Modeling the Cumulative Watershed Effects of Forest Management Strategies

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ABSTRACT

There is increasing concern over the possibility of adverse cumulative watershed effects from intensive forest management. It is impractical to address many aspects of the problem experimentally because to do so would require studying large watersheds for 100 yr or more. One such aspect is the long-term effect of forest management strategies on erosion and sedimentation and the resultant damage to fish habitat. Is dispersing activities in time and space an effective way to minimize cumulative sedimentation effects? To address this problem, Monte Carlo simulations were conducted on four hypothetical 10 000-ha fifth-order forested watersheds: one watershed was left undisturbed, one was completely clearcut and roaded in 10 yr, with cutting starting at the head of the watershed and progressing toward the mouth, another was cut at the rate of 1% each year beginning at the watershed's mouth and progressing upstream, and another was cut at a rate of 1% each year, with individual cut areas being widely dispersed throughout the watershed. These cutting patterns were repeated in succeeding centuries, rebuilding one-third of the road network every 100 yr. The parameters governing the simulations were based on recent data from coastal Oregon and northwestern California, Mass wasting, the most important source of sediment in that environment, was the only hillslope process modeled. The simulation results suggest that (i) the greatest differences between management strategies appeared in the first 100 yr and were related primarily to the rate of treatment. By the second 100 yr, when all watersheds had been treated, the principal difference between logging strategies was the timing of impacts. (ii) Dispersing harvest units did not significantly reduce cumulative effects. (iii) The frequency of bed elevation changes between 1 and 4 cm is dramatically increased by logging.

Environmental concerns have increasingly turned in recent years to problems that cannot be solved experimentally. The long-term consequence of intensive forest culture is one such problem. Timber crops typically take from 25 yr to more than 100 yr to mature. Consequently, the effect of repeated harvests could be estimated experimentally only in a study lasting hundreds of years. Even if that approach was practical, it would likely be too late to take corrective action by the time the study's findings were known. Therefore, of necessity, one must resort to simulations incorporating current understanding of the relevant processes in order to estimate the long-term consequences of current forest management practices.

A simulation approach is appropriate, quite apart from the time constraints just mentioned, because of the complexity of the forest ecosystem and the uncertainty concerning the spectrum of environmental conditions that would prevail during a period spanning hundreds of years. A Monte Carlo simulation permits the explicit inclusion of estimates of variability and uncertainty in a model. These properties are essential for the characterization of meteorological inputs and can be used to account for uncertainty in hydrologic and geomorphic parameters.

Paired-watershed experiments are frequently used to investigate the effects of land use on hydrologic processes. Normally the results of paired-watershed experiments are assumed to be more real than those obtained from computer simulations. That assumption should be scrutinized a little more carefully. Paired-watershed experiments record the natural interplay of all the relevant processes. They do so, however, at one location during a relatively short period of time. Therefore, statistical inferences of such studies apply only to the study watersheds and only to the conditions operating during the study periods. All else is extrapolation based on professional judgement, not statistical inference.

A simulation has both strengths and weaknesses when compared to watershed experiments. Its greatest weakness is that it is a simplification of nature and dependent upon the modeler's skill in programming natural processes accurately. The strength of a simulation is that it can represent the mean conditions of the area being modeled and that it can explore the effect of a larger spectrum of possible sequences of events. Unlike a watershed experiment, the results of a simulation need not be the victim of the unique series of meteorological events occurring during the study. When considering long-range problems, this is a particularly desirable property. Nonetheless, it must be remembered that measuring the performance of actual watersheds is the only way by which the reasonableness of model assumptions can be tested. Such testing, however, is limited to those conditions to which the watersheds were subjected. The main values of a simulation are not to make numerically accurate evaluations of variables that quantify watershed behavior, but to scale processes and variables in terms of their importance to integrated watershed behavior and to reveal gaps in information on linkages between watershed processes. Both paired-watershed studies and model simulations must be closely linked if cumulative watershed effects are to be understood.

What follows is a primitive simulation of the changes in stream bed conditions resulting from increased bedload transport associated with three logging strategies. Only the effect of landslide erosion was considered. This limited scope was chosen because the effect of logging on erosion and sedimentation and the resultant damage to fish habitat is an important concern in the coastal environment being modeled. The model is in a continual state of expansion and improvement to more realistically address this and other environmental conflicts. A next important step is to conduct sensitivity analyses on the model inputs and to begin to validate simulation accuracy.

