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AN APPROACH TO EVALUATING THE LONG-TERM EFFECTS OF LAND USE  
ON LANDSLIDES, EROSION, AND STREAM CHANNELS

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SUMMARY; There is increasing concern about how land management practices influence the frequency of mass erosion and sedimentation over large temporal and spatial scales. Monte Carlo simulations can identify fruitful areas for continuing cooperation between scientists in the U.S.A. and Japan.

1. INTRODUCTION

There is world-wide concern that environmental quality is becoming increasingly degraded by the accumulation of multiple human activities. This has become a particularly thorny scientific, legal, and political issue. Concerns of human activities such as pollutant discharges at point sources can first be identified and then regulated directly. However, when there are many and widely dispersed point discharges, such as automobile emissions, even when the level of individual emissions is reduced, the total emission from many automobiles can produce a "cumulative effect" that degrades air quality below acceptable levels.

To deal with non-point sources of pollution, such as stream sediment produced by erosion from forest management operations, regulations require land managers to reduce on-site erosion in order to keep the amount of sediment discharged from each project area within acceptable limits. The activities developed to meet these regulations are sometimes referred to as "Best Management Practices". As with the example of reduced automobile emissions, Best Management Practices are designed to reduce pollutant discharge from a single project, but may not solve the larger problem of the cumulative effect of multiple projects. Land managers and regulatory agencies are increasingly being required to address the cumulative effect of each proposed project within the context of all other projects within a specified area. At this time, however, managers and agencies have not yet clearly resolved what a cumulative effects analysis should contain, or even what constitutes a cumulative effect.

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## 2. CUMULATIVE EFFECTS

The question of what is a cumulative effect has been argued at technical meetings and in the courts for many years. In 1971, the Council on Environmental Quality (CEQ) issued their guidelines for implementing the National Environmental Quality Act of 1969. The CEQ defined cumulative effects in a way that identified an approach to land management and impact mitigation that had not been employed in the past. This definition set the tone for subsequent legal decisions.

"'Cumulative impact' is the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency or person undertakes such other actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time."  
(CEQ Guidelines, 40 CFR 1508.7, issued 23 April 1971)

There are some key phrases in this definition that will continue to shape impact mitigation and the need for present and future research. First, in order for there to be a cumulative effect there must be an impact on the environment. Second, the action can be individually minor but collectively significant. Third, an evaluation of an action must account for past, present, and reasonably foreseeable future actions. And finally, the incremental effect of these minor actions can accumulate over a period of time.

Out of this important definition emerge two critical issues, the spatial scale and temporal scale of the analysis.

### 2.1 Spatial scale

Traditionally, impact analyses have concentrated upon the on-site effects of land management proposals. On-site effects generally have a scale that range from several square meters to several hectares. More recently, regulators and land managers have become increasingly concerned about off-site effects. Historically, off-site effects have been considered to extend a relatively short distance from the immediate project--such as individual pools or individual stream reaches draining small upland watersheds, usually smaller than 100 ha. Managers are beginning to be required to evaluate the effect of a proposed project within the context of a drainage basin up to perhaps 20,000 ha. The size of the appropriate area of concern continues to expand. In some cases, land managers are now being asked to evaluate the effects of proposed projects within the context of entire drainage systems. An example is the emerging concerns related to the influence of forestry operations, hydroelectric dams, agriculture, and other human activities on salmon production in the Columbia River Basin. To provide an answer to a question of such an enormous scale requires understanding the influence of land management on survival of these anadromous salmonids from hatching in the River's headwaters in Idaho and British Columbia, migrating downstream through its' estuary, to the the ocean, and finally, after several years in the ocean, migrating up-river to spawn. An analysis at this spatial scale is much more demanding and comprehensive than simply evaluating on-site effects.

