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Hydrology in a California oak woodland watershed: a 17-year study

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Abstract

The western foothills of the Sierra-Nevada are some of the most rapidly developing lands in California. Use of these lands includes vineyards, retirement and family home construction, livestock grazing, and fuelwood harvesting. These many uses require varying levels of woodland conversion and oak tree removal that alters the nutrient cycling, wildlife habitat and hydrology of these watersheds. There is little long-term hydrologic data to help determine the impact of these land use changes on water yield or quality. To fill this gap, precipitation and stream flow data were collected for 17 years in a 103 ha California oak woodland watershed, from which oaks were removed from 14% of the land area. These data were combined with measured potential evapotranspiration (PET) to develop a simple water balance and to investigate changes in water yield from oak removal. Hydrologic data included continuous stage height records from a three-foot Parshall flume and a one-foot 90° V-notch weir. Rainfall measurements were made using a tipping bucket rain gage. Average annual rainfall, runoff, and estimated evapotranspiration (ET) for the 17 years were 708, 344, and 364 mm, respectively. In this Mediterranean climate, ET is less dependent upon rainfall than is runoff because the majority of precipitation coincides with the period of lowest PET. Mean annual baseflow depth was 24 mm ranging between 15 and 40 mm. Depth of baseflow was more strongly associated with the annual rainfall than with rainfall from previous years, indicating that changes in soil moisture storage approaches zero on an annual time-scale. Effective depth for watershed soils was calculated to be 217 mm. Potential soil water storage between bedrock and the top of the clay-rich subsoil (Bt Horizon) was 52 mm. This quantity accounts for summer ET and stream baseflow. A weakly significant difference between the pre- and post-harvest mean monthly effective rainfall was observed, indicating that oak removal, from 1984 to 1986, had little influence on watershed hydrology. Peak monthly effective rainfall corresponded to peak monthly runoff. The threshold of response to significantly increase water yield from oak harvesting is greater than 14% of a watershed area for the Sierra-Nevada foothills oak woodlands. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Forest hydrology; Water balance; Oak woodlands; Wildland watersheds

1. Introduction

California's oak woodlands represent an important resource for fuelwood, rangeland, aquifer recharge, and wildlife habitat (Standiford and Howitt, 1993; Bolsinger, 1987). It is also an ecosystem being rapidly developed for suburban dwellings and hillslope vineyards. Management under this multiple-use system includes varying levels of woodland vegetation conversion from complete removal of all oaks to isolated harvest of individual trees. Although past

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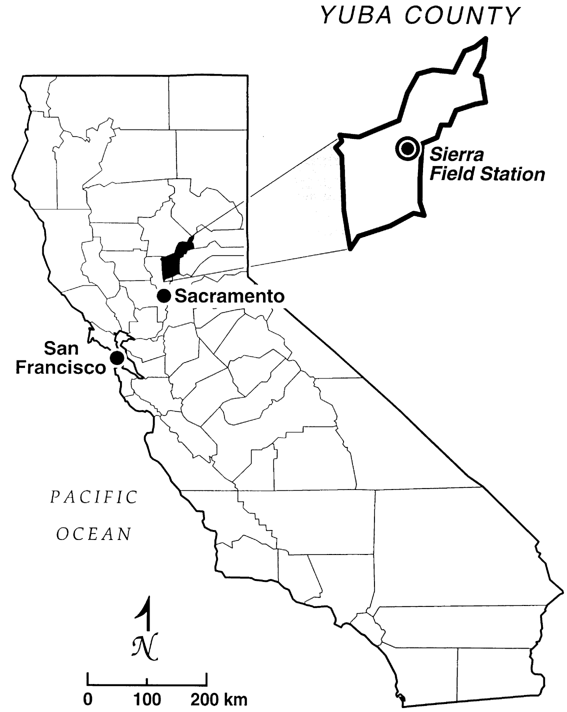

Fig. 1. Location of the University of California Sierra Foothill Research and Extension Center.

investigations included the effects of oak harvesting on changes in forage quality and quantity (Kay, 1987; Holland, 1980) and water yield (Lewis, 1968), there is little published long-term hydrologic data for oak woodland watersheds in California.

Motivated by water resource management efforts to increase water yield, research on forest conversion to grasslands has attempted to quantify the relationship between the area of land converted and increased annual water yield or runoff (Stednick, 1996; Bosch and Hewlett, 1982; Pitt et al. 1978; Burgy and Papazafiriou, 1971). Bosch and Hewlett (1982) compiled data from 94 watershed studies and found that every 10% of land area converted generated 40 mm of additional annual runoff in conifer and eucalyptus forests, 25 mm in deciduous forests, and 10 mm in scrubland. They concluded that regions of higher mean annual precipitation were more sensitive and demonstrated stronger annual runoff responses to vegetation conversion than regions of lower precipitation. Their results also indicate a lack of research conducted for small areas of vegetation conversion and the need to identify thresholds of response.

