Rates and Implications of Rainfall Interception in a Coastal Redwood Forest[1]

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Abstract

Throughfall was measured for a year at five-min intervals in 11 collectors randomly located on two plots in a second-growth redwood forest at the Caspar Creek Experimental Watersheds. Monitoring at one plot continued two more years, during which stemflow from 24 trees was also measured. Comparison of throughfall and stemflow to rainfall measured in adjacent clearings indicates throughfall and stemflow accounted for 75.1 and 2.5 percent, respectively, of annual rainfall, while 22.4 percent was intercepted and evaporated by the forest canopy. Average interception loss remains above 20 percent even for the largest storms monitored. Models that predict pre-logging peakflows from below-canopy rainfall suggest that altered interception and transpiration could account for the 54 to 70 percent average increases in peakflow observed in five gauged watersheds for two years after clearcutting. Results such as these can be used to estimate the influence of interception loss on landslide frequency at sites for which relationships between landslide frequency and storm rainfall have been defined.

Key words: evapotranspiration, interception, landslides, peakflow, water budget

Introduction

The extent to which logging might influence flood frequencies and erosion rates has long been a focus of concern, but analytical methods for reliably predicting potential impacts are not well-developed because the influence of forests on hydrologic and erosional processes is not fully understood. For example, logging has been assumed to affect peakflows in rain-dominated areas primarily through changes in transpiration, so only the smaller, early-season peaks—those for which post-logging changes in antecedent soil moisture are likely to be largest—are expected to change after logging. However, recent studies in northwest California indicate that even mid-winter peakflows with two-year recurrence intervals increase after logging (Lewis and others 2001, Ziemer 1998).

Recent landslide surveys also provide unexpected results: data provided by Pacific Watershed Associates (1998) show landsliding rates in some recently clearcut redwood lands to be almost an order of magnitude higher than in adjacent second-growth forests. Logging had not been expected to increase landsliding markedly in these areas because trees were thought to influence stability primarily through root cohesion, and root cohesion was thought to remain substantially intact after logging of second-growth redwoods because most stumps remain alive and resprout. If altered cohesion indeed were not a major influence, some other mechanism for

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[1] This paper was presented at the Redwood Science Symposium: What does the future hold? March 15-17, 2004, Rohnert Park, California

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destabilization must accompany logging.

A mechanism that might explain both observations is increased effective rainfall produced by a decrease in the amount of rain intercepted by and evaporated from foliage after logging. Such changes are appreciable elsewhere: annual interception of 22 to 49 percent was measured in New Zealand forests (Fahey 1964, Pearce and Rowe 1979), and losses of 20 to 45 percent were found in mature coastal forests of the Pacific Northwest (McMinn 1960, Spittlehouse 1998). We implemented a study at the Caspar Creek Experimental Watersheds to measure interception in a 120-year-old redwood forest, and to determine whether the process might be capable of influencing peakflow discharges and landsliding. The study is described in more detail by Lewis (2003), Reid and Lewis (in review), and Steinbuck (2002).

Methods

Six 1.2 m × 1.2 m rainfall collectors were distributed randomly across each of two forested 1-ha plots in North Fork Caspar Creek watershed, Mendocino County, California. The IVE site is in Iverson catchment on a southeast-facing slope at 220 m elevation. The stand at IVE has coastal redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*) as the primary canopy components, a patchy understory dominated by tanoak (*Lithocarpus densiflora*), and a basal area of 97 m^2/ha. The second site (MUN) is located at an elevation of 270 m on a north-facing slope in the Munn catchment, 1.5 km from IVE; here the canopy of redwood and Douglas-fir is more uniform, basal area is 108 m^2/ha, and the understory is sparse.

Each throughfall collector channeled water into a 150-l barrel suspended from a load cell, and data loggers recorded readings from load cells at five-minute intervals. At each plot, an identical control collector and a standard eight-inch tipping-bucket rain gauge were located in an adjacent clearcut. The analysis is based on data recorded between December 1, 1998 and November 8, 1999 at MUN and between December 5, 1998 and May 27, 2001 at IVE. One load cell failed after the 24th event at IVE, but that gauge had consistently reflected the plot average so its loss did not influence study results. Other missing data were filled in using relationships defined between readings at the various gauges.

