Redwood National Park - Redwood Creek Watershed

TIMBER HARVESTING AND THE HYDROLOGIC RESPONSE OF REDWOOD CREEK, CALIFORNIA

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Abstract: Timber removal on public and private land surrounding Redwood National Park exacerbates naturally high rates of erosion that are common to this region and alters hydrologic processes within the park boundaries. These alterations of the natural environment complicate the efforts of the National Park Service to preserve a remnant of the once extensive coastal redwood ecosystem in the park. A watershed model for Redwood Creek calibrated to pre-logging conditions is employed to define and quantify changes in the hydrologic response of the basin during the years when timber harvesting reduced significantly the acreage of redwoods. Analysis of modeled and observed runoff indicates that timber removal is related to increased runoff during wet months and wet years, but runoff is reduced during dry months and dry years. These alterations in the hydrologic system occur at the least beneficial time because they augment high flows, whereas low flows are depleted. Such changes in runoff contribute to magnified erosion and deposition problems and increased stress for the flora and fauna that reside in and along Redwood Creek. [Key words: Redwood National Park, hydrology, watershed model, timber harvesting.]

INTRODUCTION

Coastal redwood (*Sequoia sempervirens*) is indigenous to the cool and wet coastal mountains of northwestern California. This redwood forest is recognized as having the tallest measured individual trees in the world. Although timber harvesting has been pursued in the region for several decades, research into the harvesting of redwoods and other conifers since about 1950 has produced controversial hydrologic, geomorphic, and biologic impacts that threaten the tall trees. These ecological consequences prompted a preservation effort culminating in the establishment of Redwood National Park in October 1968. Parts of several drainage basins comprise Redwood National Park, but the largest single unit is the downstream area of Redwood Creek.

No provision for federal control of headwater areas was incorporated in the 1968 legislation establishing Redwood National Park (Iwatsubo, Nolan, Harden, Glysson, and Janda, 1975). Consequently, highly disruptive timber removal practices employed in the 1960s on non-Park land continued into the 1970s (Nolan and Janda, 1981). In March 1978, several upslope and upsteam additions were made to the Park, but about 60 percent of Redwood Creek basin remains outside the Redwood National Park boundary.

Land use activities outside Redwood National Park boundaries affect the land, water, and biotic resources inside the Park. Agencies managing the Park are particularly concerned because the Coast Ranges of northern California

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are some of the most actively eroding terrain in North America (Nolan and Janda, 1981). The naturally high erosion rates and high sediment yields in these mountains are attributed to weak rock units, moderate to steep slopes, and seasonally abundant precipitation (Nolan and Marron, 1985). Timber removal in this region accelerates the high erosion rates, increases sediment yields, and affects runoff. Controlling degradation of the Redwood National Park environment requires knowledge of the interaction between runoff and related geophysical processes inside and outside the Park boundary. The purpose of this paper is to model runoff for Redwood Creek basin and to identify and quantify runoff changes resulting from uncontrolled logging in the 1960s and regulated logging in the 1970s. Understanding the hydrologic response will complement efforts to preserve and rehabilitate Redwood National Park (Nolan and Janda, 1981; Weaver and Madej, 1981; Madej, 1984).

REDWOOD CREEK BASIN

Redwood Creek is the northernmost watershed within the Coast Ranges of northwestern California. The stream drains 720 km^2 and discharges into the Pacific Ocean near Orick about 60 km north of Eureka (Fig. 1). Runoff for Redwood Creek basin for water years 1954 to 1977 averaged 1,300 mm annually with a standard deviation of 438 mm (King, 1983). The distinctly elongated basin is situated in a fairly complex folded and faulted setting in which structural control of topography is very evident (Janda, Nolan, Harden, and Colman, 1975). The main channel of Redwood Creek drains the southern portion of the basin underlain by predominantly metamorphic rock, while Prairie Creek drains the smaller northern section underlain by coastal sediments (Harden, Kelsey, Morrison, and Stephens, 1982). Elevation within the basin varies from sea level at the mouth of Redwood Creek to a maximum of 1,581 m on Board Camp Mountain on the southwestern boundary of the watershed.