Expanding on Bosch and Hewlett's review, Stednick (1996) identified percent area thresholds of vegetation conversion at which point water yield would begin to increase. Based on results from 95 paired watershed studies in the United States, he concluded that a minimum of 20% area conversion must take place to generate changes in annual runoff. This threshold varies from 15% in the Rocky Mountain Inland Intermountain region to 50% for the Central Plains region. Potential reasons for this variability include harvest location, harvest type, pretreatment vegetation cover, or measurement error. Because only two studies were available for the Central Sierra Province region, the region in which our study is located, a threshold could not be established in Stednick's review. In addition to threshold determinations, Stednick developed a relationship for the 95 paired watershed studies between increased runoff (y, mm) and percent area of vegetation conversion (x) described by Eq. (1):

$$y = 2.46(x) \tag{1}$$

In the most recent, and arguably the only, study of hydrologic response to vegetation conversion conducted in the Sierra-Nevada Foothills, Lewis (1968) compared runoff from a control watershed to that in a watershed that had over 90% of land area converted. Lewis' research represents climate, geology, soils, and vegetation similar to those in this study. His results indicate runoff was increased by 129 mm annually for the three years studied. Thus, vegetation conversion on approximately 100% of the area resulted in increased runoff in these oak woodlands. What effects on runoff does vegetation conversion of smaller areas have, as raised by Bosch and Hewlett (1982)? Does the 14% area converted within this study site generate an increase of 34 mm in runoff as predicted by Eq. (1) and Stednick's (1996) review?

The scarcity of published data on oak woodland watersheds combined with a growing demand for their non-agricultural use highlights the need for better understanding of the hydrology of oak woodlands and the role of oaks in nutrient and water cycling. This study complements the work of Lewis (1968), Bosch and Hewlett (1982) and Stednick

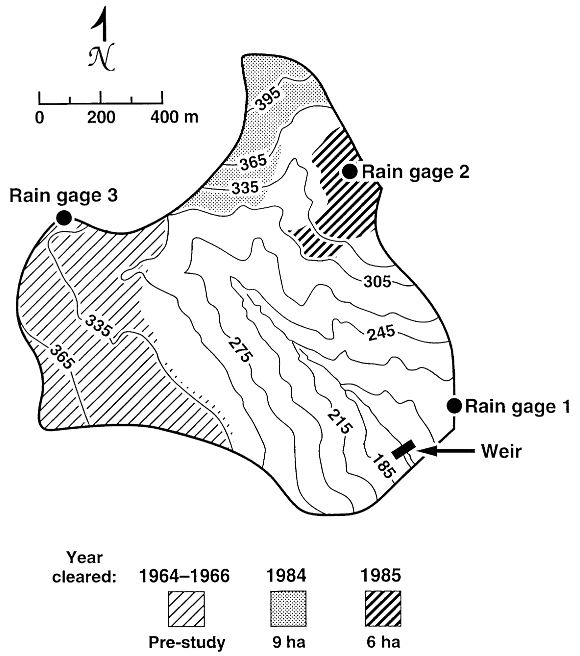

Fig. 2. Locations of oak removal and instruments in the Schubert watershed. Contours are in meters.

(1996) by presenting water yield data from 1981 to 1997 in a Northern California Sierra Nevada foothill oak woodland watershed to meet two objectives. The first is to quantitatively describe the annual rainfall, runoff, and ET, as well as monthly average rainfall and runoff for this oak woodland system. Second is to investigate the influence of selective oak harvesting on water yield. Water quality results for the study are presented in Lewis (1998).

2. Materials and methods

2.1. Site description

Located on the University of California's Sierra Foothills Research and Extension Center (SFREC), the 103 ha Schubert watershed is approximately 96 km northeast of Sacramento in Yuba County, California (Fig. 1). Elevations within the watershed range from 152 to 427 m with slopes ranging from 2 to 50% and average of 18 % (Fig. 2). The annual rainfall distribution corresponds to California's Mediterranean climate with maximum average monthly rainfall in winter and minimum average monthly rainfall in summer.

Dominated by blues oaks (*Quercus douglasii*) and intermixed with interior live oaks (*Q. wislizenii*) and foothills pine (*Pinus sabiniana*), the vegetation of the site typifies Sierra-foothills oak woodlands (Griffin, 1977). The uneven distribution of trees creates a mosaic of open grasslands, savanna, and woodlands (Epifanio, 1989; Jansen, 1987). Annual grasses and legumes dominate the ground cover, with differing species diversity under the oak canopy compared to open grasslands (Jackson et al., 1990; Jansen, 1987).

Soils in the Schubert watershed are Ruptic-Lithic Xerochrepts on the steep side slopes and Mollic Haploxeralfs on the more level areas (Lytle, 1998). Soils are shallow to moderately deep, medium textured, gravely, and rocky formed in basic metavolcanic (greenstone) bedrock (Beiersdorfer, 1979). They are rich in Fe-oxides. Soil pit observations at Schubert consistently identified very stony clay subsoils with 40% average clay content (Huang, 1997). The clay subsoil, starting at 35–40 cm depth, and bedrock at the site limit deep percolation of water (Dahlgren and Singer, 1994).

