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Wildfire-streamflow interactions in a chaparral watershed

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Abstract

The 272 km^2 Malibu Creek watershed in the Santa Monica Mountains of southern California was chosen to study the impact of wildfires on streamflow. The predominant plant community in the Malibu Creek watershed is the chaparral, a fire-prone vegetation, which has experienced 10 large wildfires since 1949. Post-fire vegetation succession in the Malibu watershed indicates long-term vegetation changes that have heightened the likelihood of wildfire incidence in the last few decades. Precipitation, streamflow, and wildfire data from 1949 to 1994 were analyzed to determine the effect of vegetation burning on catchment streamflow. A paired-catchment analysis allowed the reconstruction of the expected natural streamflow in Malibu Creek in fire-impacted years. A comparison of measured and reconstructed streamflows showed annual streamflow increases up to 20–30% in fire-impacted water years relative to non-fire years. A statistically significant difference between the mean streamflow in fire and non-fire years was also established by means of the Wilcoxon test. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Streamflow; Watershed; Wildfire; Chaparral

1. Introduction

1.1. An overview of the chaparral

The chaparral (from the Spanish adjective 'chaparro', which means short) is a complex mosaic of plant species, primarily sub-shrubs and shrubs. It is a fire-prone plant community, which burns with irregular frequency. The chaparral, or chaparral-like vegetation, is one of the most diverse plant communities found in regions with Mediterranean-like climates, such as California, areas of the Mediterranean basin (e.g. 'maquis' in France), central Chile (known as 'matorral'), the Cape region of South Africa ('fynbos'), and south-western and southern Australia ('heath', Haller, 2000).

The California chaparral is widespread from south-western Oregan to north-western Baja California (Mexico). It extends from the Pacific coast, throughout interior valleys, and up the slopes of California's interior mountains to an elevation of approximately 3000 m. In this article, the generic name chaparral includes the coastal scrub plant sub-community (sometimes referred to as 'soft' chaparral) and a variety of chaparral associations identified by local habitats (e.g. chamise chaparral, ceanothus chaparral, manzanita chaparral, etc.) or by geographic regions (e.g. southern coastal chaparral, Sierra Nevada foothills chaparral, montane chaparral, etc.), which are sometimes called 'hard' chaparral (Schoenherr, 1992). Many of the coastal scrub

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plants have soft leaves (i.e. they are non-sclerophyllous), hence the alternative name of 'soft' chaparral applied to them. Typically, they are drought-deciduous, and range in height from 0.5 to 2.0 m. Their coverage ranges from sparse to complete with variable degrees of density. Common species in coastal scrub are *Baccharis pilularis* (coyote brush), *Toxicodendron diversilobum* (poison oak), *Artemisia californica* (California sagebrush), *Salvia mellifera* (black sage), *Salvia leucophylla* (purple sage), *Salvia apiana* (white sage), *Encelia californica* (bush sunflower), *Encelia farinosa* (brittlebush), *Artemisia suksdorfii* (coastal mugwort) and *Salvia munzii* (Munz's sage). Unlike coastal scrub ('soft' chaparral), the 'hard' chaparral species are predominantly hard-leafed (i.e. sclerophyllous). In addition, they are generally evergreen, exhibit complete and dense coverage, and range in height from 1.5 to 4.5 m. Important indicator species in soft chaparral are: *Adenostoma fasciculatum* (chamise); *Ceanothus* sp. (e.g. bigpod ceanothus, buck brush, blue blossom); *Arctostaphylos* sp. (e.g. bigberry manzanita, greenleaf manzanita, Eastwood manzanita); *Quercus* sp. (e.g. California scrub oak, leather oak, Tucker's oak, Muller's oak); *Heteromeles arbutifolia* (toyon); *Prunus ilicifolia* (Holly-leaved cherry); *Cercis occidentalis* (western redbud); *Fraxinus dipetala* (chaparral ash); *Malosma (Rhis) laurina* (laurel sumac); *Rhus ovata* (sugar bush) and *Adenostoma sparsifolium* (red shank). The relative frequency of specific plant species in chaparral varies noticeably from northern California (lower temperatures and larger rainfall) to southern California (which exhibits higher temperatures and lower rainfall), as well as with elevation — from sea level to the top of California's interior ranges. Locally, chaparral species distribution is influenced by such factors as soil and slope aspect. The geographic distribution, appearance, phenology (i.e. changes in seasonal plant growth and activity), and successional status of chaparral as well as its interaction with other plant communities have been widely studied (Axelrod, 1978; Kirkpatrick and Hutchinson, 1980; Keeley, 1989; Schoenherr, 1992; DeSimone, 1995; Sawyer and Keeler-Wolf, 1995).

Wildfire, which under natural conditions is ignited primarily by lightning, is an essential element in the chaparral life cycle, as it removes aging biomass and fosters rapid new growth and vitality in the fire-adapted vegetation (Keeley, 1989; Stassforth, 1991; Thanos and Rundel, 1995). Following burning, dominant shrubs regenerate from seeds or by sprouting from root crowns (burls). Chamise and other species have seeds that require fire to break dormancy and start germination. The re-sprouting shoots of chamise, a dominant species in chaparral, can grow 50 cm or more during the year following wildfire (Plumb, 1961; Stassforth, 1991; Schoenherr, 1992). The typical post-fire cycle in chaparral includes successive domination by annual herbs, perennial herbs, sub-shrubs, coastal-scrub species, short-lived chaparral species, and long-lived chaparral species. Full regeneration may require 20 years or longer.