The northwest corner of California, including Redwood Creek basin, is the wettest area in the state (Rantz, 1968). Annual precipitation averages between 1,520 mm near the coast to over 2,280 mm along the eastern drainage divide. These values may be conservative since Coghlan (1984) suggests that the greater precipitation received in the watershed since 1950 may be more characteristic of the long-term nature of rainfall for the region. Over 75% of the precipitation occurs between October and March, but fog has an important influence on the moisture balance during the summer (Byers, 1953). Snow can be expected in the watershed every year at elevations above approximately 550 m, although snow accumulations are small and are limited to elevations above 1,100 m (Janda, Nolan, Harden, and Colman, 1975). Major floods in the basin correspond to regional flood-producing storms (Harden, Janda, and Nolan, 1978; Coghlan, 1984).

Topography and the Pacific Ocean exert complex influences on temperature in the watershed. The coolest temperatures occur at the lowest elevations near the ocean. The cool conditions are due to a combination of marine influence and the persistence of clouds along the coast and fog in the valley which limit solar radiation at the surface to about 50% of the maximum

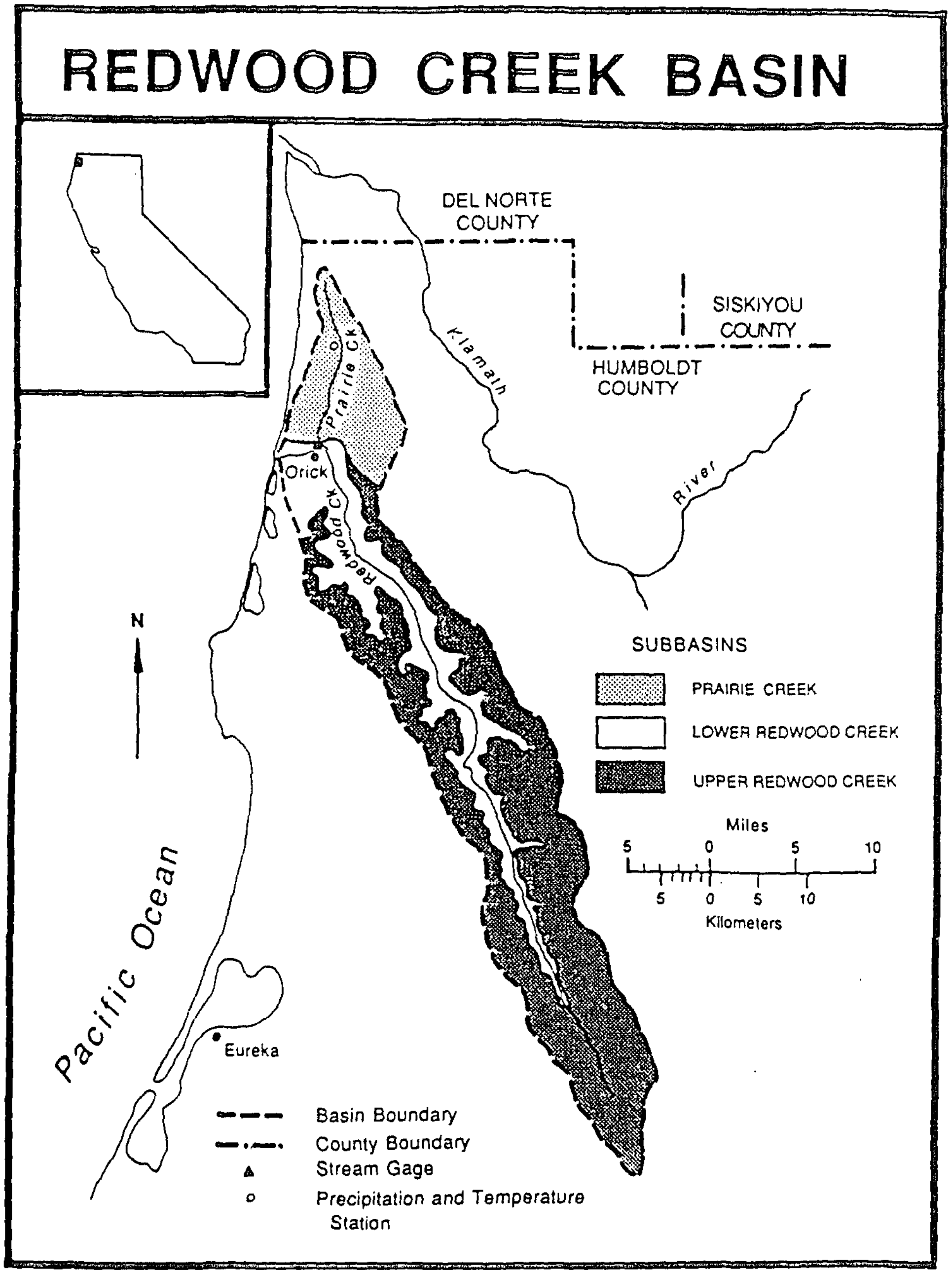

Fig. 1. The study area and model subbasins.