## 2.2 Temporal scale

Similarly, impact analyses traditionally consider only the short-term consequences of land management activities--usually several years at most. However, as with the issue of spatial scale, temporal scale effects have a wide range of appropriate scales that depend upon the question asked. For example, a domestic water user might be quite concerned about changes in turbidity during a single storm. Changes in insect production, that is in turn linked to fish growth, might be resolved at an annual scale. Changes that require a decade or more to become evident, are, for example, filling of pools with sediment or reduction in the supply of large woody debris, that, in turn, causes the stream bed to become unstable. Examples of changes requiring a time period of about a century, are the failure of stream crossings designed to withstand the 50-year storm, the aggradation of alluvial downstream reaches, and increased frequency of streamside landslides. A specific example illustrates the long-term nature of some cumulative effects. Placer mining conducted in the Sierra Nevada of California in the 1840's placed a large quantity of coarse-grained sediment in tributaries. Slugs of this material continue to enter the Sacramento River system, 150 years later.

Consequently, both environmental analyses and research programs must increase the size of the area of concern and the time period of concern related to land management. In addition, there must be an increased emphasis on dealing with complexity and interactions between issues. For example, it is important to integrate the physical and biological consequences of land management actions. It will no longer suffice to simply report the quantity of increased sediment output related to land management. The effect of that sediment on riparian ecosystems must be better understood.

A serious problem is that long-term cumulative effects can not be measured. Increased measurement and monitoring at some point downstream from a proposed project is not an adequate strategy to evaluate long-term cumulative effects, because by the time a change is detected, the projects that caused the change have often been completed--in some instances, several decades or perhaps even a century before. In such a case, no amount of on-site project mitigation could be effective. Consequently, it is necessary to be able to predict what the consequences of the proposed project might be. That is, the cumulative effects of the proposed project must be modeled.

## 2.3 Cumulative effects model

To illustrate an approach, ZIEMER et al. (1991a,b) conducted Monte Carlo simulations of the long-term effect of three forest management strategies on erosion, sedimentation, and salmon egg survival within hypothetical 10,000-ha fifth-order forested watersheds. One watershed was left undisturbed, one was completely clearcut and roaded in 10 years, and another clearcut and roaded at a rate of 1% each year. These cutting patterns were repeated in succeeding centuries, rebuilding one-third of the road network every 100 years. Each watershed was composed of five 2000-ha fourth-order tributaries (Fig. 1). The model predicted changes to twelve 1-km-long reaches of the fifth-order channel.

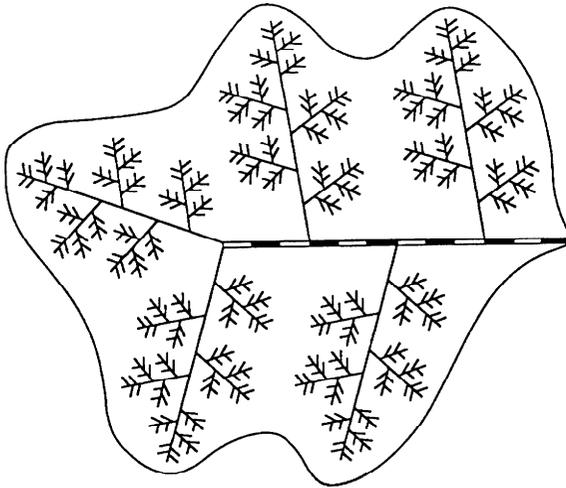


FIGURE 1. Modeled hypothetical 10,000-ha fifth-order watershed.

Rainfall is one of the primary causes of erosion in forested steepplands. CAINE (1980) presented a relationship between rainfall intensity and duration that seemed to describe a "threshold" of world-wide occurrence of landslides. RICE et al. (1982) reasoned that a good index of storm severity, and hence the probability of a landslide occurring, might be the distance in the intensity/duration space of a storm from Caine's landslide threshold function (Fig. 2). So, by knowing the amount and duration of rainfall expected for storms in particular watersheds, one could obtain the relative probability of landslides occurring during a specified time period.

