximum Temperature during Floods	True	False	7.35E-01
Average Total Snowfall until Floods since October	True	True	3.24E-01

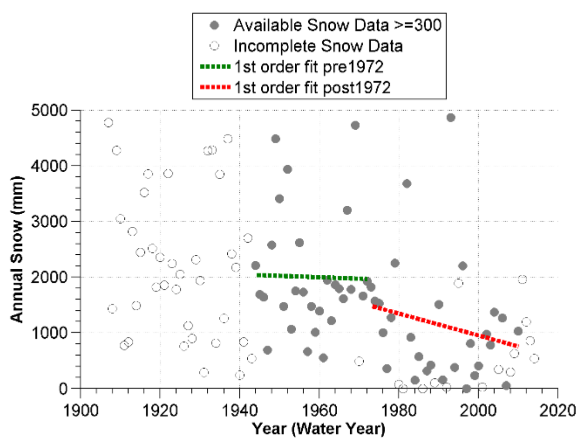


Figure 5: Time series of annual snowfall.

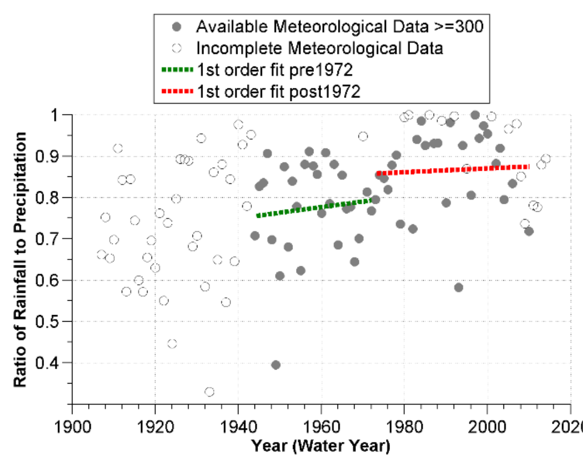


Figure 6: Time series of ratio of annual rainfall to annual precipitation

Univariate regression model

Among all possible combinations of independent and dependent variables, I found forty one combinations were significant in a univariate regression model, rejecting the null hypothesis that changing the value of independent variables have no impact on dependent variables specified in Table 8. For the linear regression combinations with p-value $\leq$ 0.05, R^2 values of ranged from 0.14 to 0.96, indicating that these independent variables predicted 14% - 96% of the variability in dependent variables when looked at individually. Of these significant combinations, only annual runoff ratio is dependent on vegetation condition and fire history variables. The independent variables of vegetation and fires predicted 16% - 47% of the variability in annual runoff ratio (Table 8; Figure 7 – 12). The remaining annual flow and flood variables are dependent on either meteriological or other hydrological variables.