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THE MODELED ENVIRONMENT

The Setting

Our model simulates conditions found in the coastal watersheds of Oregon and California between 37° N and 45° N lat. These watersheds have an average elevation of 300 to 500 m and extend about 30 km inland from the coast. The region is tectonically active and is dominated by late Mesozoic and Cenozoic marine sedimentary rocks. Consequently, erosion and sedimentation rates are high. The annual rainfall of about 1500 mm supports lush forests dominated by redwood [*Sequoia sempervirens* (D. Don)Endl.] and Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco)] in the south and Sitka spruce [*Picea sitchensis* (Bong.) Carr.)] and Douglas-fir in the north.

Precipitation

The precipitation module of the model was based on records collected in the Caspar Creek Experimental Watershed of the Jackson Demonstration State Forest, 10 km south of Fort Bragg, CA. The data included the duration and total rainfall of 108 storms producing more than 50 mm of precipitation. Smaller storms in this region have low geomorphic impacts. The data spanned the hydrologic years 1963 to 1989. Snow was not an important component of any of these events. The rain gage was sited at 50 m elevation 6 km inland from the coast. To adjust this record so that it yielded storm duration and amounts more representative of the targeted elevation range (Rantz, 1968), the storm amounts were multiplied by 1.5 and storm durations by 1.65.

First, the regression of duration as a function of total precipitation was computed (Fig. 1). For the simulations, a storm amount was selected at random based on the mean and standard deviation of the adjusted data. The storm duration was then estimated from the regression equation and its standard error of estimate. An average of six storms were selected each year of a simulation, because that has been the average number of bedload-moving events recorded at the monitoring station on the North Fork of Caspar Creek. This sampling resulted in significant landslide-producing storms on an average of once every 4 yr, corresponding to the frequency estimated for the region by Rice et al. (1985).

The landslide producing capabilities of a storm were based on an extrapolation- of the work of Caine (1980), who analyzed 73 descriptions of storms that caused landslides on slopes unmodified by construction, agriculture, or stream erosion at their bases. His landslide threshold was defined by the function

$$I = 14.82\ D^{-0.39} \qquad [1]$$

where I is the average rainfall intensity (mm h^{-1}) and D is the storm duration (h). Rice et al. (1982) reasoned that a good index of storm severity (S) might be the distance of a storm from Caine's landslide threshold function in the intensity/duration space, given by

$$S = \log(0.081\, I^{0.93} D^{0.36}) \qquad [2]$$

A severity of 0 is equivalent to a 2-yr recurrence interval storm.

The final step in the precipitation module of the simulation was to run it for 10 000 years to get estimates of the return periods of storms of various severities.

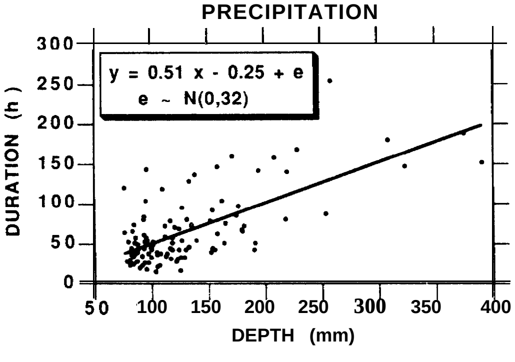

Fig. 1. Depth and duration of rainfall at Caspar Creek from 1963 to 1989, adjusted for target elevation.

Erosion

The erosion module of the simulation only estimates mass movement erosion. This simplification is adequate for the level of sophistication that exists in other elements of the model. Mass wasting is responsible for most of the erosion on forest lands in northwestern California. In addition to the quantitative importance of mass movements, they are much more likely to yield particles of a size that will affect stream bed stability than will surface, rill, or gully erosion.