At the long-term site, 24 trees (12 redwood, eight Douglas-fir, and four tanoak) were selected randomly and equipped with collars to divert stemflow into containers (Steinbuck 2002). Water depths were measured with a dipstick at two-day to four-week intervals between December 2, 1999 and April 20, 2001. Flows from six of the trees were routed through tipping-bucket gauges to record stemflow timing.

Results

Annual rainfall totals from standard rain gauges were four to seven percent higher than those from control collectors, so throughfall was calculated by comparison to control collectors instead of rain gauges, on the assumption that trap efficiency would be similar in forest and clearing. Sub-canopy collectors indicated that more than 98 percent of the post-event drip occurs within three hr of rainfall's end, but stemflow can continue to drain from the largest trees for 48 hr after major storms. Events were thus defined to be bounded by dry periods of at least 48 hr at the tipping bucket gauges.

Collectors operating during the first year showed total throughfall of 79 ± 6 percent (95 percent CI), with IVE having a slightly lower average (78 percent) than MUN (80 percent). The IVE plot, with a denser sub-canopy and less uniform canopy, showed higher variability among collectors (standard deviation of 0.16 compared to 0.04 at MUN). Annual throughfall ranged from 78 to 72 percent over three years of measurement at IVE and averaged 75.1 percent.

Lewis (2003) found that stemflow at IVE accounts for 2.5 percent of annual rainfall, leaving 22.3 percent to be trapped by foliage interception. For each species, event-based stemflow data show linear relations between event size and stemflow volumes, and this information was combined with Lewis' (2003) relations between tree diameter and annual stemflow to estimate stemflow for the plot for each event.

Stemflow was added to event-based throughfall and the result subtracted from rainfall to estimate interception loss for each event. Average interception rates are highest and most variable for the smallest storms and decrease with event size *(fig. 1)*, approaching an asymptote of about 21 percent for events larger than 70 mm.

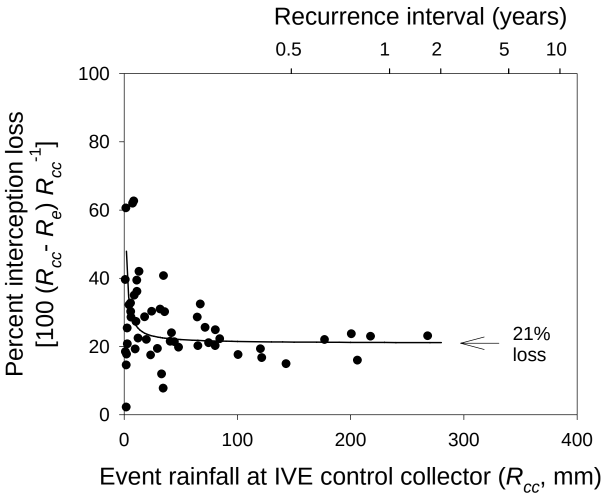

Figure 1–Variation of interception loss with storm rainfall.

Effective rainfall (R_e, mm, calculated as throughfall + stemflow) is strongly correlated with rainfall measured in the control collector (R_{cc}, mm) for events defined by 48-hr dry periods at IVE:

for $R_{cc} \geq 0.7$ mm $\quad R_e = -0.548 + 0.786\, R_{cc} \quad r^2 = 0.99$ (1a)

for $R_{cc} < 0.7$ mm $\quad R_e = 0$ (1b)

Discussion

Mechanisms of interception loss

The difference between cumulative rainfall and cumulative throughfall was plotted at five-min intervals for each storm to identify the temporal distribution of interception loss during the storm (for example, *fig. 2)*. Results show that loss rates during rainfall are appreciable; summed through the season, in-storm loss accounts for about half the overall loss, and the remainder evaporates after rainfall ceases.

Although clouds are saturated during rainstorms, the air below usually is not, so some water can evaporate (for example, Gash 1979). Because the surface area of foliage in a forest canopy is large, even low evaporation rates (in terms of loss per unit area of water surface) can evaporate large volumes of water (in terms of loss per unit area of ground surface). Similar stands nearby have a ratio of one-sided leaf area to ground area of about 14 (Kevin O'Hara, UC Berkeley, pers. comm.), implying that the actual evaporation rate per unit area of ground surface could be 28 to 44 times the rate per unit area of leaf surface, depending on the cross-sectional shape of the needles, if all surfaces are wet.