possible. The warmest temperatures in the basin are found at higher elevations in the southern headwaters which are most distant from the moderating effect of the ocean and above the fog layer (Janda, Nolan, Harden, and Colman, 1975). Inversions occur frequently and common lapse rate relationships do not apply in this setting.

Forest, woodland, and prairie-like communities are found throughout the basin in response to regional and local environmental gradients produced by temperature, moisture, and distance from the ocean (Janda, Nolan, Harden, and Colman, 1975). Land use is primarily related to the forest resource. Steep slopes and a small, discontinuous floodplain have deterred urban and agricultural development in the watershed.

Soils in the Prairie Creek drainage have the capacity to store substantial amounts of moisture, but most soils in Redwood Creek basin have low water storage capacities (Janda, Nolan, Harden, and Colman, 1975). The low soil moisture storage, an apparent lack of groundwater storage, and steep slopes combine to produce a rapid basin response to the distinctly seasonal precipitation regime (Rantz, 1968).

MODELING THE HYDROLOGIC RESPONSE

A modified form of the climatic water budget (Thornthwaite, 1948; Thornthwaite and Mather, 1957) is employed to model moisture partitioning in the Redwood Creek basin. This procedure uses moisture accounting concepts to trace the allocation of precipitation among competing environmental destinies. It has the advantage of requiring only readily available temperature, precipitation, and soil moisture capacity data, and it has been used successfully in estimating runoff from watersheds in diverse settings (Muller, 1966; Ward, 1972; Mather, 1979; Shelton, 1985). Modeling hydroclimatic conditions in Redwood Creek basin requires use of existing data that can be extrapolated with confidence to areal units.

Fluxes of energy and moisture at the earth-atmosphere interface are simulated by assuming that the land surface responds dynamically to the climatic sequence of precipitation and evapotranspiration. Precipitation is partitioned among evapotranspiration, soil moisture storage, and gravity water according to priorities determined by the coincidence and magnitude of energy and moisture. The surface moisture flux depends critically upon the physical properties of the soil and vegetation as well as meteorological conditions during intermittent inputs of precipitation and the more continuous upward directed moisture flux represented by evapotranspiration (Eagleson, 1978). Evapotranspiration is estimated using the temperature-based equation developed by Thornthwaite (1948) and monthly adjustments for computing evapotranspiration at California stations suggested by Shelton (1978). The water balance calculations are derived using a computer program developed by Willmott (1977).

Climatic, topographic, edaphic, and biotic heterogeneity is incorporated in the model by dividing the watershed into three homogeneous subbasins that are assumed to act independently (Fleming, 1975; Kirkby, 1975; Shelton, 1985). Spatial disaggregation of the watershed emphasizes the importance of areal variations in physical processes and the complex interaction between processes in simulating the watershed response to precipitation. The response of the total watershed is represented by area-weighting the moisture fluxes for each of the subbasins (Shelton, 1985). Lumping of model variables achieved through spatial disaggregation of the watershed helps to reduce uncertainty concerning the magnitudes and the spatial and temporal attributes of inputs, outputs, and storages (Bennett and Chorley, 1978), and it permits more of the naturally occurring variation in the watershed environment to be incorporated in the model.

The 104 km^2 drainage basin of Prairie Creek (Fig. 1) is readily distinguished as a subbasin on the basis of geology, topography, and soils (King, 1983). Delimiting subbasins within the 614 km^2 area draining into the main channel of Redwood Creek is guided by recognition of significant differences in moisture allocation processes related to diurnal marine air mass invasions from the coast. The fog carried inland by these air masses has a nonuniform affect within the Redwood Creek basin during the summer. An elevation based division of the Redwood Creek mainstem drainage permits the influence of fog on energy and moisture fluxes to be incorporated in the model in a spatially coherent manner.