Insofar as chaparral phenology is concerned, active growth begins in the spring and continues into early summer. Transpiration is highest during this high-growth season. Growth, and transpiration, slows downs as California's dry weather settles in during the summer and continues at a low rate into the fall (Hanes, 1977; Keeley and Keely, 1988). Plants at higher, colder, elevations may be essentially dormant in the winter. Most chaparral species flower during late winter and late spring. Most chaparral wildfires occur between July and December, when vegetation dryness is most pronounced. During low-precipitation years, wildfires may occur year-round.

1.2. Related literature on chaparral wildfires and hydrology

There is a large body of literature on forest fires and associated environmental impacts (Albini, 1978; Biswell, 1989; Keeley, 1989; Goldammer and Jenkins, 1990; Crutzen and Goldammer, 1990; Keeley and Scott, 1995; Simon, 1996; DeBano and Neary, 1998). The scholarly literature dealing with the effects of vegetation burning on watershed-scale streamflow in chaparral ecosystems is, in comparison, relatively sparse. Many related studies deal with (controlled) silvicultural practices which lead to vegetation conversion and subsequent modification of hydrologic processes (Hirata, 1929; Hoover, 1944; Maruyama and Inose, 1956; Katsumi, 1956; Rowe and Reimann, 1961; Penman, 1963; Lewis, 1968; Hibbert, 1971; Anderson et al., 1976; Bosch and Hewlett, 1982), rather than with the effect of chaparral burning and subsequent streamflow variation at the watershed scale. Other studies have dealt with wildfire impacts on hydrologic processes and water quality in non-chaparral environments (Bates and Henry, 1928; Brown, 1972; Helvey, 1972; Tiedemann, 1979; Scott, 1993; Lavabre et al., 1993; Townsend and Douglas, 2000), or addressed primarily post-wildfire geomorphic processes rather than the streamflow regime per se (Swanson, 1981; Wells, 1987).

Several authors have studied erosion and fluvial transport immediately after chaparral wildfires (Laird and Harvey, 1986; Florsheim et al., 1991; Keller et al., 1997). DeBano et al. (1979) addressed the problem of soil heating during chaparral wildfires and its effects on soil, plant, nutrients and runoff. Menke et al. (1984) examined water quality issues related to chaparral management. Hoyt and Troxel (1934) analyzed the effect of a wildfire that occurred in September 1924, in the Fish Creek watershed (17 km^2) of the San Gabriel mountains, southern California. Using pre-fire (1917–1924) and post-fire (1925–1930) rainfall and runoff data, Hoyt and Troxel (1934) demonstrated, by means of a paired-catchment comparison with the adjacent (non-burned) Santa Anita basin (26.8 km^2), that streamflow augmentation by vegetation burning vanished three years after the wildfire. Vegetation in the Fish Creek basin, which originates above 1200 m of elevation, was primarily upper chaparral plants such as western mahogany *(Cercocarpus betuloides),* sagebrush scrub *(Artemisia tridentata),* grasses, and yuccas *(Yucca bacata* and *Yucca schidigera).* Hoyt and Troxel (1934) indicated that the short vegetative cover that re-colonized the previously forested area became rapidly effective in restoring transpiration to pre-fire levels. In a comprehensive study of prescribed burning in California wildlands, Biswell (1989) reports empirical evidence on the effect that vegetation burning has on spring flow. Biswell (1989) describes several short-term studies in small catchments of California's Sierra Nevada foothills that were conducted nearly five decades ago. He noted, for example, that the replacement of deep-rooted chaparral and oak woodlands species with shallow-rooted grasses increased spring flow at Tank Spring and baseflow contribution to streamflow in Finegold Creek, California, within days after vegetation burning.

1.3. Study objective

Controlled, long-term studies of wildfire impacts on watershed-scale streamflow in chaparral watersheds are difficult to carry out. This is partly due to the inherent obstacles raised by prescribed burns and the unavoidable threats to property and the environment which arise during shrubland burning (Biswell, 1989). Therefore, one must resort to long-term data, which have been collected in association with natural and accidental wildfires in order to study their potential impact on watershed streamflow. This study examines the effect of wildfires on annual streamflow variation in the Malibu Creek watershed of the Santa Monica Mountains, California, a prototypical example of a chaparral watershed. Our analysis of wildfire-streamflow interactions is based on a long-term (i.e. 1949–1994) wildfire, land-cover, precipitation and streamflow database for the Malibu Creek watershed. In addition, precipitation and streamflow data for the Upper Santa Ynez River watershed, Santa Barbara County, California were used in this study to reconstruct natural streamflows in the Malibu watershed during fire-impacted years. The long-term Malibu Creek and Upper Santa Ynez databases provide unique opportunities to study the long-term interaction between wildfires and annual streamflow in chaparral watersheds.