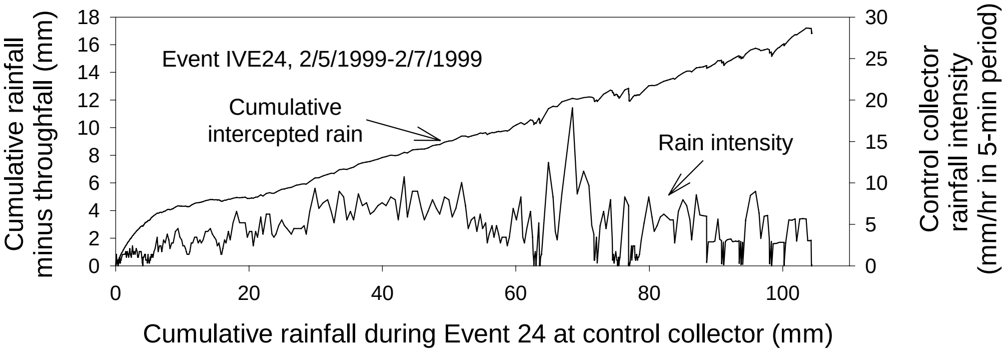

Figure 2–Cumulative intercepted rain and rainfall intensity versus cumulative rainfall at the control collector for Event 24 at IVE. The slope of the intercepted-rain curve defines the in-rain interception rate.

As an example, standard open-pan evaporation data from an area with similar climate 90 km north of Caspar Creek suggest that winter in-rain evaporation might average about 0.006 mm^3/hr (95 percent CI: 0.0005 to 0.012 mm^3/hr) per mm^2 of wetted surface, leading to an estimated loss of 0.17 to 0.26 mm^3/hr per mm^2 of ground surface for the Caspar canopy. This rate would produce about 7 to 10 mm of interception loss during the 40-hour event shown in *figure 2*. Canopy evaporation rates may be higher than open-pan rates because of increased airflow and turbulence. Some water may also be absorbed by leaves and bark for later evaporation. However, the relatively uniform loss rate during storms, as well as results of isotopic studies (Dawson 1996), suggest that absorption by leaves is less important than evaporation.

Interception and the seasonal water balance

We carried out a monthly water balance calculation, as described by Dunne and Leopold (1978 p. 238), for the North Fork Caspar Creek watershed. Rainfall and runoff have been measured in the watershed since 1963, soil moisture storage capacity can be estimated from information provided by Wosika (1981), and the present study provides estimates of interception loss. The forest-floor litter layer is also expected to intercept and evaporate rainfall, but this component was not measured during the study. Interception losses of two to five percent have been measured for litter in deciduous forests of eastern North America (Helvey and Patric 1965), and we assume a loss of three percent for these calculations.

The Thornthwaite equation for evapotranspiration implicitly considers both transpiration and interception but incorporates only solar input and temperature as driving variables, so the equation characterizes transpiration more effectively than interception. We assumed that the equation could provide the seasonal distribution of potential transpiration but would not accurately reflect its magnitude, so we rescaled the calculated monthly values using the water balance calculations to find a total annual potential transpiration that best predicts the measured mean annual runoff from North Fork Caspar Creek prior to second-growth logging.

Results suggest that interception accounted for about 70 percent of wet-season evapotranspiration before logging *(fig. 3)*. Transpiration may be partially suppressed during rain because water films can block stomatal openings. However, application of the estimated potential transpiration for each month to the average duration of rain in the month suggests that suppressed transpiration can compensate for no more than 13 percent of interception loss. Actual compensation is likely to be less because stomata are most concentrated on the parts of leaves most likely to remain dry.

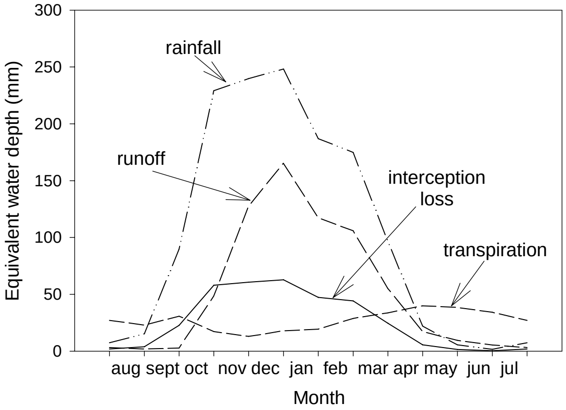

Figure 3—Average annual distribution of components of the North Fork Caspar Creek water budget for pre-logging conditions.