The loss of root strength was assumed to be the

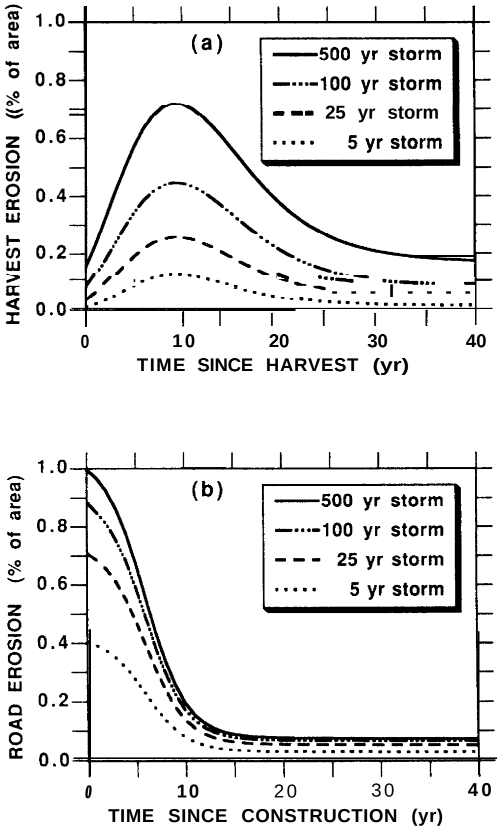

Fig. 2. The erosion module. (a) Harvest erosion was a function of storm "severity" and the changes in soil reinforcement by live and dead roots after cutting. (b) Road erosion rapidly declines after construction and its magnitude was a function of storm severity.

principal factor predisposing clearcut areas to accelerated landslide erosion (Ziemer, 198la). The loss of root reinforcement as a function of time since logging was patterned after Ziemer's (198lb) results, modified to fit data collected on the coast of central Oregon (Ziemer, 1976, unpublished data). The area affected by a storm having a severity with a 5-yr return-period was estimated from Lewis and Rice (1990). The equations relating erosion to severity and time since logging (Fig. 2a) were

$$E_h = 0, \qquad S < 0 \quad [3]$$

$$\log_{10} E_h = (1.980B + 2.565)S - (1.566B + 2.707), \qquad S \geq 0 \quad [4]$$

$$B = \frac{1}{1 + 21.674e^{-0.1758t}} + e^{-0.2303t} \quad [5]$$

where E_h is the proportion of logged area eroded, B is the sum of the proportions of maximum root reinforcement due to live and dead roots, and t is the time in years since logging. Area was converted to volume using an average landslide depth of 1 m.

The resulting erosion function reaches its peak 9 yr after logging, when root reinforcement is at a minimum. The maximum height of the erosion curve for a 500-yr-return-period storm was based on the estimate of the total harvest area susceptible to landslide erosion based on data from Lewis and Rice (1990).

The road erosion function (Fig. 2b) had a similar origin. It has been observed that most erosion occurs soon after construction and diminishes to a relatively low constant level in about 15 yr. Again, the 5-yr-storm-severity curve was constrained to fit the Lewis and Rice (1990) data for area affected by a road network occupying 5% of the land. Erosion by the 500-yr storm was set to the estimate of the total amount of the road right-of-way susceptible to landslides immediately after road construction. The equation relating erosion to storm severity and time since road construction (Fig. 2b) is

$$E_r = \begin{cases} 0, & S < 0 \quad [6] \\ \left(0.0008 + \dfrac{0.02}{1 + 0.0908e^{0.4848t}}\right) S^{0.644}, & S \geq 0 \quad [7] \end{cases}$$

where E_r is the proportion of logged area in road failures. Area was converted to volume using an average landslide depth of 1.5 m.

Tributary Sediment Transport

All processes, from precipitation and erosion to the entry of water and sediment into the fifth-order main channel of the modeled watersheds, were lumped into tributary channel algorithms. Changes in rainfall interception and other transmission losses due to logging were considered to be negligible. This assumption seems reasonable since, in the region being modeled, almost all of the important runoff occurs after the watersheds have been wetted-up in the fall, making them respond rapidly to rainfall. Runoff was delivered to the fifth-order main channel as one cycle of a sine wave representing rainfall intensity. Streamflow and sediment transport were computed using a 10-min-iteration interval.