Summer fog affects the hydrologic balance in Redwood Creek basin by decreasing sunlight duration, reducing air temperature, decreasing evapotranspiration, and increasing available moisture through fog interception and drip (Byers, 1953; Azevedo and Morgan, 1974). An estimate of the average vertical extent and horizontal penetration of fog in Redwood Creek basin is derived from research on vegetation patterns and fog drip along the northern California coast (Byers, 1953; Waring and Major, 1964; Azevedo and Morgan, 1974; Janda, Nolan, Harden, and Colman, 1975). Land below 381 m is assumed to be in the fog-influenced zone and this portion of the watershed is designated as Lower Redwood Creek. Those areas draining into the main channel of Redwood Creek and at elevations above 381 m are considered to be in the fog-free zone constituting the Upper Redwood Creek subbasin (Fig. 1).

Temperature, precipitation, and soil moisture storage capacities representative of the three subbasins are estimated from available data by commonly used procedures described by Linsley, Kohler, and Paulhus (1975) and King (1983). Direct runoff processes, not incorporated in the standard climatic water budget accounting, are included in the Redwood Creek model using an adaptation of the Soil Conservation Service method (U.S. Department of Agriculture, 1972) as recommended by Dunne and Leopold (1978) and Mather (1978). These calculations identify a proportion of monthly precipitation not subject to evapotranspiration; rather it is allocated immediately to runoff. Monthly precipitation less direct runoff is identified as effective precipitation in the model.

The derived data are used to calculate monthly water balances for each of the three subbasins. The variable of principal concern is surplus, which represents the residual moisture available as runoff. Delayed surplus is computed using the convention suggested by Thornthwaite and Mather (1957), namely that a percentage of available surplus in a given month will be carried forward to the next month as water in transit to the stream channel. Delaying 50% of available surplus is judged reasonable for the Lower Redwood Creek and Upper Redwood Creek subbasins, but a value of 70% is more appropriate for conditions in the Prairie Creek subbasin (King, 1983). Direct runoff and delayed surplus combine to define the water available as runoff from the subbasin each month.

Runoff for the Redwood Creek watershed is modeled as the product of the area-weighted contributions of the three subbasins. This approach provides information about the spatial differences in the processes as well as defining runoff in quantitative terms that can be compared to observed runoff during different periods of land use.

MODELED AND MEASURED RUNOFF

Analysis of the hydrologic impact of selected land use changes requires calibration of the watershed model for a period prior to the land use change (Fleming, 1975). An acceptable fit of computed and measured runoff during the calibration years gives confidence to the assumptions incorporated in the model. After the calibration years, divergence of computed and measured runoff is interpreted as a change in soil moisture storage capacity and/or evapotranspiration resulting from the land use change (Mather, 1979).

Continuous stream gauging for Redwood Creek began in 1953; consequently, water years 1954–1957 are employed to represent prelogging conditions for calibrating the model. Measured runoff varies by more than 1,000 mm during the four calibration years, and modeled runoff estimates annual measured values closely (Table 1). The greatest disparity is in 1955 when modeled runoff exceeds the measured quantity by 205 mm or 22%. However, modeled runoff is within 1% of measured runoff for the high flow years of 1954 and 1956 and the moderate runoff in water year 1957 is modeled within 7%. Modeled runoff can never exactly match recorded values due to measurement errors, and simulated runoff within 15% of measured values is acceptable (Mather, 1981).

The agreement between monthly measured and modeled runoff for 1954–1957 is illustrated in Figure 2. An objective comparison of the agreement between the two time series is provided using 6 commonly employed tests described by Aitken (1973). The ability of the model to estimate mean monthly runoff indicates the overall agreement between measured and modeled values while replication of monthly runoff variability is revealed by the stand-

Table 1. Annual Runoff for Redwood Creek Basin, Water Years 1954–1957

Water year	Measured runoff (mm)	Modeled runoff (mm)	Modeled minus measured (mm)	Modeled divided by measured (mm)
1954	1534	1528	- 6	1.00
1955	939	1144	205	1.22
1956	1996	1976	- 20	0.99
1957	1304	1397	93	1.07
Total	5773	6045	272	1.05