2. The study watersheds

2.1. Malibu Creek

The 27 221 ha (1 ha = 1 hectare = 100 000 m^2) Malibu Creek watershed, located within the Santa Monica Mountains (Fig. 1) was selected to evaluate wildfire incidence and associated variation in watershed-scale streamflow. The Malibu Creek watershed is almost entirely covered by chaparral. Radtke et al. (1981) noted that the Santa Monica Mountains in general, and the Malibu Creek watershed in particular, exhibit diverse ecosystems due to the interaction of such factors as a Mediterranean climate, rugged topography, gusty and warm (Santa Ana) winds, and varied soils that support a rich mosaic of plant communities throughout their mountain ranges. The Malibu Creek watershed features rugged topography, with elevations ranging from sea level to 800 m, and has a semi-arid Mediterranean climate typical of coastal southern California. Mean annual rainfall and streamflow are 51 cm and 28.3×10^6 m^3 (10.4 cm), respectively (Los Angeles County Public Works Department, 1997). Precipitation falls almost entirely between November and April. The most intense storms, which account for most of the watershed runoff, occur between mid-January and mid-March, the peak period of the rainy season. These storms are of a cyclonic type and occur along cold fronts moving landwards from the Pacific Ocean. Their durations range typically from 2 to 24 h. Storm intensities are highly irregular throughout the duration of the storms. Some of the largest storm intensities in the study watersheds have been recorded during strong El Niño years. A compilation of storm intensity-duration-frequency for the study areas (and elsewhere in California) can be found in Goodridge, (1999). Winter and spring streamflow in Malibu Creek is supplied mostly by runoff generated from seasonal precipitation. Summer and autumnal streamflow is derived from baseflow. Bedrock in the basin is predominantly sandstones and shales with various degrees of primary and secondary porosity. Isolated limestone and extrusive igneous rocks are also found in the Malibu Creek watershed (Norris and Webb, 1976). From field inspection, the predominant soils in the study area can be classified as entisols, which originate from weathering of the underlying bedrock, and exhibit a thin organic horizon (less than 5 cm, typically). These soils vary from a few centimeters to 1 m in thickness, have a coarse granular structure, and are relatively permeable.

Wildfires are common in the Malibu Creek watershed, and their occurrence has been exacerbated by humans. This is believed to be an important factor behind the change in vegetative cover observed in the Malibu Creek watershed over the last few decades. Fig.

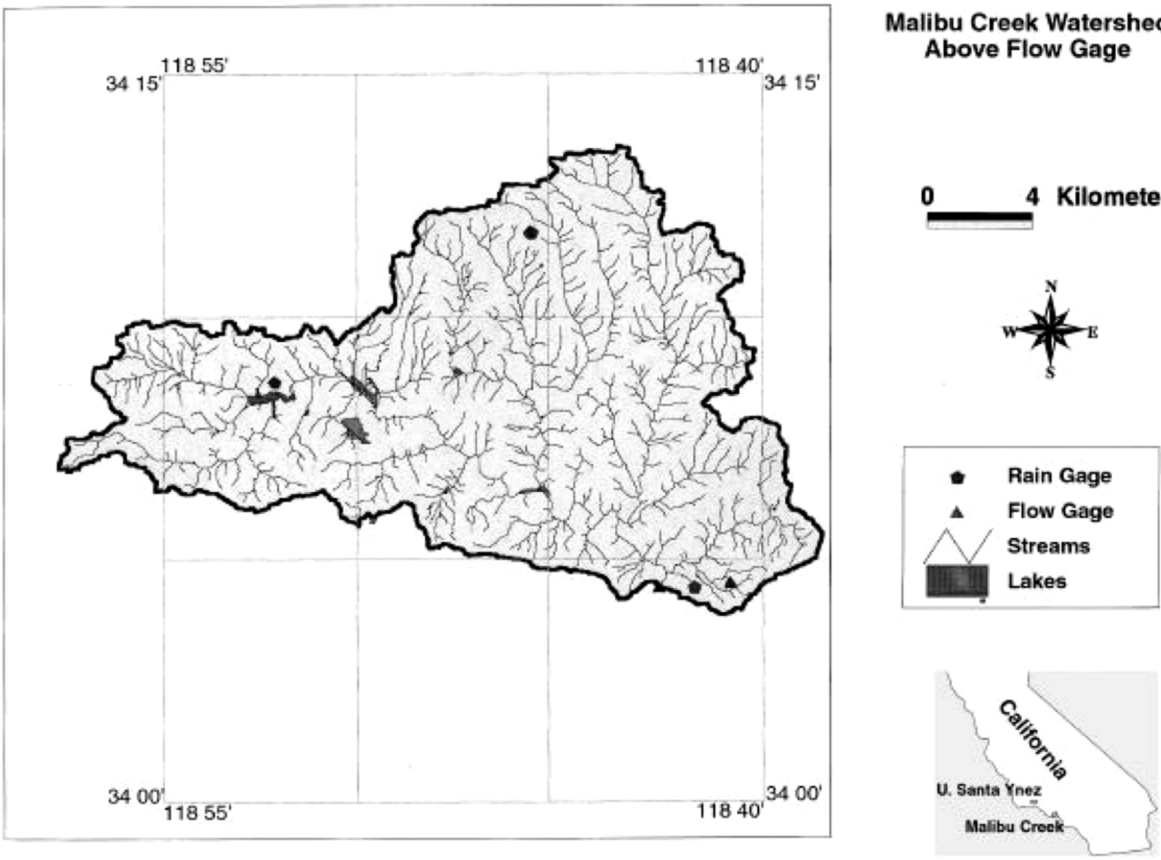

Fig. 1. Location of study area and delineated boundary and hydrographic network of the Malibu Creek watershed.