During landslide-producing storms, 20% of the eroded material was delivered to the fifth-order main channel and the other 80% was stored in the source tributary or subcatchment. A 0.23 delivery ratio was reported at Caspar Creek (Rice et al., 1979). Of the sediment delivered to the main channel, half was assumed to be suspended load that passed through the watershed, This seemed to be a reasonable allocation for conditions in the modeled region. During all storms, whether or not they were large enough to cause landslides, sediment was also exported from the five fourth-order tributaries as a function of water discharge and the amount of sediment stored in the tributaries

$$Q_s = 1.97Q_w^{2.80}S_s^{0.769} \times 10^{-10} \quad [8]$$

where

Q_s = tributary bedload sediment discharge (kg s^{-1})
Q_w = tributary water discharge ($m^3 s^{-1}$)

and

S_s = tributary sediment supply (kg).

Throughout the simulations, each tributary had a base flow of 0.14 m^3 s^{-1}. The values of the parameters in Eq. [8] were determined during initial calibration runs of the full model to provide stable stream bed elevations in the uncut watershed ever 500 yr.

Flows entering the fifth-order main channel were routed to the watershed's mouth using the Muskingum flood routing technique (Linsley et al., 1982). Flood peaks traveled through the main channel, which was divided into 12 l-km-long reaches, in about 2 h. Bankfull discharge was set using Young and Cruff's (1967) equation for a 1.2-yr-recurrence-interval flood (annual series) as a function of drainage area and mean annual precipitation. The uppermost fifth-order segment was modeled after Jacoby Creek (Lisle, 1989), a 36.3-km^2 drainage in north coastal California. Width was increased downstream according to common hydraulic geometry parameters reported by Carlston (1969). Fixed channel slopes were assigned to each of the 12 reaches based on an assumed reduction in mean channel gradient from 0.55 to 0.40% downstream and a random component based on a coefficient of variation of 0.20, The uppermost reach began at the junction of two fourth-order tributaries, was 20 m wide, and had a slope of 0.678%. Other tributaries joined the main channel between reaches 3 and 4, 6 and 7, and 9 and 10. The lowest reach, reach 12, was 28 m wide and had a slope of 0.398%.

Bed Dynamics

Channel aggradation or degradation can result when the bedload transport into a reach differs from transport out of the reach. The bedload transport rate depends on a balance of forces between the shear stress on the bed exerted by the flowing water and the resistance to movement of the bed material. Bed dynamics were modeled using the Meyer-Peter and Muller (1948) formula, where bedload transport is a function of excess shear stress

$$I_b = \frac{8.0w(\tau - \tau_c)^{1.5}}{\rho^{1/2}(\rho_s - \rho)g} \quad [9]$$

with

$$\tau = r_w ds \qquad [10]$$

and

$$\tau_c = 0.06(\rho_s - \rho)gD_{50} \qquad [11]$$

where

I_b = bedload transport rate (kg m^{-1} s^{-1}),
w = bed width of assumed rectangular channel (m),
τ = shear stress (kg $\mathrm{m}^{-1}\,\mathrm{s}^{-2}$),
τ_c = critical shear stress for bed material entrainment (kg $\mathrm{m}^{-1}\,\mathrm{s}^{-2}$),
ρ = density of water (kg m^{-3}),
ρ_s = density of sediment (kg m^{-3}),
d = flow depth (m),
s = channel slope,
r_w = unit weight of water (kg $\mathrm{m}^{-2}\,\mathrm{s}^{-2}$),
D_{50} = median particle diameter of bed surface (m),

and

g = acceleration due to gravity (m s^{-2}).

Critical shear stress (Eq. [11]) was derived from Shield's (1936) criterion for bed material entrainment, using D_{50} as a grain-size parameter. Depth and discharge were related by the following equations

$$Q = wdU \qquad [12]$$
$$U = 2.5\,(gds)^{1/2}\ln(1.59d/D_{50}) \qquad [13]$$

where

Q = water discharge ($\mathrm{m}^3\,\mathrm{s}^{-1}$)
U = mean flow velocity (m s^{-1}).

Equation [13] is a form of Hey's (1979) friction equation. Since depth had to be determined from the Muskingum discharge, and the above relationship between Q and d cannot be explicitly solved for d, an exponential rating curve dependent on D_{50} was fit to the relationship at each 10-min iteration.