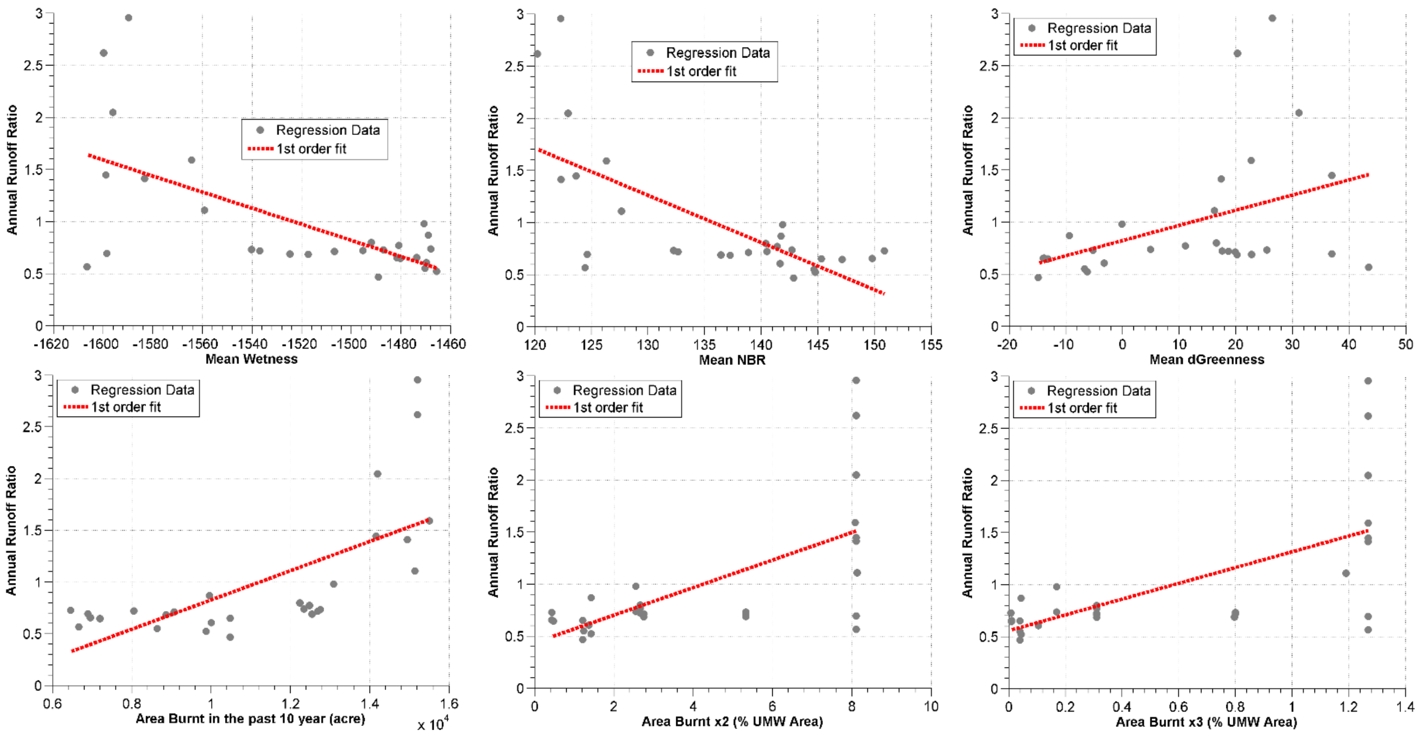


Figure 7 - 12: ULRs of Vegetation and Fire Variables and Annual Runoff Ratio.

Table 8: Individual regression models with trended and detrended p-value<=0.05. Degree of freedom = 27.

Dependent Variable	Independent Variable	Trended P-value	Trended R^2	Detrended P-value	Detrended R^2
Annual Runoff Ratio	Mean Wetness	2.93E-04	40.18%	3.56E-02	15.90%
	Mean NBR	4.90E-05	47.57%	6.21E-05	46.64%
	Mean dGreenness	3.29E-02	16.35%	2.03E-02	19.04%
	Area Burnt in the past ten year	8.28E-05	45.50%	1.95E-03	31.35%
	Area Burnt x2	2.14E-04	41.54%	9.65E-03	23.09%
	Area Burnt x3	2.08E-04	41.66%	1.25E-02	21.70%
	Area Burnt x6	4.76E-05	47.69%	6.26E-03	25.39%
Date of 0.5 Annual flow	Frequency	4.16E-02	15.01%	4.16E-02	15.02%
	Average Total Flow	9.98E-03	22.91%	8.88E-03	23.54%
	Annual Rainfall	1.88E-02	19.46%	8.20E-03	23.96%
	Average Annual Maximum Temperature	1.40E-03	32.96%	1.09E-03	34.15%
	Average of Mean Maximum Temperature during Floods	2.06E-02	18.96%	1.26E-02	21.64%
	Average Total Snowfall until Floods since October	3.29E-03	28.71%	1.14E-03	33.95%
Base flow magnitude (30-day moving-window flow average)	Base flow magnitude (7-day moving-window flow average	1.06E-19	96.00%	6.71E-20	96.14%
	Average of Mean Maximum Temperature during Floods	2.17E-02	18.66%	3.35E-02	16.23%
Base flow magnitude (7-day moving-window flow average)	Base flow magnitude (30-day moving-window flow average)	1.06E-19	96.00%	6.71E-20	96.14%
	Annual Rainfall	1.03E-02	22.76%	2.18E-02	18.64%
	Average Total Rainfall during Floods	2.26E-02	18.44%	3.71E-02	15.66%
	Average of Mean Maximum Temperature during Floods	5.83E-03	25.76%	1.15E-02	22.15%
Frequency	Date of Half Annual flow	4.16E-02	15.01%	4.16E-02	15.02%
	Average Duration	5.00E-02	13.98%	4.23E-02	14.92%
Average Total Flow	Date of Half Annual flow	9.98E-03	22.91%	8.88E-03	23.54%
	Average Duration	2.26E-16	92.79%	2.32E-16	92.78%
	Average Max Magnitude	2.53E-07	64.67%	3.74E-07	63.61%
	Average Annual Maximum Temperature	2.91E-02	17.03%	1.39E-02	21.11%
	Average Total Rainfall during Floods	3.68E-02	15.71%	1.23E-02	21.77%
	Average Total Snowfall until Floods since October	1.28E-02	21.57%	9.78E-04	34.68%
Average Timing	Average Recession Curve coefficient	3.32E-03	28.67%	8.58E-04	35.30%
	Average of Mean Maximum Temperature during Floods	1.43E-02	20.95%	2.30E-03	30.52%
Average Duration	Frequency	5.00E-02	13.98%	4.23E-02	14.92%
	Average Total Flow	2.26E-16	92.79%	2.32E-16	92.78%
	Average Max Magnitude	1.52E-06	59.56%	2.24E-06	58.36%
	Average Total Rainfall during Floods	4.65E-02	14.40%	1.16E-02	22.11%
	Average Total Snowfall until Floods since October	4.56E-02	14.50%	3.86E-03	27.90%
Average Max Magnitude	Average Total Flow	2.53E-07	64.67%	3.74E-07	63.61%
	Average Duration	1.52E-06	59.56%	2.24E-06	58.36%
	Annual Rainfall	1.82E-02	19.62%	1.51E-03	32.58%
	Average Total Rainfall during Floods	1.13E-02	22.24%	3.16E-03	28.92%
	Average Total Snowfall until Floods since October	3.83E-02	15.48%	6.73E-03	25.01%
Average Recession Curve coefficient	Average Timing	3.32E-03	28.67%	8.58E-04	35.30%
	Average of Mean Maximum Temperature during Floods	2.71E-03	29.70%	4.93E-03	26.63%