2 (developed from aerial photograph analysis, analysis of Landsat Thematic Mapper data and field surveys) shows that in the period between 1930 and 1992, land-cover changes in the Malibu Creek watershed took place primarily by the conversion of woodland to urban, grasslands to urban, sagebrush to urban, chaparral to sagebrush, chaparral to urban, and riparian to urban. Land-cover changes were determined by comparison of a 1992 satellite-derived map by Franklin and Swenson (1995) to a 1930s historical Vegetation Type Map of the area (Pedreros, 1998). The derived long-term trend of land cover change has heightened wildfire hazards in the Malibu Creek watershed.

2.2. Upper Santa Ynez River

The Upper Santa Ynez River watershed (surface area = 55 940 ha) is located within the Santa Ynez mountains of Santa Barbara County, California, 80 km west of the Malibu watershed (see Fig. 1). It ranges in elevation from 406 to 1370 m, while the Malibu watershed lies between sea level and 800 m. Its mean annual precipitation and streamflow are 65.3 cm and 60.2×10^6 m^3 (10.8 cm), respectively — Santa Barbara County Flood Control and Water Conservation Agency, 1997; United States Geological Survey, 1997, and its vegetation is predominantly (hard) chaparral with scattered oak woodlands, conifers and other hardwoods. The Upper Santa Ynez river watershed, like other chaparral watersheds, is subject to sporadic wildfires. For example, the Coyote fire of 1964 burned it in its totality.

The surface rock formations in the Upper Santa Ynez river watershed are predominantly sandstones and shales, which are typically underlain by relatively thin, poorly developed entisol soils. A comprehensive survey of its hydrologic and geologic resources can be found (Upson and Thomasson, 1951). The rainfall regime in the Upper Santa Ynez River watershed is similar to that described earlier for the Malibu watershed. The Upper Santa Ynez River watershed is used as a 'control' watershed in this study to estimate the non-impact or natural streamflow in Malibu Creek in years following a wildfire, as explained below.