Dietrich et al. (1989) have shown that surface grain size can adjust to rates of bedload input. Therefore, D_{50} was allowed to vary as a function of bed elevation

$$D_{50} = e^{(-0.41E-2.30)} \qquad [14]$$

where

E = bed elevation (m)

The values of the parameters in Eq. [14] were determined during initial calibration runs of the full model to obtain a stable stream bed elevation in the uncut watershed. Bed elevations were measured relative to initial bed elevations defined as 0 for each reach. At each iteration of the simulation, D_{50} was adjusted for changes in bed elevation due to bedload transport in the previous iteration.

THE SIMULATIONS

We ran this model in an undisturbed watershed condition for 500 yr to tune the tributary channel sediment delivery algorithms so that the whole model was approximately in a steady state and each of the main channel reaches had come to equilibrium with respect to bed elevation and D_{50}. These steady-state conditions became the initial state of the undisturbed and manipulated watersheds during the experimental simulations.

The objective of the experimental simulations was to contrast three different timber harvesting strategies. Each strategy was based on clearcut logging and a 100-yr cutting cycle.

Two strategies called for clearcutting 1% of the watershed each year: a dispersed strategy and a progressive strategy. One percent of the total road network was constructed during each year of the first 100 yr in each simulation. During subsequent hundred-year periods 0.33% of the road system was rebuilt each year to simulate the land disturbance that would likely result from road rehabilitation, minor realignment, and the reopening of temporary spur roads. In the 1% dispersed-logging strategy, five widely dispersed 20-ha first-order basins were clearcut each year. Dispersion in this manner is usually presumed to decrease the accumulation of sediment downstream. In the 1% progressive-cutting pattern, logging began at the mouth of the watershed and spread upstream at a rate of 100 ha yr^{-1}. A cutting pattern of this type has been proposed as being less disruptive to wildlife than the dispersed logging strategy. The cutting progressed upstream in order to minimize the chance of cumulative sedimentation effects. Such a cutting pattern increases the opportunity for excess sediment produced in 1 yr to be exported past any point in the watershed before sediment generated in subsequent years has a chance to move that far downstream.

The third logging strategy was expected to cause the greatest environmental impact. In this strategy, logging began in the headwaters of the watershed and progressed downstream at a rate of 1000 ha yr^{-1}. That is, the entire drainage would be logged in the first 10 yr of each 100 yr, followed by 90 yr of regrowth with no disturbance. The construction of 10% of the transportation system accompanied each year's logging during the first century. During the first 10 yr of subsequent 100-yr periods, 3.33% of the road was rebuilt each year. This rate of cutting was assumed to be the fastest that was technically feasible in a watershed of 10 000 ha. Moving the logging operation in a downstream direction theoretically increases the opportunity for cumulative watershed effects to occur.

The effect of these logging strategies, in excess of natural variability, was recorded in terms of the magnitude and frequency of changes in bed elevation (Fig. 3). The principal threshold of concern was a within-storm change in bed elevation >0. 10 m. Such changes have a high probability of either burying and smothering spawning redds or scouring and destroying fish eggs. We realize that changes in spawning success may not always affect fish populations in a stream, but such changes can be incorporated in models of stream-bed dynamics more readily than other aspects of fish habitat.

The model did not allow any logging-related streamflow increases because studies at Caspar Creek (Ziemer, 1981c; Wright, 1985) have indicated that logging in this environment does not cause greater storm flow or peak discharges for any but the smallest autumn storms.

Our experimental results are the averages of ten 200-yr simulations. The simulations were terminated at