The watershed is used for light to moderate seasonal beef cattle grazing primarily from January to March and August to October. Total animal unit months, AUM/ha, averaged 0.24 with a minimum of zero in 1986–1987 and a maximum of 0.56 in 1984–1985. Trends in grazing intensity as a function of time were not detected for the duration of this study ($r^2 = 0.004$).

In addition to grazing, oaks were harvested on 14% of the site from 1984 to 1986 (Epifanio, 1989). A total of 1352 trees were removed from 15 ha, or 14% of the watershed, during three periods of cutting. From 7/22/84 to 8/16/84, 880 trees were removed, followed by removal of 416 trees between 4/1/85 and 9/30/85 and 56 trees between 4/26/86 and 5/26/86. Woodcutters were prohibited from cutting in obvious waterways whether or not water was present. They were also prohibited from cutting on slopes over 30%. Cutting was allowed in winter but wood removal was restricted to summer months. Converted areas remain covered by annual grasses since oak harvesting.

2.2. Watershed instrumentation

In 1978, the watershed was instrumented with a

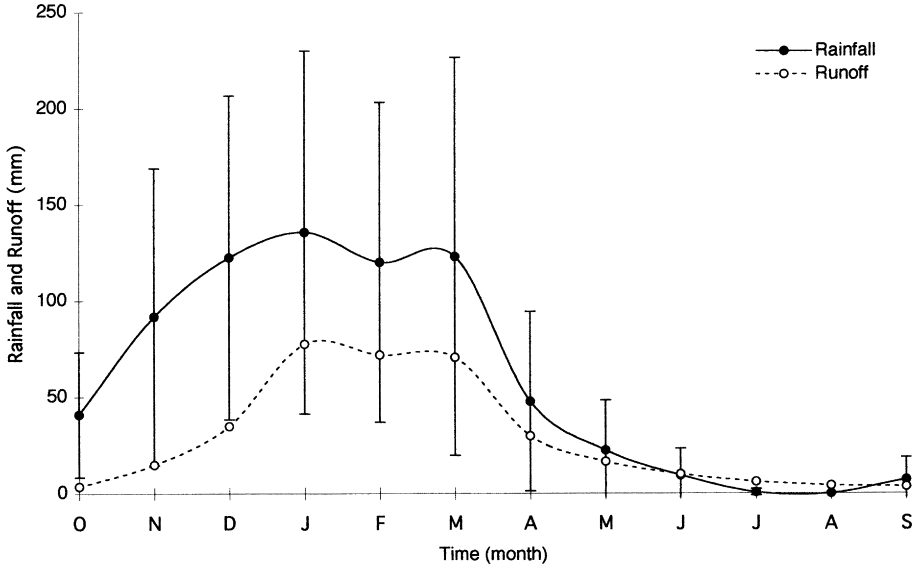

Fig. 3. Schubert watershed mean monthly rainfall and runoff. Error bars represent one standard deviation from the mean rainfall.

three-foot Parshall flume for storm flow measurements and a one-foot 90° V-notch weir for base flow measurements (Fig. 2). Stage height was continuously recorded with stage height recorders inside stilling wells connected to the flume and weir. Rainfall amount and intensity were recorded with tipping bucket rain gages and recorders at three different elevations within the watershed to provide redundancy and account for rainfall variability resulting from orographic influences. Comparisons of annual and storm-event rainfall indicate that the variability between these three gages is negligible (Huang, 1997). Rainfall reported here is for one gage at the highest elevation. Because of instrument inconsistencies and settling of disturbed soil around the flume and weir, data from 1978, 1979, and 1980 were not included in the long-term record.

2.3. Data analysis

Annual rainfall and runoff were calculated as the respective sums of every rainfall event and daily discharge measured during each water year (October 1 to September 30). Monthly average rainfall and runoff were calculated as the mean of each month's rainfall and runoff from 1981 to 1997. In addition, rainfall–runoff relations were investigated by calculating annual and mean effective rainfall according to Haan et al. (1994) and Pilgrim and Cordery (1992).

Evapotranspiration (ET) on an annual basis was estimated as the difference between rainfall and runoff using a simple water balance method (Haan et al., 1994; Peters, 1994; Hewlett, 1982). Annual potential evapotranspiration (PET) values were obtained from the SFREC's weather station and evaporation pan (SFREC, 1997).

Mean annual baseflow, effective rainfall, and mean annual rainfall that initiated observable stream runoff increase from storms were determined. These were compared to effective depth calculations made from soil bulk density data presented by Dahlgren et al. (1997). Baseflow separation was made using annual runoff hydrographs and hydrograph separation methods (Haan et al., 1994; Pilgrim and Cordery, 1992). Storm runoff was identified as the runoff between the points on the annual hydrograph where tangents to the recession curve touched. This runoff depth was excluded from the summation of inter storm-events and summer baseflow.

Water yield analysis was conducted using effective rainfall (Haan et al., 1994) on annual and monthly time scales. For purposes of this paper, effective rainfall represents runoff as a percent of precipitation at annual and monthly time steps (Black, 1990).