One of the most important parameters contributing to differences in erosion rate between forested and harvested watersheds is the contribution of roots to soil strength. The roots of the trees provide pickets that tie the weak or unstable soil mass to the stronger stable

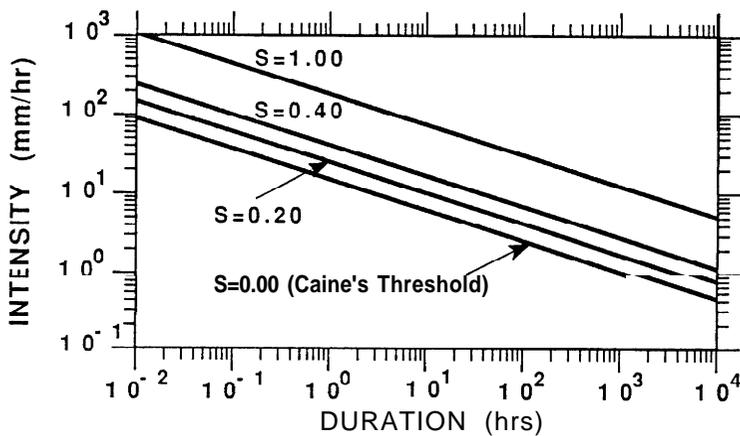


FIGURE 2. Storm severity (S) as a function of rainfall duration and rainfall intensity.

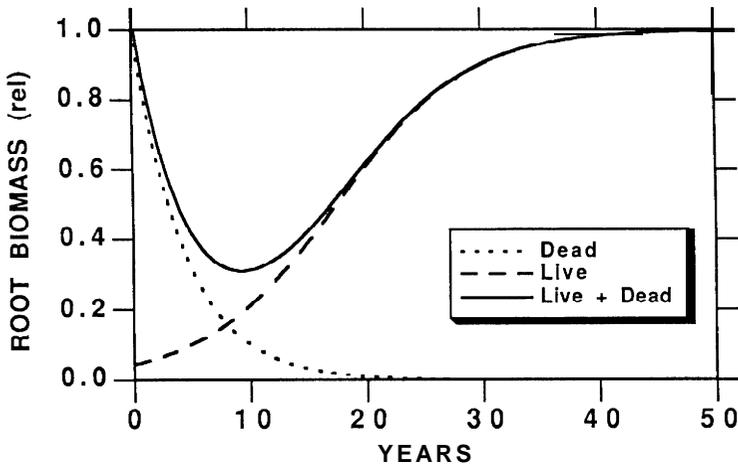


FIGURE 3. Change in live, dead, and total root biomass as a function of time following logging (from ZIEMER, 1976, unpublished data).

bedrock underlying the soil. Also, roots provide tensile binders that strengthen the weak soil mass itself. When trees are cut, root biomass and consequently root strength declines quickly (ZIEMER, 1981). In studies conducted in coastal Oregon (ZIEMER, 1976, unpublished data), root biomass declined to approach zero approximately 20 years after cutting (Fig. 3). Roots from the regenerating forest begin grow soon after the area is cut and root biomass recovers after some period of time to that found in the uncut forest. The net root strength of the watershed is related to the sum of the declining root biomass of the cut forest and increasing root biomass of the recovering forest. This U-shaped relationship reaches a minimum about eight to ten years after

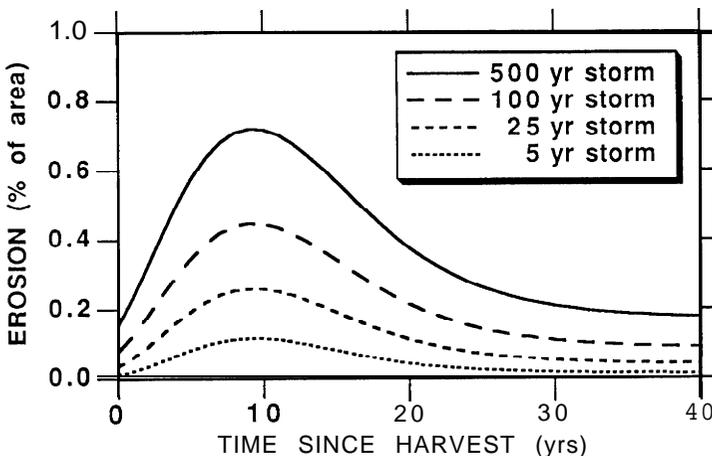


FIGURE 4. Relationship between the proportion of the logged watershed affected erosion resulting from changes in reinforcement of the soil by roots as a function of time following logging for different storm frequencies (from ZIEMER et al., 1991a).

cutting. The inverse of this root biomass or root strength relationship can be expressed as the relative rate of landslide erosion from harvested areas (Fig. 4). This rate is influenced by storm severity.