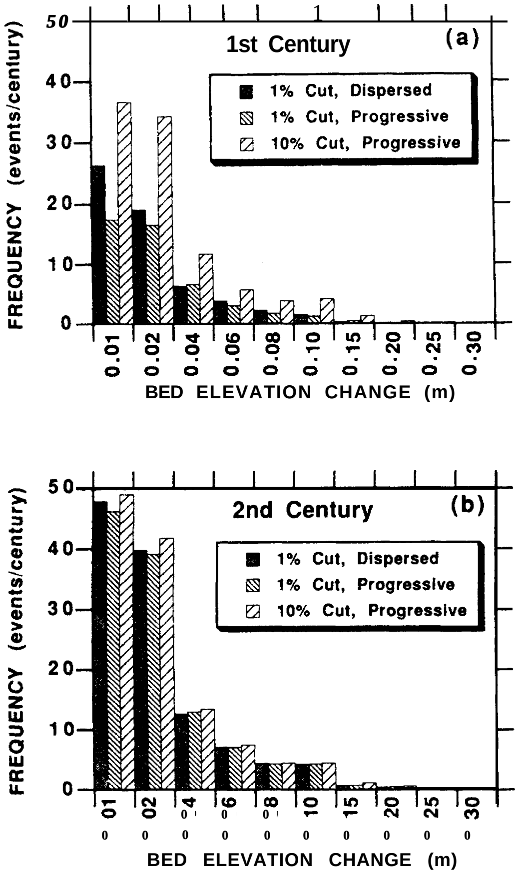

Fig. 3. The distribution of within-storm changes in bed elevation, in excess of the number occurring in the undisturbed watershed, for (*a*) the first 100-yr period and (*b*) the second 100-yr period. The values are averaged over all 12 reaches and 10 simulations.

200 yr because earlier, longer simulations had shown that there was little change in the pattern of disturbance effects after the second 100-yr period.

RESULTS AND DISCUSSION

The distribution of magnitudes of within-storm changes in bed elevation (in excess of those occurring in the undisturbed watershed) was averaged for each strategy over all 12 reaches and 10 simulations during each 100-yr period (Fig. 3a and 3b). As expected, there was a decline in frequency with increasing magnitude of bed elevation change. However, the results suggest some important problems associated with estimating long-term cumulative watershed effects.

The differences between the 10% progressive logging and the two 1% logging strategies were much greater in the first 100-yr period (Fig. 3a) than in the second 100-yr period (Fig. 3b). In the first 100-yr period, the 10% strategy produced about twice the frequency of bed elevation changes as did the 1% strategies. In the second 100-yr period, there was little difference between the strategies, when averaged over all reaches for a century.

The reason for the differences between strategies observed in the first 100-yr period is related primarily to the rate of treatment. For the 10% strategy, the entire watershed was treated within the first 10 yr, whereas the entire 100 yr was required to treat the watershed under the 1% strategies. In other words, after the first 50 yr under the 1% strategies, one-half of the watershed was still uncut and unroaded. By the end of the first 100-yr period, the road network and logging was complete under each strategy, and thereafter comparisons are of completely managed watersheds representing different temporal sequences of treatment.

Most watersheds in western North America have experienced varying amounts of logging during this century. Consequently, the actual field conditions available to evaluate cumulative watershed effects represent conditions similar to that modeled during the first 100-yr period. The second and subsequent 100-yr periods better represent the steady-state condition of managed watersheds. Therefore, contemporary field data are not available to effectively test whether reduced rates of logging and dispersion will reduce cumulative watershed effects. It is doubtful that designed experimental field data spanning several hundred-year periods will ever be available to test such hypotheses.

The frequency of treatment-induced bed elevation changes was consistently greater in the second 100-yr period of treatment than in the first 100-yr period for each logging strategy. As just discussed, such an increase is expected for the 1% strategies, because treatment of the watershed was not completed until the end of the first 100-yr period. In addition, some of the excess sediment that was produced during the first 100-yr period was initially stored in the tributaries, resulting in increased delivery rates to the main channel during the second 100-yr period. Consequently, there was a time lag between the erosion event and the transport of that material to the main channel. A recent sediment budget for North Fork Caspar Creek, a third-order stream in north-coastal California, revealed that channels are still adjusting to logging that occurred in the late nineteenth and early twentieth centuries (M.B. Napolitano, 1990, personal communication). Thus, both simulated and measured lags in treatment effects suggest that appraisals based on contemporary inputs may underestimate long-term cumulative watershed effects. Estimates of future impacts should consider the condition and changes in sediment storage in third-order and smaller streams, because routing of sediment from these channels will eventually affect mainstem channels.