PCA and regression with principal components

Of all significant combinations of independent and dependent variables from ULRs, I divided the independent variables in three groups, namely fire and vegetation, meteriological, and hydrological variables. For variable sets of fire and vegetation, and meteriology, I found two principal components. The first principal components of the fire and vegetation variable set explained 83.05% of the inputs, while the first principal components of the meteorological variables set explained 72.71% of the inputs. The first principal components of the fire and vegetation variable set, which is most influenced by mean wetness and NBR as well as cumulative area burnt twice and trice (Table 9), also predicted 47% of the variability in annual runoff ratio (Table 11; Figures 13). Meanwhile, the first principal components of the meteorological variable set, which is most influenced by annual rainfall as well as average total snowfall until floods since October (Table 10), only predicted 0.8 to 24% of the variability in the remaining hydrological variables (Table 11).

Table 9: Principal Components of PCA1.

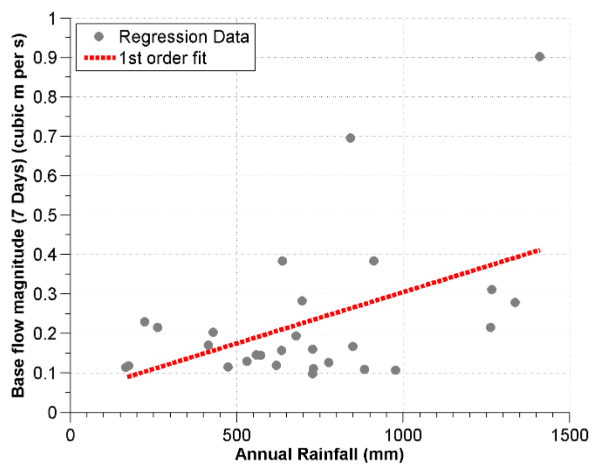
PCA 1 Variables	Coefficient 1	Coefficient 2
Mean Wetness	-0.401	0.210
Mean NBR	-0.409	-0.019
Mean dGreenness	0.356	-0.317
Area Burnt in the past 10 year	0.246	0.921
Area Burnt x2	0.413	0.010
Area Burnt x3	0.412	-0.033
Area Burnt x6	0.380	-0.072

Table 10: Principal Components of PCA2.

PCA 2 Variables	Coefficient 1	Coefficient 2
Annual Rainfall	0.489	-0.069
Average Annual Maximum Temperature	-0.357	0.751
Average Total Rainfall during Floods	0.427	0.576
Average of Mean Maximum Temperature during Floods	-0.460	-0.279
Average Total Snowfall until Floods since October	0.488	-0.148

Table 11: Linear Regression of PCAs.