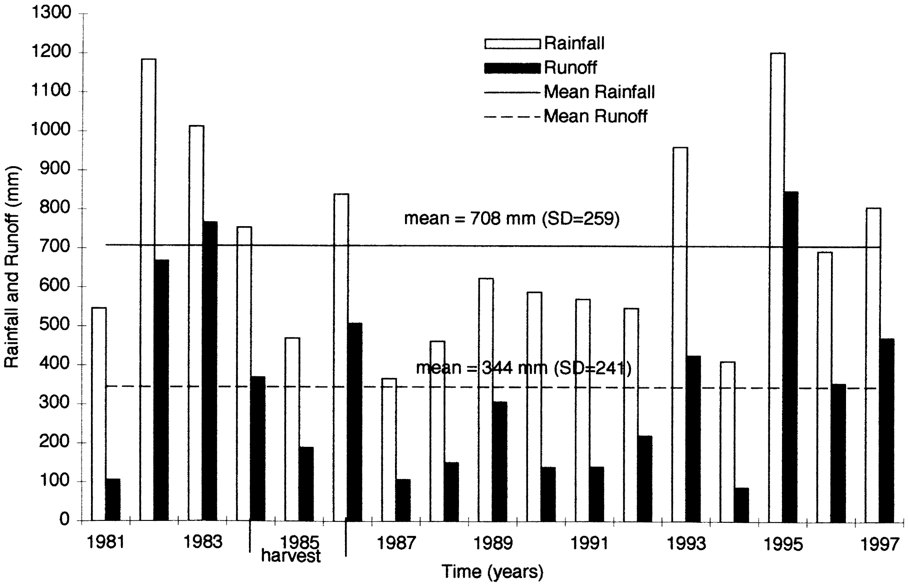

Fig. 4. Schubert watershed annual rainfall and runoff from 1981 to 1997.

Monotonic trends and step trends were developed for effective rainfall using statistical methods recommended by Helsel and Hirsch (1995) as well as Hirsch et al. (1991, 1982). These included linear regression and *t*-test of means on data transformed to natural logarithmic values. Normal distribution of data was tested using the probability plot correlation coefficient test (Looney and Gulledge, 1985). This test indicated that monthly effective rainfall was not normally distributed but natural logarithmic transformed data was. Use of step trends is in keeping with the structure of a before and after treatment study (Spooner et al., 1985), and facilitates the comparison of pre- and post-oak harvest effective rainfall. Time series analysis of pre- and post-cutting runoff was made using the SAS statistical program autoreg procedure after data transformation.

3. Results and discussion

3.1. Monthly rainfall and runoff

Mean monthly rainfall and runoff for the 17-year period are typical of the annual pattern found in California's Mediterranean climate, with 88% of rain falling from October to March (Fig. 3). Mean monthly rainfall and the resulting monthly runoff are highly variable, with the greatest variability in the winter and the least variability in the summer. Peak mean monthly rainfall and runoff occurred in January followed by a second maximum in March (Fig. 4).

Interannual climatic variability is also high. Rainfall and runoff were below average in water years 1987 to 1992. This time span corresponds to a recognized regional drought and contrasts with the time periods of above average rainfall and runoff that preceded and followed it. This variability was not limited to time spans of several years but was observed between sequential years, as demonstrated in the annual hydrographs for the 1994 and 1995 water years (Fig. 5a and b). Water years 1994 and 1995 represent the minimum and maximum runoff measured over the 17-year period. Similar juxtaposition of high and low rainfall and runoff years occurred in 1981 and 1982, as well as 1985 and 1986.

Consistent with the mean annual rainfall pattern presented in Fig. 3, 85 and 86% of all rainfall fell between October and March for 1994 and 1995, respectively. In response to this rainfall pattern, the runoff for both years was elevated during this same period. Initial rainfall events produced little or no stream flow response until soil water holding capacity was recharged. The initiation of increased runoff