In the undisturbed watershed, the pattern of occurrence of >0.10-m bed disturbances, the threshold of concern, was similar in the two hundred-year periods (Fig. 4a). For this watershed, the threshold was exceeded an average of two to three times every 100-yr period. The two 1% logging strategies, however, had about 1.7 times the rate of bed disturbance of that in the uncut watershed during the first 100-yr period and 3.2 times more disturbances during the second 100-yr period (Fig. 4b and 4d). As expected, during the first 100-yr period, the number of >0.10-m bed disturbances increased as the logging proceeded. Using *t*-tests for paired comparisons of these bed disturbances within 25-yr segments, the 1% dispersed strategy was not significantly different (experiment-wise $P = 0.05$) from the uncut for the first 50 yr of the first 100-yr period. However, for subsequent years, the 1% strategy produced significantly more bed disturbances than did the uncut watershed. There was no significant difference between the 1% progressive and dispersed strat-

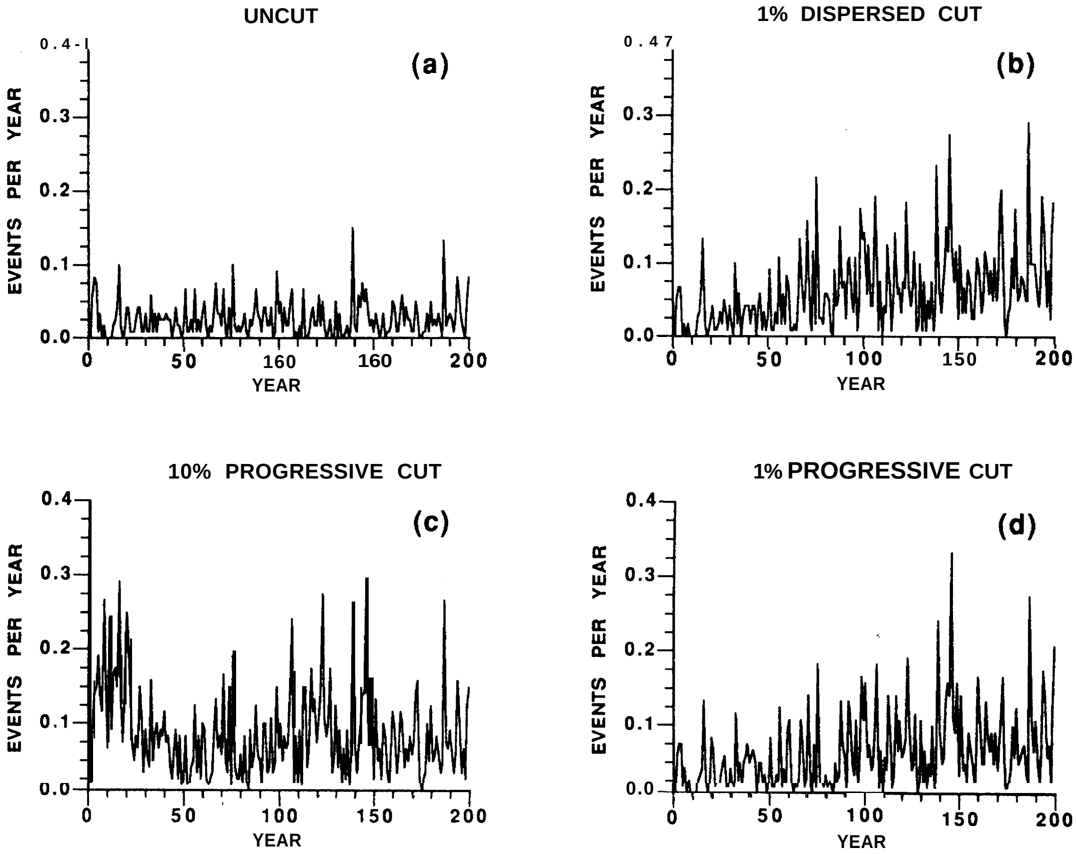

Fig. 4. The pattern of occurrence of >0.10-m bed elevation changes in the (a) uncut, (b) 1% dispersed cut, (c) 10% progressive cut, and (d) 1% progressive cut watersheds. The values are averaged over all 12 reaches and 10 simulations.

egies for any 25-yr period. The 10% progressive logging strategy produced significantly more bed disturbances (Fig. 4c) than did the 1% strategies during the first 75 yr of the first 100-yr period and the first 50 yr of the second 100-yr period. For the final 25 yr of the second 100-yr period, the 10% strategy produced fewer > 0.10-m bed disturbances than did the 1% strategies. Late in each century, effects of the 10% treatment diminished as the watershed recovered, while treatment was continuing in the 1% strategies. The residual and continuing influence of road-related erosion is the principal reason for the long recovery time.