		Trended	
Dependent Variable	**Independent Variable**	**P-value**	**R^2**
	PCA1Coefficient 1	5.37E-05	47.21%
Annual Runoff Ratio	PCA1 Coefficient 2	8.77E-05	45.26%
	PCA2 Coefficient 1	8.12E-03	24.02%
Date of Half Annual flow	PCA2 Coefficient 2	3.21E-03	28.84%
Base flow magnitude	PCA2 Coefficient 1	6.61E-02	12.40%
(30-day moving-window flow average)	PCA2 Coefficient 2	1.47E-01	7.91%
Base flow magnitude	PCA2 Coefficient 1	1.53E-02	20.60%
(7-day moving-window flow average)	PCA2 Coefficient 2	4.13E-02	15.06%
	PCA2 Coefficient 1	1.28E-01	8.70%
Frequency	PCA2 Coefficient 2	9.39E-02	10.42%
	PCA2 Coefficient 1	2.51E-02	17.85%
Average Total Flow	PCA2 Coefficient 2	3.25E-02	16.40%
	PCA2 Coefficient 1	2.28E-01	5.54%
Average Timing	PCA2 Coefficient 2	4.47E-01	2.24%
	PCA2 Coefficient 1	8.34E-02	11.08%
Average Duration	PCA2 Coefficient 2	1.13E-01	9.38%
	PCA2 Coefficient 1	2.17E-02	18.66%
Average Max Magnitude	PCA2 Coefficient 2	6.08E-02	12.88%
	PCA2 Coefficient 1	3.06E-01	4.02%
Average Recession Curve coefficient	PCA2 Coefficient 2	6.51E-01	0.80%



Figures 13: ULRs of annual runoff ratio and first principal components of the fire and vegetation variable set.

DISCUSSION

Since the adoption of WFU, annual flow variables, such as runoff ratio and base flow have respectively increased by 27% and 69+%. However, flood properties remained stable despite frequent disturbances from WFU. Both URM and PCA demonstrated strong relationships between vegetation and fire variables and annual runoff ratio. However, the vegetation and fire variables have non-significant correlations with the variation in flood and other annual flow variables. These results support the hypothesis that WFU has changed UMW's runoff ratio through frequent fires and post-fire vegetation changes, but provide no evidence on whether WFU induced fires and vegetation changes has impacts on UMW's base flow, or other annual flow and flood variables.

Annual flow

Although both annual runoff ratio and base flow magnitude increased substantially after 1972, their underlying mechanisms appear to be different. URM indicates that vegetation variables (i.e. Mean Wetness, NBR, and dGreeness) and fire variables have strong relationships with annual runoff ratio. Specifically, Mean NBR, a vegetation condition satellite images index commonly used in accessing fire severity, has the greatest explanatory power compared to both individual (URM) and combined (PCA) fire and vegetation variables. The importance of this variable aligns with our hypothesis that fire events reduce canopy interception of rainfall and reduces transpiration (uptake of water from the soil), increasing a watershed's flow output. Meanwhile, annual runoff ratio does not have a significant correlation with any meteorological variables. The lack of correlation also supports one of our hypotheses that we made according to previous fire studies (Stoof et al. 2012; Descheemaeker et al. 2006) - fire events, and its subsequent vegetation changes are the primary drivers in changing UMW's runoff ratio.

Alternatively, URM indicates that both vegetation and fire variables have non-significant relationships with base flow magnitudes, as derived from both the 30-day and 7-day moving-window flow average. Instead, these base flow magnitude variables are weakly related to meteorological variables. Both base flow magnitudes are related to the average of the mean maximum temperature during floods. In addition, the average total rainfall during floods and annual rainfall is related to base flow magnitude derived from the 7-day moving-window flow average. Although it is unclear as to how meteorological variables during flood events are related to annual base flow, most hydrologists agree that annual rainfall are instrumental to soil moisture, which in turn sustain base flow magnitude (Dinçer et al. 1970; Hewlett and Hibbert 1967). Despite the URM shows a relationship between rainfall and 7-day moving-window base flow, longitudinal analysis did not detect a significant increases in either rainfall or snowfall. Thus, further investigation is needed to study the factors and mechanisms contributing to the increase we observed in base flow since WFU implementation.

Unlike annual runoff ratio and the 7-day and 30-day base flow magnitudes, the date of half of the annual flow did not change significantly since WFU. URM reveals that the date is significantly related to both year-long and flood related meteorological variables. It is not clear on how the date is related to annual flood frequency and meteorological variables during flood. Meanwhile, it is commonly believed that most of UMW's precipitation were deposit as snow during winter (Kane et al. 2015, Collins and Stephens 2007). With less snowpack, the snowpack will completely melt earlier on an earlier date, decreasing the date of half annual flow. Similarly, increase in annual maximum temperature would accelerate the melting process of snowpack, which align with the URM's correlation between annual maximum temperature and the date of half annual flow. To my surprise, summary of annual rainfall to annual precipitation ratio suggests that majority of precipitation are deposit as rain. The discrepancy may be caused by effect of elevation on precipitation phase the location of weather station. Since the station locate at the valley floor, rain precipitation being measured at station could have been deposited as snow in higher elevation. If this phenomenon has significant influence over the accuracy of snowfall and rainfall estimation, then a portion of precipitation from the valley floor rainfall variable should be covert and accounted into UMW's snowfall variable. This phenomenon may also explain the URM's correlation between annual rainfall and the date of half annual flow.