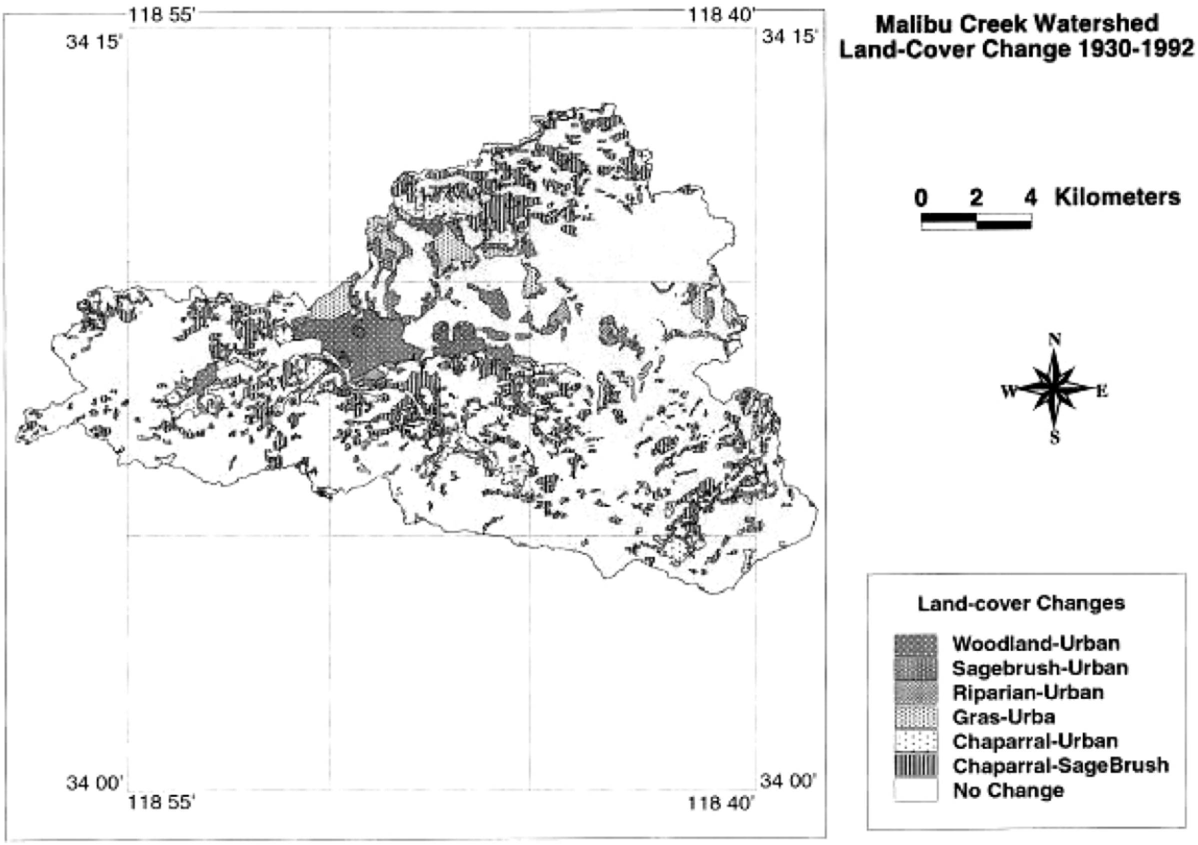

Fig. 2. Map of land-cover change in the Malibu Creek watershed, 1930–1992.

3. Data analysis and results

3.1. Wildfire and land-cover changes in the Malibu Creek watershed: 1949–1994

The determination of areas burned by wildfires in the Malibu Creek watershed was done by first developing a digital map of its drainage area from a 30-m Digita Elevation Model (DEM). Digital wildfire maps (i.e. 'wildfire coverages') were obtained from the US National Park Service and 'intersected' with the digital map of the Malibu Creek watershed using the ARCINFO Geographic Information System (GIS, Environmental Systems Research Institute, 1996). The intersection of the drainage area map which is shown in Fig. 1 with the wildfire coverages rendered the maps of burned areas for individual wildfires.

A total of 23 wildfires of different size, shape, and location occurred between 1949 and 1993 in the Malibu Creek watershed. Only 10 wildfires, those, which burned 4% or more of the watershed, are considered in our analysis. Wildfires, which burn less than 4% of the watershed, are deemed to have marginal hydrologic impact. Table 1 shows the month and year of occurrence of the ten large wildfires, as well as their burned areas (in ha). According to Table 1, five wildfires occurred in October, two in November, and one each in July, September and December.

Fig. 3 shows the burned areas for four large wildfires that occurred in the period 1949–1994. The burned areas ranged between 2216 ha (8.1% of the watershed area in October of 1993) and 12569 ha (46.2% of the drainage area in October of 1982). Notice in Fig. 3 that sections in the north-eastern part of the watershed were burned by the 1949, 1970 and 1982 wildfires. The 1993 wildfire, which burned 2216 ha, exhibited a peculiar spatial pattern. Burning was concentrated in the western and eastern ends of the watershed, while a few acres burned towards its center.

Wildfire geography in Malibu Creek is characterized by a few general patterns. Wildfire maps, including those shown in Fig. 3, suggest that most wildfires tend

Table 1
Large-fire data for the Malibu watershed (27 221 ha), 1949–1994

Month/year	Area burned (ha)[a]	Percentage of area burned
July 1949	4915	18.1
December 1956	1413	5.19
November 1958	3831	14.1
October 1967	3202	11.7
September 1970	11 180	41.1
October 1978	4245	15.6
November 1980	1100	4.04
October 1982	12 570	46.2
October 1985	1080	3.97
October 1993	2216	8.14

[a] $1\ ha = 10\,000\ m^2$.

to be concentrated in the eastern part of the watershed and propagate westward due to the warm and gusty (easterly) Santa Ana winds. The Santa Ana winds are strongest in the autumn and they are a key cause of wildfire conflagration in the study area. These winds are caused by high-pressure cells in the western Great Basin. Easterly airflow is subsequently funneled through the Cajon Pass, located between the San Gabriel Mountains and the San Bernardino Mountains of southern California, towards lower pressure zones in the Los Angeles basin and further west along the Santa Monica Mountains and the Santa Ynez Mountains. The Santa Ana winds converge on the chaparral of the study area immediately after several months of hot and dry summer weather, when there is abundant, dry, combustible biomass. Under propitious natural conditions — dry and warm weather, dry vegetation, gusty winds and sometimes aided by lightning, the chaparral ignites and wildfire ensues.

The post-1965 years have seen several large brushfires, which include those in October 1967 (3202 ha burned), September 1970 (11 184 ha), October 1978 (4245 ha), October 1982 (12 569 ha) and October 1993 (2216 ha). There is ample anecdotal and factual evidence that links the occurrence of some of these large-scale wildfires to population growth in the Malibu region, to increased recreational use of the watershed, and to ever-increasing traffic along the Malibu Canyon road, which traverses the watershed's eastern section north-south.