The rate of erosion from roads decreases rapidly after construction (Fig. 5), based on data reported by LEWIS & RICE (1990). Once a road is constructed, the erosion rate remains higher than that on hillslopes without roads. As with harvest area erosion, the rate of road erosion at any time after construction increases with storms of progressively greater severity.

Once erosion occurs on the watershed, it is routed from the hillslope to and through progressively larger streams using a number of storage and routing equations. These equations were described in detail by ZIEMER et al. (1991a). Eventually, the sediment reaches the modeled 1-km stream reaches in the main stem where it is deposited or transported from the reach.

The model was run in an undisturbed watershed condition for 500 years to tune the tributary sediment delivery algorithms so that the parameters produced a watershed in approximately a steady state. Once a steady-state condition was attained, the logging strategies were applied. The effect of these logging strategies were calculated as the magnitude and frequency of changes in bed elevation in excess of those occurring in the undisturbed watershed (Fig. 6). The values for each strategy are averages of all 12 reaches and 10 simulations during each 100-year period. The frequency of bed elevation changes, or events, declined with magnitude.

The importance of such changes in bed elevation depends upon the specific problem being addressed. For example, if one was concerned about survival of salmon eggs in redds, small bed elevation changes might be of less concern than those greater than some magnitude, perhaps 0.10 m.

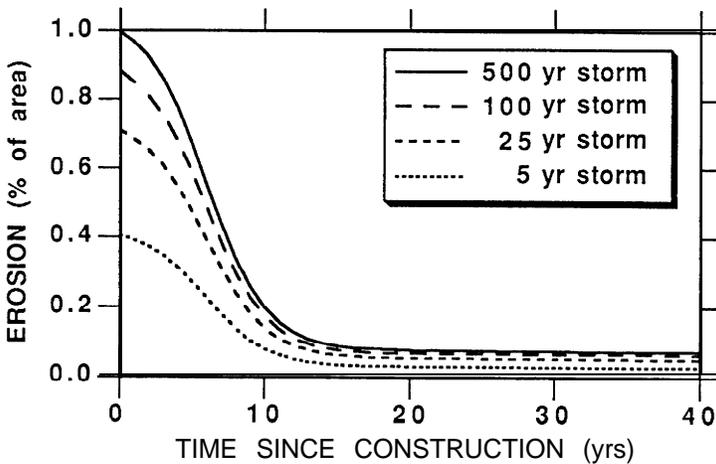


FIGURE 5. Relationship between the proportion of the logged watershed affected by road erosion and time since construction for different storm frequencies (from ZIEMER et al., 1991a).