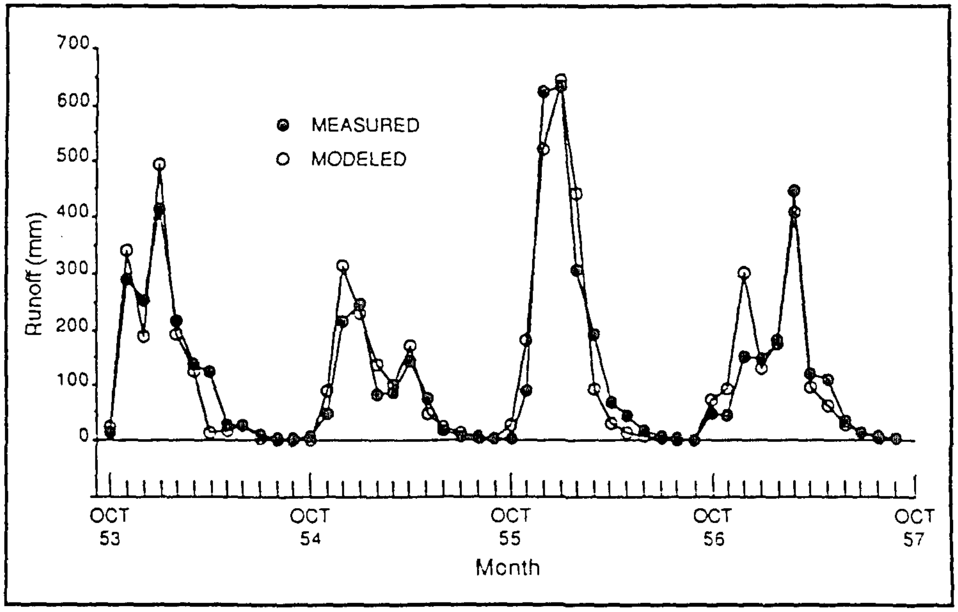

Fig. 2. Monthly measured and modeled runoff for Redwood Creek, water years 1954–1957.

ard deviation. The data in Table 2 show that the modeled values closely estimate these statistics for measured runoff. Although both the mean and standard deviation are slightly overestimated, there is no statistical difference.

A simple sign test is useful for testing the modeled time series for systematic errors. A Chi-square test indicates whether the number of runs of underestimated and overestimated monthly runoff differs significantly from the expected number. The 19 runs for Redwood Creek modeled runoff are not statistically different from the 25 expected runs. Therefore, the sign test indicates that modeled runoff does not introduce systematic error.

Additional information about the relationship between measured and modeled runoff is provided by three dimensionless coefficients of agreement (Aitken, 1973). These coefficients are expressed as

$$D = \frac{\Sigma(q_c - \bar{q}_c)^2 - \Sigma(q_c - q_r)^2}{\Sigma(q_c - \bar{q}_c)^2} \tag{1}$$

$$E = \frac{\Sigma(q_c - \bar{q}_c)^2 - \Sigma(q_c - q_m)^2}{\Sigma(q_c - \bar{q}_c)^2} \tag{2}$$

$$R = \frac{\Sigma(D_c - \bar{D}_c)^2 - \Sigma(D_c - D_e)^2}{\Sigma(D_c - \bar{D}_c)^2} \tag{3}$$

where D is the coefficient of determination; q_c is observed runoff; $\bar{q}_c$ is the mean of observed runoff; q_r is estimated runoff obtained from the regression of q_c on q_m which is modeled runoff; E is the coefficient of efficiency; R is the

Table 2. Assessment of Watershed Model, Water Years 1954–1957

	Measured runoff	Modeled runoff
Months	48	48
Mean Monthly Runoff (mm)	120	124
Standard Deviation (mm)	152	159
Coefficient of Determination (D)	—	1.00
Coefficient of Efficiency (E)	—	0.89
Residual Mass Curve Coefficient (R)	—	0.88
Sign Test		
Expected Runs	—	25
Observed Runs	—	19*

*Significant at the 0.05 level.

residual mass curve coefficient; D_c is the departure from the mean for the observed residual mass curve; $\bar{D}_c$ is the mean of the departures from the mean for the observed residual mass curve; and D_e is the departure from the mean for the modeled residual mass curve.

The degree of association between measured and modeled monthly runoff is expressed by the coefficient of determination. The value of unity for D (Table 3) indicates excellent results for the model. The coefficient of efficiency is used to reveal bias in the modeled values even when the coefficient of determination is high. The slightly lower value of E suggests that modeled Redwood Creek runoff may contain some systematic error even though the sign test does not indicate the presence of such error.