3.2. Precipitation and streamflow analysis

Daily records of streamflow and precipitation in the Malibu Creek watershed were obtained from the Hydrology Unit of the Los Angeles County (California) Public Works Department for the period 1949 to 1994 (Los Angeles County Public Works Department, 1996). Streamflow was measured at gauge F130-R located

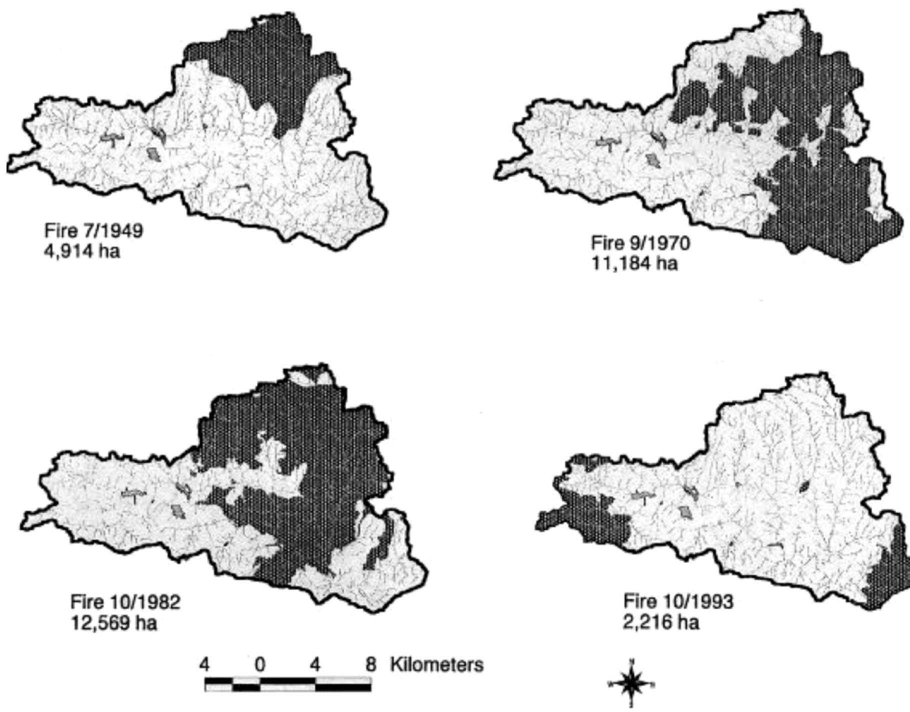

Fig. 3. Burned areas by four large wildfires in the Malibu Creek watershed.

below Cold Creek (a tributary to Malibu Creek) at the watershed's outlet as shown in Fig. 1. Rainfall was measured at several stations ranging in elevation from 0 to 700 m and averaged by the isohyetal method (Pedreros, 1998). Daily streamflow and precipitation data were summed for each water year (October 1 to September 30) to obtain the annual totals for the period of analysis (i.e. 1940–1950 through 1993–1994). Streamflow data for the Upper Santa Ynez River watershed were obtained from US Geological Survey (USGS) surface water data reports for California (Rockwell et al., 1997) and from Naftali and Alroth (1997). Streamflow was measured at the gaging station above Gibraltar reservoir (USGS station 11122000, latitude 34°31′34″N and longitude 119°41′08″W). Basin-wide precipitation data were obtained from the Santa Barbara County Flood Control and Water Conservation Agency (1995).

Annual precipitation in the Malibu watershed and in the Upper Santa Ynez watershed exhibit strong statistical correlation. Fig. 4 shows a regression of the annual precipitation totals (in cm year^{-1}) in the Malibu and Upper Santa Ynez watersheds. The following regression equation for the annual precipitation in the Malibu watershed (P_M) in terms of the annual precipitation in the Upper Santa Ynez watershed (P_{SY}) was obtained:

$$P_M = 0.773 P_{SY} + 0.860 \qquad (R^2 = 0.93) \qquad (1)$$

in which P_M and P_{SY} are expressed in cm year^{-1}. The observed strong, statistical correlation ($R^2 = 0.93$) is logical given that the sources of precipitation for the two watersheds are identical (Loaiciga et al., 1993). Differences arise primarily from unequal elevation. The Upper Santa Ynez watershed ranges in elevation from 406 to 1370 m, while the Malibu watershed ranges from sea level to approximately 800 m.

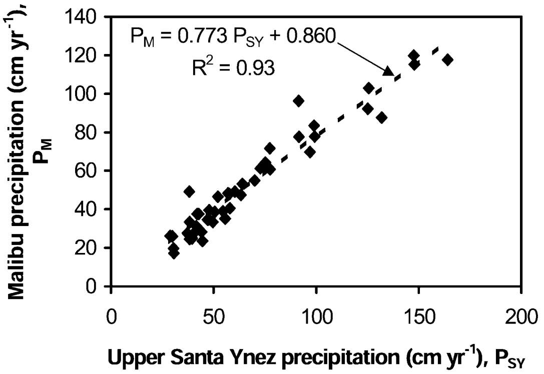

Fig. 4. Graph of regression equation between annual precipitation in the Malibu Creek and in the Upper Santa Ynez River watersheds.

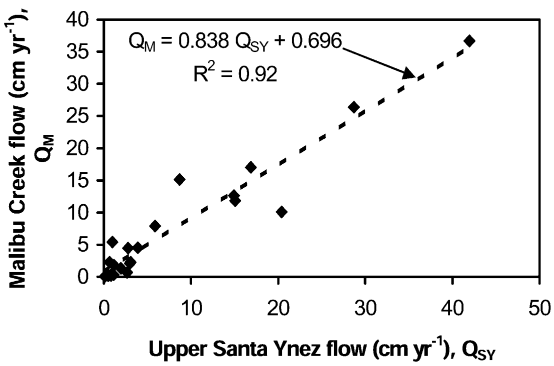

Fig. 5. Graph of regression equation between annual streamflow in Malibu Creek and Santa Ynez River at Gibraltar station.