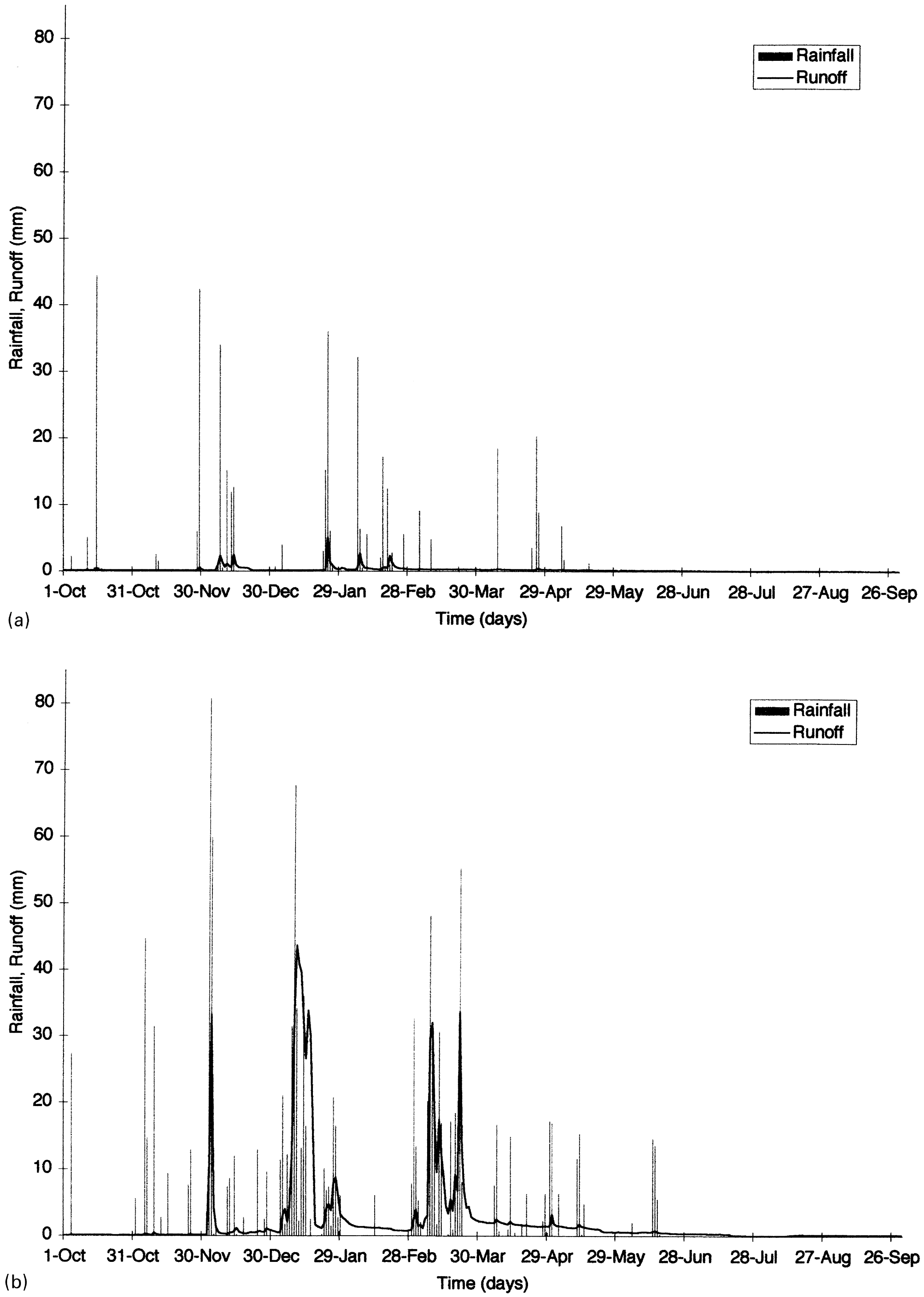

Fig. 5. (a) Schubert watershed annual hydrograph for October 1 1993 through September 30 1994. (b) Schubert watershed annual hydrograph for October 1 1994 through September 30 1995.

occurred in early December for both years, indicating a similar soil recharge response. Once in the excess moisture phase, subsequent rainfall events were recorded as increased stream flow. Peak runoff for 1995 was more than four times that of 1994 because of greater precipitation and closer timing of storm-events during 1995. During 1995, 21 observable storm runoff events occurred, as indicated by the rise and fall of the annual hydrograph. In 1994 only ten such events occurred. In addition, baseflow between storm runoff events was greater in 1995 than in 1994.

3.2. Annual rainfall, runoff and ET

Mean annual rainfall, runoff, and ET over the 17-year record were 708 (SD = 259), 344 (SD = 241), and 368 mm (SD = 89), respectively (Table 1). The 17-year average rainfall is comparable to 749 mm (SD = 276) recorded at the nearby SFREC weather station for the same time period (SFREC, 1997). Annual total runoff and rainfall were significantly correlated $r^2 = 0.90$ ($p = 0.001$) while annual ET and rainfall were not $r^2 = 0.14$ ($p = 0.139$) (Fig. 6). These relationships were similar to those for an oak woodland watershed in Northeastern Spain receiving 857 mm annual precipitation (Avila and Roda, 1990). Furthermore, the site is responding as a humid watershed with relatively constant ET in the face of highly variable annual precipitation (Likens et al., 1995). Lastly, this response is consistent with the precipitation threshold identified by Bosch and Hewlett (1982) for the behavior of mean annual ET. ET is constant and not correlated with rainfall where precipitation is greater than 600 mm and increasingly variable and correlated with rainfall below this threshold.

Although the water balance method is not effective for short-time-scale water budget calculations and lacks a control for climatic factors, it does provide an efficient way to calculate annual ET and is often used to check the accuracy of other methods. A relevant example is work conducted in a California coastal oak woodland watershed by Fisher et al. (1996).