For watershed models, the residual mass curve coefficient is particularly useful because it measures the relationship between the sequence of flows rather than the relationship between individual flow events as indicated by the values of D and E. The R value of 0.88 (Table 2) indicates that the general seasonal trend of runoff is simulated well by the model. This evidence and the

Table 3. Calibration Period Major Flood on Redwood Creek

Flood episode	Basin* precipitation (mm)	Measured runoff (mm)	Measured runoff divided by precipitation	Modeled runoff (mm)	Modeled runoff divided by precipitation	Modeled minus measured runoff (mm)
Nov. 1955	330	89	0.27	181	0.55	92
Dec. 1955	630	622	0.99	520	0.83	-102
Jan. 1956	698	631	0.90	644	0.92	13
Total	1658	1342	0.81	1345	0.81	3

*Basin precipitation estimated following King (1983).

ability of the model to simulate closely the wide fluctuations in runoff provide strong support for the model as a satisfactory representation of the basin hydrologic cascade.

An additional perspective on the good agreement between measured and modeled runoff during wet months is provided by the major flood in water year 1956 (Table 3). Coghlan (1984) suggests that the December 1955 flood in Redwood Creek basin has a recurrence interval of 25–30 years. The offsetting differences between measured and modeled runoff in November and December may be explained largely by the occurrence of intense storms during the last 10 days of November 1955 which drenched the watershed with over 200 mm of rainfall (King, 1983). While the model allocates a large proportion of this precipitation to direct runoff in November, the elevated streamflow response does not occur at the stream gauge until the early days of December. This major flood episode indicates that the model accurately defines the quantity of moisture allocated to runoff, but the temporal constrains imposed by the monthly input data and accounting of moisture processing hinder more accurate depiction of how a large moisture pulse late in the month is processed through the watershed.

HYDROCLIMATIC CHANGE RELATED TO TIMBER REMOVAL

Timber harvesting by private commercial companies after 1958 reduced the acreage of redwoods in Redwood Creek basin significantly (Schrepfer, 1980). This harvesting employed a variety of logging methods on various sized tracts and created an apparent random pattern of deforestation within the basin (Nolan and Janda, 1981; Madej, 1984). A comparison of measured and modeled seasonal runoff reveals that significant changes in the hydrologic response of the watershed occurred during these years.

Most experimental watershed studies have established that timber harvesting is expected to increase annual runoff and peak flow volumes (Bosch and Hewlett, 1982). For Redwood Creek, the runoff increase is concentrated in the wet season while runoff during the drier months is reduced. These conditions are illustrated by the data for water years 1965 and 1966 in Table 4.

Annual precipitation for these 2 years differs by only 37 mm or about 2%. In water year 1965, 75% of the precipitation occurs from November to January. December alone accounts for 33% of the annual total. Coghlan (1984) estimates that the heavy rainfall in December 1964 has a recurrence interval of 45–50 years. Precipitation in water year 1966 is less concentrated with 87% of the precipitation occurring in November through March.

Measured annual runoff during the 2 water years is different by 725 mm or 40%, but modeled runoff differs by only 53 mm or 4% (Table 4). The data reveal distinct differences in how moisture is processed in the watershed. Modeled runoff reflects monthly variations in the precipitation input throughout the 2 years. Measured runoff displays a complex pattern of monthly variability that is poorly linked to precipitation and markedly different during 1965 and 1966. For the months of November 1964 through January 1965, measured runoff

Table 4. Precipitation and Runoff for Redwood Creek Basin, Water Years 1965–1966

Month	Water year 1965				Water year 1966			
	Basin precipitation (mm)	Measured runoff (mm)	Modeled runoff (mm)	Modeled minus measured (mm)	Basin precipitation (mm)	Measured runoff (mm)	Modeled runoff (mm)	Modeled minus measured (mm)
Oct.	47	3	5	2	50	3	45	42
Nov.	451	125	163	38	294	34	61	27
Dec.	644	939	572	-367	367	92	190	98
Jan.	358	445	346	- 99	515	434	552	118
Feb.	96	82	100	18	182	132	138	6
Mar.	32	39	52	13	362	247	258	11
Apr.	220	112	78	- 34	68	89	69	- 20
May	36	36	33	- 3	3	26	37	11
Jun.	12	13	17	4	26	12	20	8
Jul.	0	6	9	3	19	6	11	5
Aug.	44	3	5	2	16	2	6	4
Sep.	2	2	3	1	77	3	49	46
Total	1942	1805	1383	-422	1979	1080	1436	356

exceeds estimated basin precipitation by 56 mm. The intense rainfall occurring in these months appears as runoff relatively soon after it falls on the watershed.