Fig. 5 shows a regression of annual streamflow in Malibu Creek (Q_M, cm year^{-1}) and the Upper Santa Ynez streamflow above Gibraltar Dam (Q_G, cm year^{-1}). The derived regression equation was:

$$Q_M = 0.838 Q_{SY} + 0.696 \qquad (R^2 = 0.92) \qquad (2)$$

Eq. (2) was based on data from water years in which wildfires did not affect streamflow in either one of the watersheds, and used in a paired-watershed analysis described in a later section. A 3-year carryover effect following a wildfire was used as the criterion to establish whether or not streamflow was affected by vegetation burning. Thus, for example, the October 1967 wildfire in the Malibu watershed was considered to impact streamflow during water years 1967–1968, 1968–1969, and 1969–1970. If a wildfire occurred within 3 years of a previous one, then the 3-year carryover period was measured from the time of the last wildfire. The 3-year carryover effect of wildfires was determined based on field observations reported by a number of chaparral researchers (Hoyt and Troxel, 1934; Plumb, 1961; Albini 1978; Keeley, 1989; DeBano and Neary, 1998), and information provided by agencies that manage chaparral wildlands in central and southern California (i.e. the California Department of Forestry and the United States Forest Service). The reviewed data indicated that vegetation recovery in the chaparral ecosystem reestablishes transpiration to pre-fire levels, on average, 3–5 years after vegetation burning.

Only large wildfires (i.e. those which burned 4% or more of a watershed, as defined earlier), were included in the analysis that led to Eq. (2). In the Upper Santa Ynez watershed, there was only one large wildfire between 1949–1950 and 1993–1994, the Coyote Fire of 1964, which burned 100% of the watershed (Ford, 1991). Prescribed burns are regularly carried out in the Upper Santa Ynez watershed by the US Forest Service

(USFS) to prevent large-scale wildfires. The regression Eq. (2) was used to estimate the Malibu Creek streamflow that would have occurred in post-fire years if vegetation had not been burned. Thus, the Upper Santa Ynez River streamflow was used as a 'control' with which to estimate 'normal' flow in Malibu Creek in fire-impacted water years. The difference between the estimated and measured streamflow in Malibu Creek was then used to quantify fire impacts on streamflow in post-fire water years, as detailed below.

3.3. Test of wildfire enhancement of streamflow in Malibu Creek

The precipitation and streamflow data for the Malibu Creek watershed suggests streamflow increase following large-scale vegetation burning. For example, the average annual precipitation in fire and non-fire years in the Malibu watershed was 51.5 cm and 54.4 cm, respectively. Yet, the average annual streamflow in fire and non-fire years was 10.7 cm (29.1×10^6 m^3) and 10.1 cm. (27.5×10^6 m^3), respectively. Two questions that arise are: (1) is there conclusive statistical evidence of streamflow enhancement by wildfires?; and (2) if so, is it possible to quantify that enhancement? The first question was addressed by means of the Wilcoxon rank-sum test (Lehmann, 1975, pp. 5–18), while the second is addressed in the next sub-section.

The Wilcoxon test is a non-parametric (i.e. distribution-free) statistical procedure suitable to test for wildfire-streamflow interactions. Wildfire is assumed to play the role of a 'treatment' on annual streamflow. The time series of annual streamflows was divided into two sets. The first set, herein called the 'non-fire' years, consisted of streamflow in years in which there was no wildfire impact. These were (water) years without wildfires and prior to which a large wildfire had not occurred for at least 3 years. The second set, or 'fire' years, was made up of streamflows in years in which a large wildfire occurred or prior to which a large wildfire had happened in the last 3 years. The 'control' water years are the non-fire years. In $N = 45$ years of record, $n = 25$ were fire years and $m = N - n = 20$ were non-fire years. The streamflows in fire and non-fire years were pooled, sorted in ascending order, and assigned ranks after sorting. The Wilcoxon rank-sum statistic W_S is defined as the sum of the ranks (S_i) of the n streamflows in fire years, that is, $W_S = S_1 + \ldots + S_n$, which equaled 588 in our case. The null hypothesis 'H' that wildfire has no effect on annual streamflow is rejected if $W_S \geq c$, where the critical value c is such that the probability of W_S satisfies $P_H(W_S \geq c) = \alpha$. The significance level of the test, α, is set typically at 5%. The rationale behind the rejection criterion in the Wilcoxon rank-sum test (i.e. reject H if $W_S \geq c$), is intuitive; when the sum of ranks W_S is too large it indicates that there is an effect of treatment, in this case wildfire enhancement of streamflow, thus, negating the null hypothesis H of no effects. Lehmann (1975) shows that for $m,\ n > 10$ and $\alpha = 0.05$, the critical value c in the Wilcoxon test is given by:

$$c = -1.645\sqrt{mn(N+1)}\,/12 + \frac{1}{2}n(N+1) + \frac{1}{2} \qquad (3)$$

which, for $m = 20$, $n = 25$, and $N = 45$ yields $c = 503$. Since $W_S = 588 > 503$, the null hypothesis of no wildfire impacts on annual streamflow is rejected; there is definitive statistically significant evidence that wildfires enhance water-year streamflow.