Assumptions made in using this method include integration of surface and lateral flow in stream discharge or runoff, changes in soil water storage approaching zero when analyzing a long record, and minimal water flux to deep seepage as a result of site soils and geology. Previous ET calculations for the watershed showed that site conditions met the first two of these assumptions (Huang, 1997 and Dahlgren and Singer, 1994). Fisher et al. (1996) also confirmed that changes in soil water storage approached zero at the annual time scale for the California oak woodland watershed in their study. Dahlgren and Singer (1994) used the field capacity method of Maule and Chanaskye (1987) for ET calculation and estimated that deep seepage at our site was less than or equal to 5% of precipitation for the 1992–1993 water year. In contrast, Huang (1997) and Parton and Jackson (1989) estimated it to be as much as 20% of precipitation. Thus, site conditions might be met for the third condition. A lack of deep percolation is further supported by the observed high subsoil clay content and shallow depth to bedrock that restrict downward flow and promote lateral flow at the site (Dahlgren et al., 1997; Epifanio, 1989).

Mean annual ET was 19% of mean annual PET (Table 1). This is expected in Mediterranean climates where ET is a larger component of the annual water budget than runoff (Peters, 1994; Swift et al., 1988) and maximum PET occurs during summer when little or no precipitation occurs (Fig. 3). For example, monthly average PET for December and January were 41 and 42 mm compared to 303 and 281 mm for July and August (SFREC, 1997). The lack of synchronous PET and ET with precipitation results in the large disparity between PET and ET over the 17-year record. Further indication of this rainfall, runoff, and ET relationship is the significant ($p < 0.001$) positive correlation, $r^2 = 0.90$, between rainfall and effective rainfall on an annual basis. The inference is that additional rainfall primarily contributes to runoff but does not increase ET.

3.3. Baseflow

With the differences in runoff volume in response to rainfall during the winter, it is interesting to note a consistent decline and endpoint value of baseflow during the summer months in 1994 and 1995. The minimum daily runoff for 1994 and 1995 was 0.05 and 0.04 mm, respectively, and total summer baseflow for 1994 and 1995 was 15 and 9 mm,

Table 1

Schubert watershed annual rainfall, runoff, potential (PET) and estimated (ET) evapotranspiration, effective rainfall, cumulative rainfall to annual peak runoff, peak runoff, annual cumulative rainfall to sustained rise in runoff, runoff at sustained rise in runoff, baseflow, and baseflow as a percentage of rainfall for water years 1981–1997

Year	Rainfall (mm)	Runoff (mm)	PET[a] (mm)	ET[b] (mm)	Effective rainfall (%)	Cumulative rainfall to annual peak runoff (mm)	Annual peak runoff (mm)	Cumulative rainfall to sustained rise in runoff (mm)	Runoff at sustained rise in runoff (mm)	Baseflow (mm)	Baseflow as % rainfall
1981	545	106	2207	439	19	467	9	278	3	36	7
1982	1184	668	1865	516	56	725	38	156	1	16	1
1983	1014	766	1811	247	76	266	28	91	1	17	2
1984	754	369	2178	386	49	429	30	94	4	23	3
1985	469	189	2232	281	40	333	36	113	1	19	4
1986	840	507	2062	333	60	617	62	113	1	21	3
1987	366	107	2264	259	29	252	8	152	1	40	11
1988	461	150	2166	311	33	350	8	167	1	27	6
1989	623	307	1859	317	49	508	35	154	3	18	3
1990	589	139	1745	450	24	284	12	179	1	28	5
1991	570	139	1722	431	24	291	19	175	3	30	5
1992	547	220	1768	327	40	398	39	175	2	32	6
1993	962	426	1684	536	44	693	21	181	3	15	2
1994	411	87	1702	324	21	241	5	141	2	33	8
1995	1205	848	1670	357	70	559	44	161	5	16	1
1996	694	354	1892	340	51	381	27	170	1	21	3
1997	807	470	1738	337	58	711	57	163	2	19	2
Mean	708	344	1916	368	44	441	28	157	2	24	4
SD	259	241	217	89	17	167	17	43	1	8	3

[a] Potential evapotranspiration reported in SFREC (1997) annual report.

[b] Evapotranspiration estimated as the difference between rainfall and runoff.