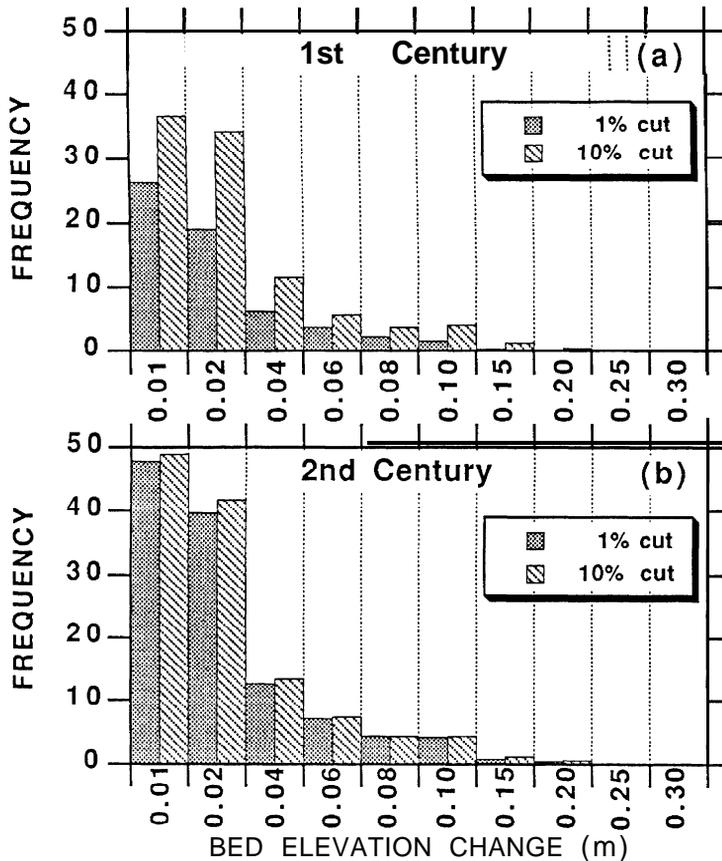


FIGURE 6. The distribution of the number of within-storm changes in bed elevation, in excess of that occurring in the uncut watershed, during (a) the first 100-yr period and (b) the second 100-year period (after ZIEMER et al., 1991a).

The amount of erosion, sediment transport, and change in bed elevation is dependent on the timing and severity of storms (Fig. 7a). During a single 300-year simulation, the largest storm occurred during year 280. This storm caused the bed to aggrade by about 0.2 m in the uncut watershed, but more than 1 m of bed aggradation occurred in the logged watershed (Fig. 7b). Over the 300 years, the bed elevation in the uncut watershed fluctuated between -0.4 and 0.3 m. In the logged watersheds, the bed elevation increased from 0.0 to about 0.6 m during the first 100 years, and then established a new equilibrium bed elevation of about 1.1 m--about 1 m higher than that in the uncut watershed. In addition, the bed elevation in the logged watersheds became more responsive to severe storms than in the uncut watershed.

A cumulative effects analysis might require translating physical changes in the stream bed into biological consequences--for example, the loss of salmon eggs deposited in redds (ZIEMER et al., 1991b). During the first century, the 10% logging strategy produced a much greater egg loss for

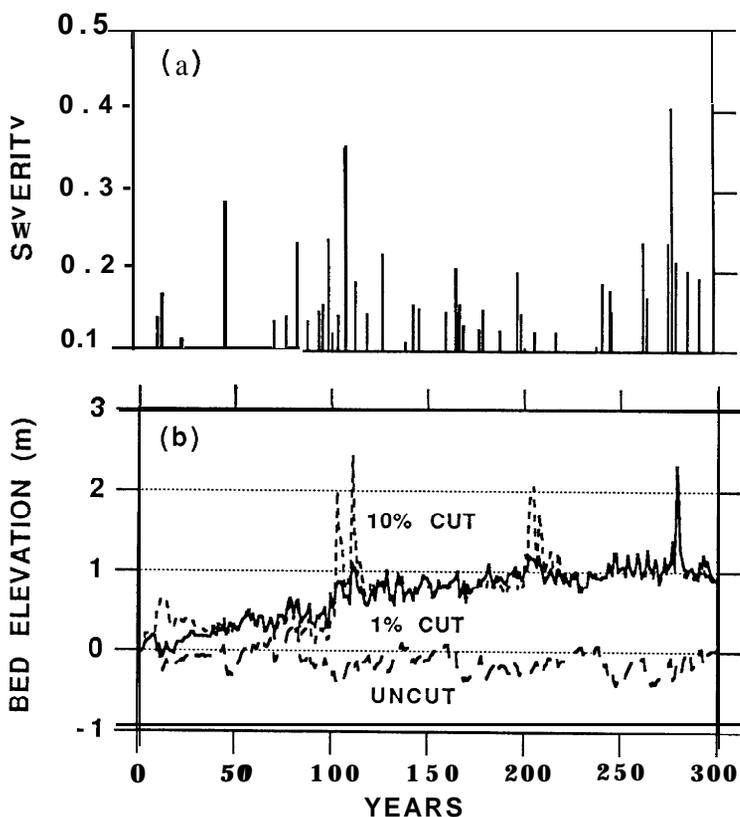


FIGURE 7. Distribution and magnitude of (a) severe storms and (b) bed elevation in the uncut, 1% cut, and 10% cut watersheds during a single 300-year simulation.

the first 50 years than did the 1% strategy (Fig. 8). But during the last half of the first century, there was little difference between the 10% and 1% strategies. The 10% strategy required the watershed to be completely logged in the first ten years of each century. The egg loss peaked about year 15, then declined as the watershed recovered from the logging. By year 50, only half of the watershed had been logged following the 1% strategy, while the watershed following the 10% strategy had been recovering from logging for 40 years. During the last 25 years of the first century, there was less egg loss using the 10% strategy than the 1% strategy (Fig. 9). Both watersheds entered the second century having been completely logged and roaded. Consequently, there was substantially less difference between the two strategies during the second century. During the first half of the second century, the 10% strategy produced more egg loss, while during the second half, the 1% strategy produced more egg loss.