During the 1964–65 flood, modeled runoff is surprisingly small compared to the volume of measured runoff. Modeled runoff is less than measured during 2 of the 3 months, and the 3 month total of modeled runoff is about 72 percent of measured runoff. This is a dramatic departure from the 1955–56 flood when modeled runoff for the 3 flood months was within 3 mm of measured runoff. The larger size of the deforested area and the surface disturbances related to falling and removal of redwoods (Janda, Nolan, Harden, and Colman, 1975; Nolan and Janda, 1981) during the intervening 10 years contributed to the large volume of measured runoff.

Other evidence of an altered response in the runoff process is provided by monthly data throughout water years 1965 and 1966. While the estimated total basin precipitation during these years is very similar and modeled annual runoff varies by only 53 mm (Table 4), measured runoff for 1966 is about 60% of 1965 measured runoff. In addition, measured runoff is 93% of precipitation in 1965 and only 55% in 1966. Timber removal is usually expected to increase water yield (Bosch and Hewlett, 1982; Harr, 1987), but the runoff increase should be approximately the same in 2 consecutive years with similar amounts of available moisture. The disparity in measured runoff in these years and the overestimation of modeled annual runoff by 356 mm in 1966 are atypical conditions. Furthermore, modeled runoff overestimates measured runoff in 15 of the 16 months from June 1965 through September 1966 (Table 4). The consistent overestimation of runoff during the dry months in water years 1965 and 1966 contrasts markedly with the underestimation of runoff during dry months in 3 of the 4 calibration years.

Two other flood episodes illustrate that the altered runoff conditions observed during 1965 and 1966 are not spurious. Redwood Creek experienced a 10-year flood in March 1972 and a 25 to 30-year flood in March 1975 (Coghlan, 1984). In both 1972 and 1975, measured runoff approximates estimated basin precipitation for the flood months and measured runoff exceeds modeled runoff significantly during both the flood months and the entire water year (King, 1983). Still, modeled runoff is greater than measured runoff during the dry months of 1972 and 1975 and modeled runoff exceeds measured runoff in each of the following water years. Although precipitation decreases in each year following these floods, the streamflow response is similar to the pattern of underestimation and overestimation seen for water years 1965 and 1966.

A test for seasonal flow changes in Redwood Creek is provided by computing the flow-duration properties of the stream. Flow-duration is determined by arranging daily mean flows according to magnitude and computing the percent of time the flow equals or exceeds a specified discharge in a given period without regard for the chronological sequence of flows (Searcy, 1959). Water years 1955 and 1956 are selected to represent the calibration years and water years 1973 and 1974 are selected for the post-logging years. Both sets of years provide a diverse range of daily high and low flows characteristic of relatively dry and wet years. The first year in each pair has an annual runoff of about 950 mm while annual runoff during the second year is about 2,000 mm or more.

The results of the flow-duration analysis (Table 5) indicate that low flows and moderately high flows are more common during water years 1973 and 1974. While both periods have approximately the same number of days with flows less than 6 $m^3 s^{-1}$, 1973–74 has over 7 times as many days when the mean flow is less than 0.6 $m^3 s^{-1}$. In addition, 4% of the days during 1973–74 have mean daily flows of 0.3 $m^3 s^{-1}$ or less. The lowest mean daily flow in 1955–56 is 0.5 $m^3 s^{-1}$ and flows less than 0.6 $m^3 s^{-1}$ occur on only 1 percent of the days. For high flow conditions, 18% of the days during 1973–74 have mean daily flows between 45 and 105 $m^3 s^{-1}$. Mean daily flows of these magnitudes occur only 12% of the time in 1955–56. These data support the inference that timber removal has resulted in greater runoff during wet periods and decreased runoff during dry periods. Nolan and Janda (1981) reach a similar conclusion after analyzing synthesized flow-duration curves to study the effects of individual storms on small study basins in the watershed.

DISCUSSION AND RESULTS

The data for the 4 calibration years (Fig. 2) indicate that the accuracy of the model is greatest during wet years and typically wet months. Modeled runoff for the wet season is most disparate from observed runoff as annual runoff decreases, and the largest percentage errors for modeled runoff are associated with the typically dry months of May to October. Nevertheless, simulating the conversion of precipitation to runoff in the watershed is accomplished with good accuracy by the model.