Modeling the effect of altered interception on peakflows

Reduced rainfall interception after logging would increase effective rainfall, thereby increasing both storm runoff and soil moisture recharge. Such changes tend to increase peakflow discharge, as does the accompanying decrease in transpiration. The expected peakflow response to such changes can be estimated by developing a model to predict peakflow from effective rainfall under forested conditions, and then reapplying the model to the same events after modifying effective rainfall to reflect canopy removal from logging *(table 1)*. Predicted changes can then be compared to those observed in the treated watersheds. The remainder of this section describes this modeling strategy in more detail and presents modeling results.

Table 1—*Strategy for modeling the influence of interception on peakflows.*

1 Develop equations to predict peakflows in control watersheds from antecedent and in-storm effective rainfall under forested conditions
2 Calculate antecedent and in-storm effective rainfall for each post-treatment storm to reflect conditions after logging at each treatment watershed
3 Apply equations from step 1 to effective rainfalls from step 2 to estimate peakflows for each control watershed, had each been logged similarly to each treated watershed
4 Regress pretreatment peakflows in each treated watershed against mean of peakflows at H and I for the same storms (the "H-I mean"), producing five calibration relations
5 Apply calibration relations to the H-I mean for each post-treatment storm to estimate the expected peakflow for the storm in each treated watershed under forested conditions
6 Apply calibration relations to the results of step 3 to estimate peakflows in each treated watershed on the basis of expected interception and transpiration after logging

Models to predict peakflows from daily rainfall records at Caspar Creek *(table 1,* step 1*)* were constructed for the control watersheds because the controls have the longest record of peakflows for forested conditions. Three general runoff modes may be important in the area: surface quickflow, rapid subsurface stormflow, and groundwater-fed flow. These components respond at different time scales and so would be associated with different descriptors of rainfall. The most useful predictor found for peakflow at the Henningson control watershed (P_H, $m^3ha^{-1}s^{-1}$) indeed incorporates three measures of rainfall *(fig. 4a)*:

$$\ln P_H = -10.9 + 1.42 \ln A0_{85} + 0.00448\, A2_{90} - 151\, A2_{99}^{-1} - 1.67\text{x}10^{-6}\, A2_{99}^{2} \qquad (2)$$

with $r^2 = 0.84$, and where $A0_{85}$ is calculated as the rainfall on the day of the peak plus 0.85 times that of the previous day, $A2_{90}$ is a standard antecedent precipitation index calculated for the second day before the peak with a recession coefficient of 0.90, and $A2_{99}$ is an equivalent index having a recession coefficient of 0.99; in both cases, daily transpiration estimated from the water budget is subtracted from rainfall before the index is calculated. The $A0_{85}$ index reflects rain falling during the rise to peak and is likely to be associated with quickflow. $A2_{90}$, which has a half-life of eight days, is set to 0.0 for calculated negative values; this index may be most relevant to subsurface stormflow. In contrast, $A2_{99}$ is allowed to accumulate negative values, and, with a half-life of 70 days, is expected to reflect a dominant control on groundwater-fed flow. The short- and long-term indices most strongly influence results.

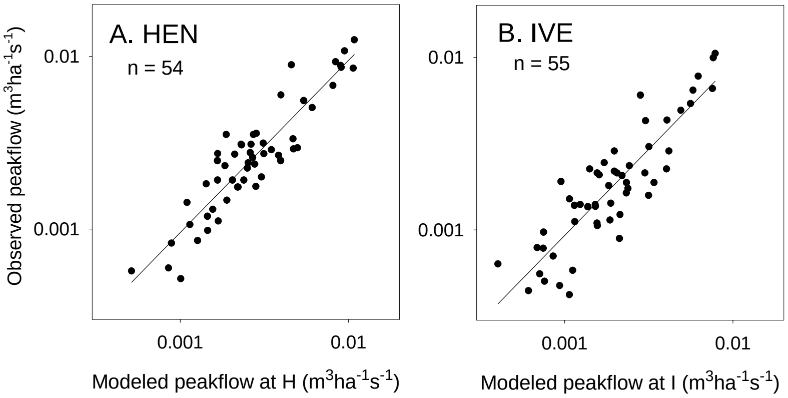

Figure 4—Observed and modeled peakflows at control watersheds A. Henningson and B. Iverson.