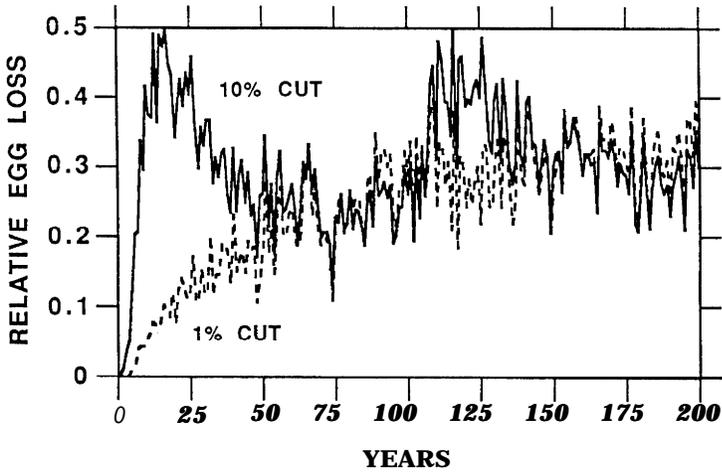


FIGURE 8. Comparison of relative salmon egg loss between logging strategies. Relative egg loss for a logging strategy is the difference in egg survival in the uncut watershed minus that in the treated watershed divided by the survival in the uncut watershed (after ZIEMER et al., 1991b).

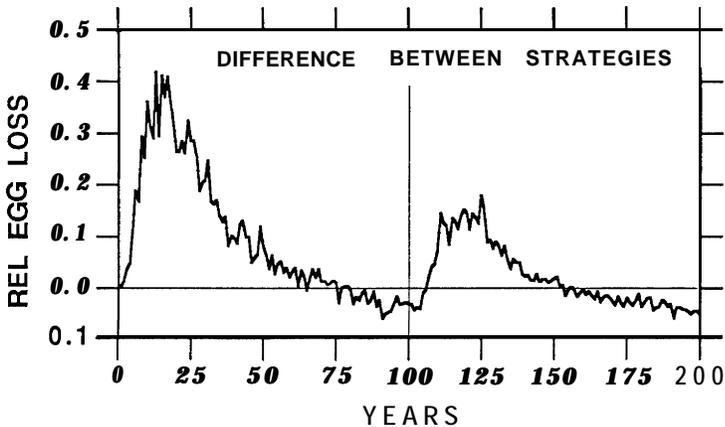


FIGURE 9. The difference in relative salmon egg loss between the 10% and 1% logging strategies (after ZIEMER et al., 1991b).

### 3. CONCLUSION

Although logging began in the coniferous forests of northwestern North America in the mid-1800's, intensive logging in much of the Pacific northwest did not begin until the 1950's. Consequently, the present condition of most watersheds in northwestern North America represent only that of the first century of the simulations. The simulations suggest that at least a century is required for the treated watersheds to attain a "steady-state++ condition. With such long response times, it is difficult to collect contemporary field data to evaluate model predictions. However, without a long-term steady-state perspective, comparisons of the environmental costs among alternative land management strategies will be incorrect. Monte Carlo methods can be used effectively to identify critical gaps in knowledge that require additional research and data collection. For example, as a first approximation, a rainfall threshold (CAINE, 1980) and storm severity (RICE et al., 1982) can provide useful information when linked to other processes contributing to landslide occurrence, such as changes in root strength (ZIEMER, 1981). However, the nature of the interaction between rainfall, vegetation, and landslides needs to be tested under the local conditions for which the evaluation is intended.

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