The more accurate runoff estimates by the model during wet years and wet months may reflect the extent to which precipitation at the index station is representative of the precipitation regime throughout the watershed. Storm systems covering the entire region dominate the moisture input for the watershed during most wet months, and frequent regional storm systems produce the wettest years. Consequently, the relationship between precipitation at the index station and precipitation occurring over the entire watershed is strongest during these months and years. During drier years and the months of May to October, rain-producing storms are less frequent and more variable spatially, and precipitation at the index station is expected to be a less precise indicator of precipitation throughout the watershed. While it would be desir-

Table 5. Selected Redwood Creek Basin Flow Duration Characteristics*

Water years	Mean daily discharge ($m^3 s^{-1}$)					
	< 0.3	< 0.6	< 1.2	< 6	45–105	> 105
1955 and 1956	0	8	101	280	85	54
1973 and 1974	31	59	146	284	134	64

*Number of days with given mean daily discharge.

able to employ a larger number of weather stations, the absence of data precludes using sites other than that at Orick-Prairie Creek State Park (Fig. 1).

An additional factor that may adversely influence the accuracy of the model during May to October is that runoff during these dry months is a product largely of groundwater storage and transmission. Groundwater processes are included in the model in a very general manner through the use of the surplus delay coefficients. A lack of hydrogeologic data for the basin prevents incorporation of a more physically-based and comprehensive representation of groundwater processes in the model.

In the post-calibration years, changes in seasonal runoff volumes for Redwood Creek are identified by comparison of measured and modeled runoff (Table 4) and by flow-duration analysis (Table 5). The watershed model provides a simulation of the runoff that would have occurred with land use conditions existing prior to water year 1958. Comparison of measured and modeled runoff indicates that, in general, wet season runoff increases and dry season runoff decreases relative to the calibration period. However, the runoff changes display a variable magnitude that results in an irregular pattern of annual underprediction and overprediction by the model (King, 1983).

The increased measured runoff that leads to underestimation of runoff by the model during wet years and wet months may be explained, at least in part, by the logging practices used for harvesting redwoods in the watershed. The falling and removal of redwoods involves larger harvest unit sizes and greater use of tractor yarding and bulldozed layouts than for logging other species (Janda, Nolan, Harden, and Colman, 1975). Extensive ground disturbances related to these practices result in soil compaction which reduces surface infiltration rates, soil disturbances which may capture subsurface flow, and road and skid trail convergence that channelizes and concentrates surface runoff (Nolan and Janda, 1981; Harr, 1987). The hydrologic effect of these surface alterations is that a large proportion of precipitation is delivered to the stream channel as runoff. Consequently, runoff during wet months and wet years is greater than runoff estimated by the model.

Enhanced wet season runoff limits the fraction of the precipitation input available for recharging soil moisture storage and groundwater storage. The model overestimation of measured runoff during the dry months and in the fall following a major flood is a manifestation of this change in moisture allocation which makes less water available to sustain runoff during dry months. Other evidence supporting diminished dry season runoff in Redwood Creek basin is the increased frequency of extremely low flows reported by Janda, Nolan, Harden, and Colman (1975), and the decline of ephemeral streams and springs reported by Coats, Miller, and Kallstrom (1979).

The reduced dry season runoff may be influenced to some degree by a decrease in fog interception and fog drip accompanying timber harvesting as suggested by Harr (1982). The high incidence of fog in Redwood Creek basin means that fog drip has the potential to be a quantifiable component of the runoff process (Azevedo and Morgan, 1974). This is especially the case since most of the timber removal has occurred in that portion of the watershed influenced by fog. Unfortunately, fog drip data are too meager to provide a quantitative estimate of runoff supported by this mechanism in the Redwood Creek watershed.

Modeled runoff demonstrates that timber removal in Redwood Creek basin has altered the hydrologic response of the watershed in a manner that emphasizes the least beneficial aspects of the natural hydrologic regime. The increase in moderately high flows contributes to accelerated erosion, mass movement, and sediment transport. The increased frequency of low flows promotes channel aggradation and increases water temperature, which may in turn restrict the diversity and growth of aquatic organisms. The watershed model provides insights that complement continuing research on land and water resource management in Redwood National Park and efforts to reduce erosion rates and to rehabilitate land disturbed by timber harvesting and road construction (Weaver and Madej, 1981). Modeled runoff provides quantiative data that can be employed to assess management programs from the perspective of the hydrologic response of the watershed.

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