Peakflows at a second control watershed, Iverson, are characterized by longer lags and lower unit-area discharges than at Henningson, suggesting that the influence of groundwater may be greater there. The most effective peakflow predictor for Iverson indeed shows a different form than that found for Henningson:

$$\ln P_I = -11.0 + 1.31 \ln A0_{99} + 0.00520\, A2_{88} - 146\, A2_{99}^{-1} \quad r^2=0.77 \qquad (3)$$

In this case *(fig. 4b)*, the index associated with quickflow ($A0_{99}$) is nearly equivalent to the two-day effective rainfall preceding the peak, and the intermediate index has a recession coefficient of 0.88.

The effect on peakflows of hypothetical logging in each control watershed was then predicted using equations (2) and (3) and incorporating effective rainfall calculated for each post-treatment storm in each treated watershed (*table 1*, steps 2 and 3). Estimates of effective rainfall must take into account interception by both foliage and forest floor litter; after logging, the litter layer is augmented by logging debris, which sometimes is burned. Kelliher and others (1992) found that interception per unit leaf area on live trees is about 3.6 times greater than on slash in a *Pinus radiata* plantation in New Zealand, and this value is assumed for the present analysis. Calculations for clearcut conditions incorporate decreased canopy interception and transpiration, increased litter interception for unburned watersheds, and no increase in litter interception for burned watersheds.

The modeled results for hypothetically clearcut control watersheds must then be converted to apply to the watersheds that were actually logged. This conversion is possible using relations calibrated before treatment between peakflows in control and treatment watersheds. These calibration relations are also used to estimate peakflows that would have occurred in treated watersheds, had they not been logged. Here we use the calibration relations first to quantify the observed changes in peakflow after logging (*table 1,* step 5), and then to calculate the effects of altered interception on peakflows in the treated watersheds (*table 1,* step 6).

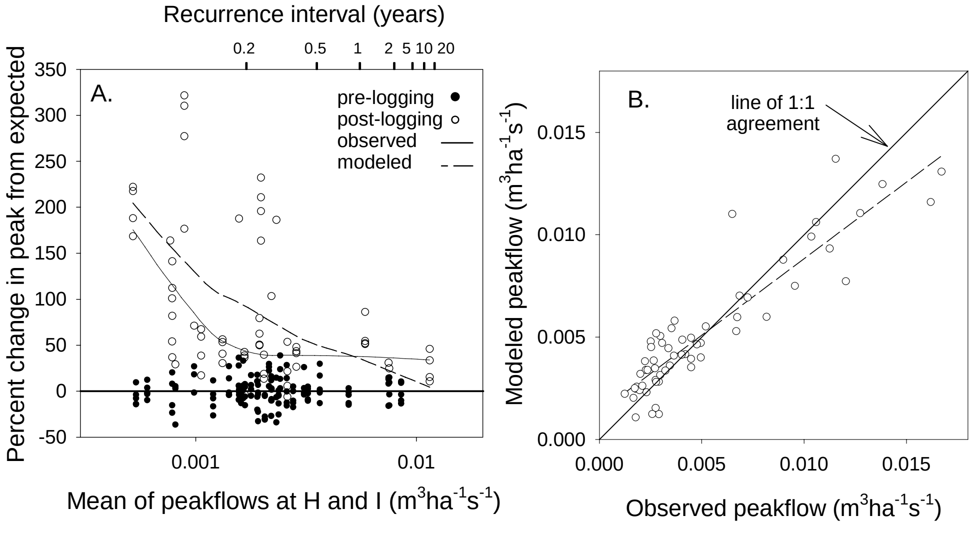

Figure 5—A. Percent deviation of observed and modeled peakflows from expected peakflow before and after logging at five clearcut watersheds as a function of mean peakflow at two control watersheds. B. Comparison of modeled and observed peakflows for two years following logging in the five clearcut watersheds.

More than 95 percent of the canopy was removed in five gauged watersheds at Caspar Creek between 1989 and 1992. Peakflows in each watershed during the five to sever yr preceding logging correlate closely to the average of corresponding peakflows at the control watersheds (*table 1*, step 4), allowing estimation of expected peakflows in the treated watersheds under forested conditions for events taking place after logging *(table 1,* step 5; *fig. 5a)*. Results using these calibration relations suggest that the five watersheds experienced a 54 to 70 percent increase in average peakflow for flows with a greater than 0.15-yr recurrence interval in the first two years after logging *(table 2)*; the average peak in this period corresponds to about a 0.37-yr recurrence interval flow. Small peakflows increase the most, but a loess regression suggests that the proportional increase approaches an asymptote of about 1.34 for flows with recurrence intervals greater than 0.3 yr; the largest peakflow (estimated recurrence interval of 13 yr) in the two years following logging increased an average of 26 percent. These data are also presented by Ziemer (1998, his Figure 3) but our analyses differ: we exclude data from more than two years after logging and calculate recurrence intervals using the 17-yr record now available.