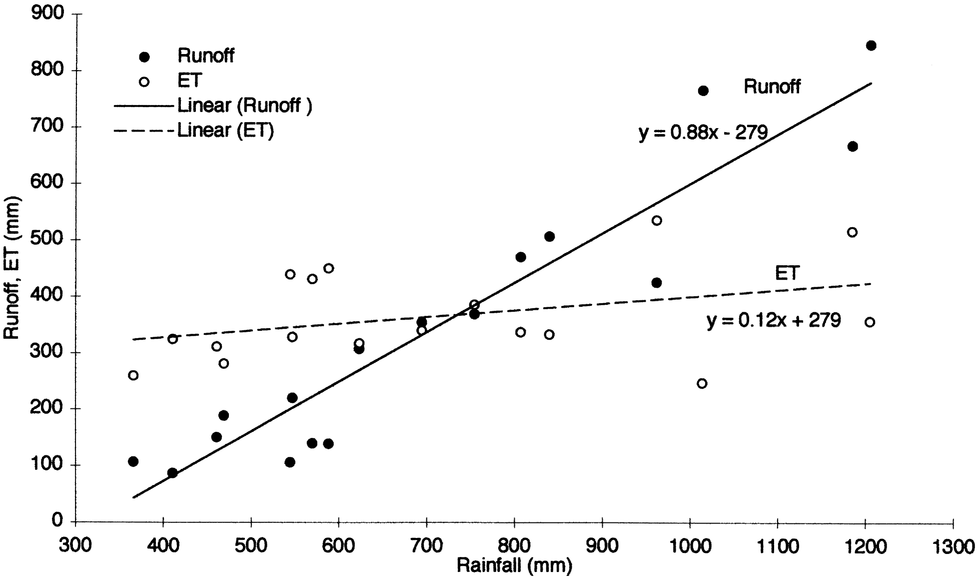

Fig. 6. Schubert watershed annual runoff and actual ET as functions of rainfall. ET was estimated as the difference between rainfall and runoff.

respectively. 1994 was preceded by a year of above average rainfall and runoff. If soil water storage at an annual time step did not approach zero the juxtaposition of the divergent winter runoff values and similar summer runoff values would not be expected.

Baseflow during the summer without precipitation raises questions about subsurface water sources. Lewis and Burgy (1964) indicated that deep cracks contributed to the water budget in a California coastal oak woodlands watershed. As an alternative to deep drainage, subsurface flow from saturated soils has been observed as the principal source of baseflow in forested watersheds (Mosley, 1979; Hewlett, 1961). Given the uncertainty in the source of baseflow and leaks either into or out of the watershed, the simple water budget approach applied in this study is only a first approximation.

Application of this approximation to the Schubert watershed is informed by discussion of effective depth and annual baseflow at the site as they relate to runoff and rainfall. Using bulk density results presented by Dahlgren et al. (1997), the estimated effective water depth stored in the soil profile at saturation is 217 mm. Above the Bt horizon we estimated potential storage of 165 mm. Lewis (1968) indicated that between 152 and 203 mm of rainfall was required to prime that study's watersheds and generate runoff. The average priming precipitation depth for sustained rise in runoff from summer baseflow to fall and winter storm flow in the Schubert watershed was 157 mm (SD = 43) (Table 1). The similarity between the 157 mm required to initiate stream response and the calculated effective depth supports the contention that water flowing through the soil above the Bt horizon is responsible for initial stream response to rainfall. These results further indicate that runoff, primarily as lateral flow (Dahlgren and Singer, 1994), increases prior to saturation of the entire soil profile, thus limiting deep water seepage.

Mean annual baseflow and baseflow as a percentage of rainfall in the Schubert watershed were 24 mm (SD = 8) and 4% (SD = 3), respectively (Table 1). There is sufficient subsoil soil water storage to generate this baseflow. We are not confident that subsoil stored water is the only source of summer baseflow because other similar watersheds in the area have seasonal, not perennial, flow. Other sources are the perennial springs, unique to this watershed, that contribute to baseflow with stored soil water that reaches the stream as flow from these springs. If, however, it is assumed that baseflow is generated from another source, that source is only a minor