3.4. Quantification of annual streamflow enhancement by wildfires

The two largest wildfires on record, i.e. the September 1970 and the October 1982 events, which burned 41 and 46% of the Malibu watershed (see Table 1 and Fig. 3), respectively, were chosen to quantify the effect of wildfire on streamflow. In fact, the impacts of the October 1967 and the September 1970 wildfires overlapped since they occurred within a 3-year span (see Table 1). This gave rise to a sequence of fire-impacted (water) years from 1967–1968 to 1972–1973. Likewise, the October 1978, November 1980, October 1982, and October 1985 wildfires (see Table 1) generated a sequence of 10 years (1978–1979 to 1987–1988) of continuous streamflow impacts.

The approach followed to quantify wildfire impacts on streamf1ow was based on a paired-watershed analysis. The Upper Santa Ynez watershed was used as a control, while the Malibu Creek watershed was used as a treatment. Eq. (2) was used to estimate the (water-year) streamflow that would have occurred in Malibu Creek during fire-impacted years if wildfires had not occurred. These are called the 'reconstructed' streamflows, which were compared to the measured streamflows during fire years.

Table 2 shows the reconstructed and actual streamflows in Malibu Creek for the two sets of fire-impacted years, 1968–1973 and 1978–1988. In the period 1968–1973, there was wildfire enhancement of streamflow in every single water year. The mean of reconstructed and actual streamflows was 39.3×10^6 m^3 (14.4 cm) and 50.8×10^6 m^3 (18.6 cm), respectively, or a 30% enhancement of annual streamflow by wildfire. A similar effect was observed in the period 1978–1988, in which the mean reconstructed and actual streamflows were 33.1×10^6 m^3 (12.1 cm) and 39.8×10^6 m^3 (14.6 cm), respectively, for a 20% annual streamflow enhancement by brushfires. In water years 1978–1979 and 1983–1984, however, reconstructed streamflow ex-

Table 2
Actual and reconstructed streamflow in fire-impacted years, Malibu Creek (27 221 ha[a])

Water year	Actual streamflow (in 10^6 m^3)	Reconstructed streamflow (in 10^6 m^3)
1967–1968	27.8	16.6
1968–1969	179	146
1969–1970	16.0	8.88
1970–1971	27.3	21.3
1971–1972	14.1	5.41
1972–1973	39.4	38.1
Mean	50.8	39.3
1978–1979	34.7	41.2
1979–1980	54.4	46.3
1980–1981	19.9	12.1
1981–1982	22.9	12.4
1982–1983	146	119
1983–1984	19.7	21.5
1984–1985	21.3	14.9
1985–1986	40.5	34.4
1986–1987	11.1	7.69
1987–1988	26.8	21.4
Mean	39.8	33.1

[a]1 ha = 10 000 m^2.

ceeded actual ones, albeit by a small amount, as seen in Table 2. This anomaly is attributed to errors in the regression predictions of reconstructed streamflow.

The quantified effects of vegetation burning on annual streamflow which range between 20 and 30%, do not seem as pronounced as one might have expected given the size of the fires considered. One plausible explanation for this is the rapid recovery of the chaparral. Another possible explanation is that the largest storms in the study area occurred during the low-growth period of most chaparral species (i.e. from mid-January through mid-March), when transpiration is low. Thus, the effect of reduced transpiration by burned vegetation on watershed runoff is somewhat mitigated due to the fact that the chaparral water use is minimal during the period of heavy rainfall anyway.

4. Conclusions

The previous analysis has shown that vegetation changes and growth within and surrounding Malibu Creek watershed has exacerbated wildfire activity in the watershed over the last decades. Two main clusters of fire-impacted years were found to have dominated wildfire streamflow interactions since 1949 in the Malibu Creek watershed. The effect of wildfire on average annual streamflow was examined based on a paired-catchment analysis which involved the Upper Santa Ynez River watershed as a control and the Malibu Creek watershed as a treatment. A comparison of reconstructed and measured streamflows showed that brushfires cause between 20 and 30% increases in the annual Malibu Creek streamflow. Vegetation changes and urban development in the vicinity of the Malibu Creek watershed appear to have contributed to wildfire activity in that area in the period from 1949 to around 1990.

Future research by the authors on wildfire-streamflow interactions in chaparral watersheds will focus on: (1) the development of a mechanistic, process-dependent, spatially-distributed hydrologic model of chaparral watersheds to study the time- and vegetation-dependent water balance at the watershed scale (e.g. streamflow, evapotranspiration, oil-moisture balance, etc.); and (2) field measurement of chaparral biomass variables (e.g. leaf area index, rooting depth) and of important hydrologic and ecological fluxes such as evapotranspiration and carbon dioxide (CO_2) exchange between the chaparral and the lower-atmosphere. The assembled databases and knowledge thus acquired about wildfire effects on long-term streamflow and chaparral dynamics, provide a solid foundation to pursue basic research on hydrologic processes in chaparral watersheds.

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