Logging impacts are seen in a different perspective if individual reaches are considered. Some reaches were relatively immune to logging-induced bed disturbances, while a disproportionate amount of the bed changes were found in other reaches (Fig. 5). Compared to the uncut watershed, there was less than one excess critical event produced by each logging strategy during the second 100-yr period in Reaches 3, 5, 6, and 12 combined. Reach 9 was most vulnerable to bed disturbance (>20 events in the second 100-yr period). Reaches 2, 4, 7, 10, and 11 ranged from 3 to 7 excess events in the second 100-yr period. Only in Reach 1 was there an observable difference related to logging strategy. The 10% cut produced about 50% more events than did the 1% strategies.

Such differences in the responses of the reaches might have important biological consequences. For example, one might expect Reach 9 to be the place where logging induced changes would be most evident. The magnitude of bed disturbance here might result in a substantial reduction in spawning success, relative to the uncut condition. Observations of logging impacts in Reaches 3, 5, 6, and 12 might be expected to show no changes compared to the unlogged condition. Successful spawning in Reaches 3, 5, 6, or 12 may or may not compensate for reduced egg survival in heavily affected reaches.

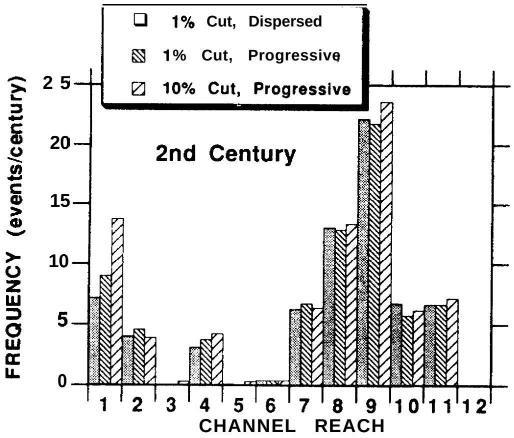

Fig. 5. The total number of >10-m within-storm bed elevation changes in the second 100-yr period, in excess of the number occurring in the undisturbed watershed. The values are averaged over 10 simulations for each of the 12 channel reaches.

The frequency of within-storm bed elevation changes (>0.10 m) that could directly affect fish spawning success varied from approximately once every 12 yr (10% strategy) to 22 yr (1% strategies) in the first 100-yr period, and was about once every 12 yr during the second 100-yr period for each strategy. However, there was a very large frequency of shallower (<0.10 m) scour and fill events. The importance of these results is the difference in frequency between deeper and shallower bed disturbances, not the specific values obtained by the simulation. The modeled channels scoured and filled uniformly in response to changes in sediment storage. Natural channels can scour and fill deeply in local areas even if reach-averaged bed elevation does not vary (Andrews, 1979; Lisle, 1989). Nonetheless, the simulations suggest an increased frequency of shallow scour and fill events. This might be a cumulative watershed effect on stream biota that warrants further investigation. For example, increased deposition and associated infiltration of fine sediment can affect fish reproduction by reducing the flow of oxygen to redds in the stream bed, as well as limit the production of the macroinvertebrate food supply.

CONCLUSIONS

This Monte Carlo simulation of the effect of different forest management strategies has resulted in some rather disturbing hypotheses:

1. Current estimates of cumulative watershed effects of logging may underestimate their magnitude, because effects accumulate over much longer periods than previously considered. Actual observations of the effects of logging western North American forests generally represent only the initial entry into previously uncut watersheds. Even where forests have been managed for many years, data bases span less than 50 yr.
2. Current cumulative effects appraisals may overestimate the benefits of dispersion as a tactic to reduce sedimentation impacts.
3. Although the average frequency of stream bed disturbances in the second and subsequent 100-yr periods are similar for each strategy, the 10% strategy concentrates the timing of these disturbances, temporarily increasing the potential damage to fish populations.
4. The frequency of small changes in bed elevation were dramatically increased by logging. Such small bed disturbances may reduce fish reproductive success or harm fish indirectly through their effect on lower trophic-level organisms. More needs to be known about the effect that minor bed disturbances have on these organisms and their recuperative powers.

If further study supports these preliminary findings, long-term forest planning decisions will need to be reexamined to better balance the trade-offs between wood products and aquatic habitat.

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