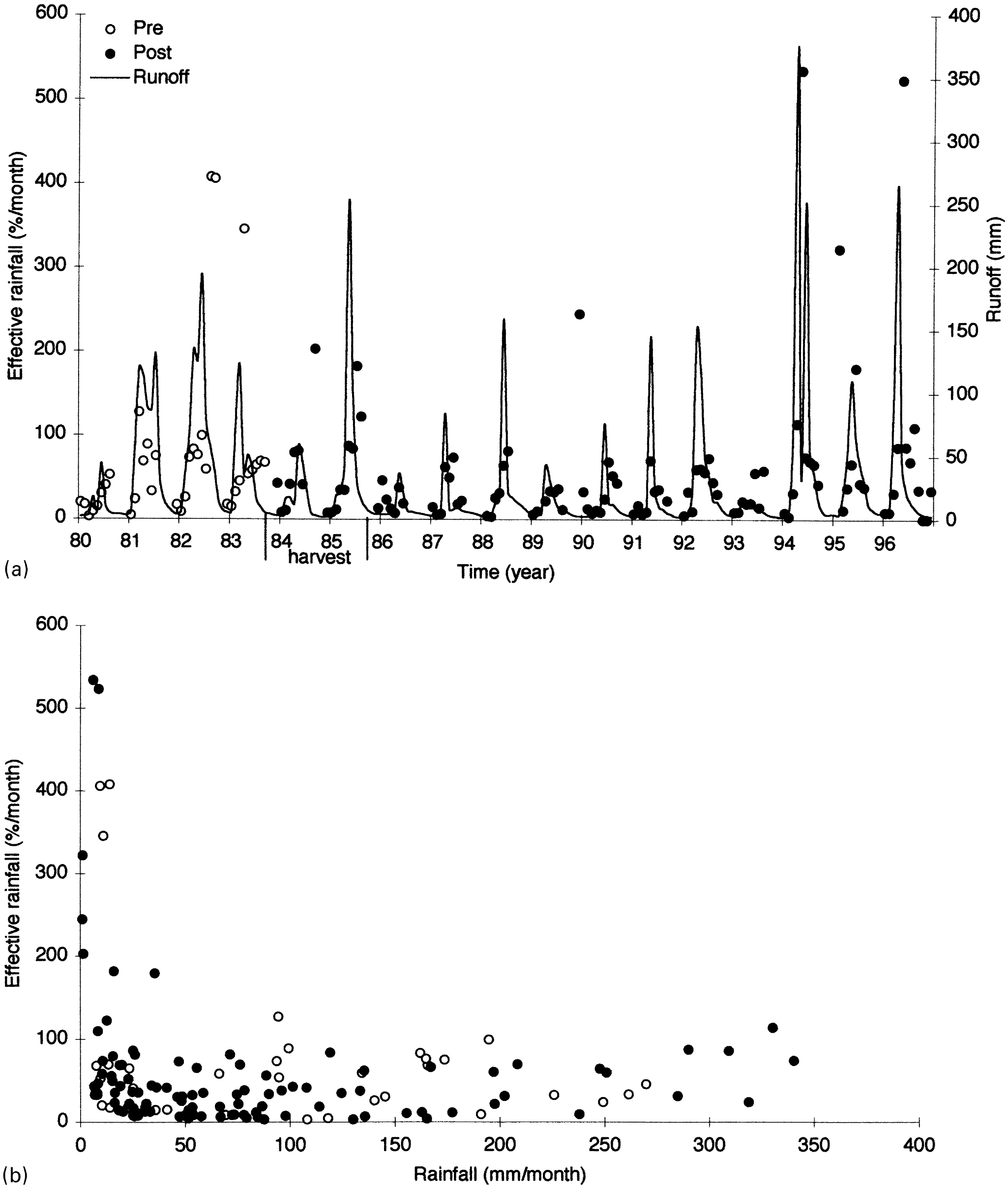

Fig. 7. (a) Schubert watershed effective rainfall and total monthly runoff over the 17-year record. Months with zero rainfall are not included. Each water year begins in October of one year and ends in September of the next year. (b) Schubert watershed pre- (open circles) and post-harvest (closed circles) monthly effective rainfall as a function of monthly rainfall.

contributor to runoff missed by the water budget approach. Further analysis using end-member mixing methods may help to determine the source of summer baseflow.

3.4. Effect of tree removal

Removal of trees from14% of the area produced no trend over time for annual ($r^2 = 0.008$, $p = 0.912$) or monthly ($r^2 = 0.002$, $p = 0.645$) effective rainfall. There was also no significant difference between the pre- and post-harvest mean monthly effective rainfall ($p_{t\text{-test}}$ means ln transformed = 0.054). The weak-significance of these results runs the risk of a Type II error, but the null hypothesis could not be rejected using the significance level of $p = 0.05$. Admittedly, the power of these tests is limited by the small pretreatment sample size.

Further analysis of the runoff data using time series analysis showed a weakly significant difference between pre- and post-harvest runoff ($\Pr > |t| = 0.041$). Before time-series analysis, a log–log transformation of the monthly runoff data was made to correct for non-normal distribution. The Shapiro-Wilk statistic ($W = 0.960$) indicated that the transformation did not fully normalize the distribution; it remained thick-tailed. A one month lag and a one year lag were significant ($\Pr > |t| < 0.0001$). As expected, the previous month's runoff was strongly correlated to the runoff in the present month. The seasonality of the watershed's behavior is shown by the strong relationship among the same months each year.

Peak monthly effective rainfall corresponded to peak monthly runoff (Fig. 7a). There was no significant correlation between effective rainfall and monthly rainfall either pre- ($r^2 = 0.085$, $p = 0.089$) or post-cutting ($r^2 = 0.020$, $p = 0.151$) (Fig. 7b). Monthly effective rainfall greater than 100% in Fig. 7a and b represent late winter and early spring months with low precipitation but continued high runoff. This high runoff results from the continued discharge of the previous month's rainfall that was held within the soil. For example, February 1995 had 6 mm of precipitation and 33 mm runoff resulting in 534% for effective rainfall. Precipitation for January 1995 was 330 mm, however, which contributed to the February 1995 runoff.

4. Conclusions

Rainfall was strongly correlated with runoff but not ET. With precipitation falling in winter when PET is lowest, there is little opportunity for abstraction of water from the watershed other than through runoff. Runoff and effective rainfall increase as rainfall increases, while ET remains relatively constant. This response is more consistent with cool–humid watersheds than more xeric conditions. Winters in northern California are cool and wet mimicking cool–humid conditions.

There is a weak indication that removal of 14% of the oak cover increased monthly effective rainfall and runoff. The threshold for significantly increased water yield from oak removal is greater than 14% of the land area. This threshold is expected to be approximately 20% of the watershed area (Stednick, 1996). In addition, the staggering of tree removal into three sequential harvesting events and the directives to woodcutters to abstain from cutting in waterways and timber removal in winter are practices that prevented significant watershed disturbance.

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