Flood properties

Like the date of half annual flow, none of the annual flood properties have changed significantly since the adoption of WFU. This lack of change is unexpected because frequent fires induced by WFU should ecologically and physically change UMW, influencing UMW's flood properties. Specifically these flood properties were expected to change through decreasing the canopy interception (Klaassen et al. 1998), reducing transpiration (Brown et al. 2005), and altering physical and chemical properties of the watershed's substrate (Moody and Martin 2001; DeBano. 2000). Furthermore, none of flood properties are significantly related to vegetation or fire variables. Each property is only related to other flood properties and/or annual and flood related meteorological variables. These results suggest that either the fire and vegetation data are not adequate to show a relationship with floods or WFU has no significant impacts on UMW's flood properties. It is unlikely that the data is inadequate because vegetation and fire variables exhibit a significant relationship with annual runoff ratio but not with annual flood variables. Because both flood and meteorological variables are derived from the data summary of the same year, the relationships among them have no practical application in predicting UMW's flood events.

Limitations and future directions

This research incorporated a large and long term dataset of river, meteorological, remote sensing, and fire records. The dataset is first analyzed to detect significant hydrological change after implementation of WFU, then analyzed to characterize the relationship between vegetation and fire variables, and the hydrological change. The two steps verification approach gave us good confidence that WFU fires in UMW have strong influences over the watershed's annual runoff ratio and have limited influences over the watershed's flood properties. Nevertheless, several parts of this research method can be further improved. Some years of meteorological record are incomplete, reducing snowfall accumulation and increasing annual runoff ratio in years with incomplete data. Further, the meteorological record is collected in the Yosemite Valley and does not necessary represent the amount of precipitation, rain to snow ratio, and temperature in UMW and the weather station has also been relocated several times within the past century. Consequently, the data may not be consistent throughout the long-term dataset. In addressing the issues, the technique of double mass curve may reduce some uncertainty resulting from inconsistent and missing data. Double mass curve assumes that precipitation at the nearby locations are proportional (Searcy and Hardison 1960), thus precipitation record of one location can be calibrated with another record from nearby locations. Second, the fire and vegetation variables derived from satellite images are as accurate as the quality and comparability of images. Because my variables summarized from preprocessed images of unknown date, the images may be taken in different season and time of the day, diminishing the comparability of the images. Nevertheless, the processed images used in this research were processed by Professor Robert Kennedy with Landtrendr, an algorithim specifically designed to capture land surface change in time series of satellite images. Regarding potential inconsistency of fire and vegetation indices from satellite images, a future study should recalculate the vegetation and fire indices directly from raw and professionally selected images. With the raw images, researcher may also calculate other indices, such as NDVI and RdNBR. Finally, the mean of fire and vegetation variables, such as NBR, have been increasing since 1982. It is unclear if the increases are solely the consequences of WFU. Several approaches are possible for examining the link between WFU and changes in NBR at UMW. The most straightforward approach is to regress NBR with other fire variables used in this thesis. A common approach is to replicate this study on comparable sites that are currently managed under fire suppression and compare the results. This approach is also known as paired catchment analysis (Brown et al. 2005; Bart and Hope 2010; Ssegane et al. 2013). Another approach is to compare mean NBR in burned area with the entire UMW's mean NBR and determine if the increase of UMW's NBR is the direct consequence of WFU fires. By masking unchanged area in UMW, such as rock and bare grounds, prior to summarizing indices images into annual variables, the means of the indices may better reflect the impacts of fire disturbances.

Broader implications

In the past decade, forests and water agencies have begun to utilize GIS and satellite imagery to support watershed assessment, analysis, and management. This study demonstrated the potential in using satellite images to monitor vegetation conditions and predict the effect of vegetation conditions on hydrology. The relationships characterized in this research may be used to model watersheds based on satellite images. To better manage California forests and water resources, it is critical to understand WFU effects on watershed's hydrology, because WFU is becoming a major fire management option in unpopulated areas, and these unpopulated areas produces large portion of California's water resources (e.g. California's national forest produces 45% of its annual runoff (Sedell et al. 2000). The results of this research support the hypothesis that WFU may increase a watershed's water production relative to its rainfall. At the same time, the results suggest that WFU has little influence on a watershed's flood properties, which may be beneficial to downstream human settlements and ecology.

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