Table 2—*Observed and modeled peakflow changes for two years following logging.*

Gauge	Area (ha)	Percent logged	Observed peakflow increase (percent)	Modeled increase from interception (percent)	Modeled increase from interception and transpiration (percent)
Ban	10	95.0	56	44	58
Car	26	95.7	54	50	67
Eag	27	99.9	58	40	64
Gib	20	99.6	70	45	69
Kje	15	97.1	67	35	78
Mean		***97.5***	***61***	***43***	***67***

The calibration relations between peakflows in treated and control watersheds were next used to convert the peakflows predicted for hypothetically logged control watersheds to corresponding peakflows in each treated watershed (*table 1*, step 6). For the two years after logging, modeled average peakflows for treated watersheds are 58 to 78 percent higher than expected under forested conditions, compared to the observed increases of 54 to 70 percent *(table 2)*. Modeled results tend to overestimate changes for small peaks and underestimate them for large peaks *(fig. 5b;* dashed curve on *fig.5a)*, but, overall, changes in interception and transpiration appear to be sufficient to account for observed increases in peakflow.

Finally, modeled results were recalculated assuming no change in transpiration after logging. The resulting mean increase in average peakflow is 43 percent *(table 2)*, suggesting that about two-thirds of the observed peakflow increase may be due to altered interception and the rest to altered transpiration.

Potential effects of interception on landslide frequency

Increased effective rainfall after logging is expected to contribute to increased sediment production from erosion processes associated with rain or wet conditions, such as bank erosion, gullies, shallow landslides, and earthflows. The potential influence of altered interception on rates of shallow landsliding can be calculated for areas where relationships between storm rainfall and landslide rates have been identified.

A relationship between areal density of landslides and storm rainfall has been defined for deforested lands in a New Zealand watershed (Reid and Page 2003). Pine plantations in the same watershed show canopy interception rates of 35 percent (Pearce and others 1987), but we carry out calculations assuming that the asymptote of 21 percent interception loss for the largest storms at Caspar Creek applies for forested conditions in order to test the potential influence of the Caspar Creek rates. The original landslide relationships for the New Zealand site were defined using gauge rainfall, which does not account for interception by grass. If grasses are assumed to intercept four percent of rainfall, gauge rainfall can be transformed to effective rainfall in the grassland areas, and the relationships can be recalculated to reflect only effective rainfall. The long-term rainfall records for the area can then be modified to reflect effective rainfall under forested conditions. Long-term landsliding rates for forested conditions were estimated by applying the recalculated landslide relationships to the modified long-term rainfall records to predict landslides generated by each storm. Results suggest that reforestation of grasslands at the New Zealand site would decrease landslide frequency by about 50 percent due to altered storm interception alone if interception rates were similar to those at Caspar Creek. Increased root cohesion would further reduce landsliding after reforestation, as would decreases in seasonal soil moisture caused by increased transpiration and foliar interception loss during smaller, non-landslide-generating storms.

Conclusions

Measurements in a second-growth redwood forest indicate that about 22.4 percent of the incoming rainfall does not reach the ground because it is intercepted by foliage. Foliage interception is expected to decrease after logging and then to gradually increase as vegetation regrows. Given the interception rates measured under forested conditions, the expected changes in interception and transpiration after logging are sufficient to account for the observed increases in peakflow in clearcut tributaries of the North Fork Caspar Creek watershed. Rainfall-peakflow models suggest that, on average, about two-thirds of the change is due to decreased interception and the rest to reduced transpiration.

Decreased interception after logging also holds implications for sediment generation. For example, a rainfall-landslide model developed for a deforested site in New Zealand suggests that shallow landslide rates would have doubled due to loss of canopy interception alone if rainfall interception rates had been equivalent to those measured at Caspar Creek.

Acknowledgements

Rand Eads, Elizabeth Keppeler, Elias Steinbuck, Randi Field, and Jason Fisher aided with various phases of the study. Funding was provided by the California Department of Forestry and Fire Protection and the USDA Forest Service. Robert Ziemer, Thomas Lisle, and an anonymous reviewer provided useful comments.

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