

Evaluating Long-Term Cumulative Hydrologic Effects of Forest Management: A Conceptual Approach¹

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Abstract: It is impractical to address experimentally many aspects of cumulative hydrologic effects, since to do so would require studying large watersheds for a century or more. Monte Carlo simulations were conducted using three hypothetical 10,000-ha fifth-order forested watersheds. Most of the physical processes expressed by the model are transferable from temperate to tropical watersheds, but data to define the parameters are generally lacking.

Concerns that environmental quality is becoming increasingly degraded by the accumulation of multiple human activities have become worldwide. An example of such concerns is the degradation of air and water quality on a local as well as national scale. Perhaps the most far reaching of these concerns is the potential effect of human activities upon changes in the world's climate. Such concerns have become particularly thorny scientific, legal, and political issues.

Pollutant discharges at point sources can first be identified and then regulated directly. However, when point sources are many and widely dispersed, such as factory discharges into a river, even when the level of individual discharge is reduced, the total pollutant discharge from many sources can produce a "cumulative effect" that degrades water quality below acceptable levels.

To deal with non-point sources of pollution, such as stream sediment produced by erosion from agriculture or forest management operations, regulations are often developed that 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 factory discharges, Best Management Practices are designed to reduce pollutant discharge from a single project, but they 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.

Cumulative Effects

The question of what a cumulative effect is has been argued at technical meetings and in the courts for many years. In 1971, the Council on Environmental Quality (CEQ) issued its guide-

lines for implementing the National Environmental Quality Act of 1969. The Council 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.

(Office of the Federal Register 1989)

Some key phrases in this definition continue to shape impact mitigation and stress 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.

Spatial Scale

Traditionally, impact analyses have concentrated upon the on-site effects of land management proposals. On-site effects generally have a scale that ranges 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 ocean, and finally, after several years in the ocean, migrating up-

¹An abbreviated version of this paper was presented at the Session on Tropical Forestry for People of the Pacific, XVII Pacific Science Congress, May 27-28, 1991, Honolulu, Hawaii.

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river to spawn. An analysis at this spatial scale is much more demanding and comprehensive than simply evaluating on-site effects.

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 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 about a century are the failure of stream crossings designed to withstand a storm size that is expected to occur once in 50 years, 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 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 consider a larger area of concern and longer 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 cannot 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.

Cumulative Effects Model

To illustrate an approach, Ziemer and others (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 (*fig. 1*). One watershed was left undisturbed, one was completely clearcut and all roads constructed in 10 years, and another clearcut with roads constructed

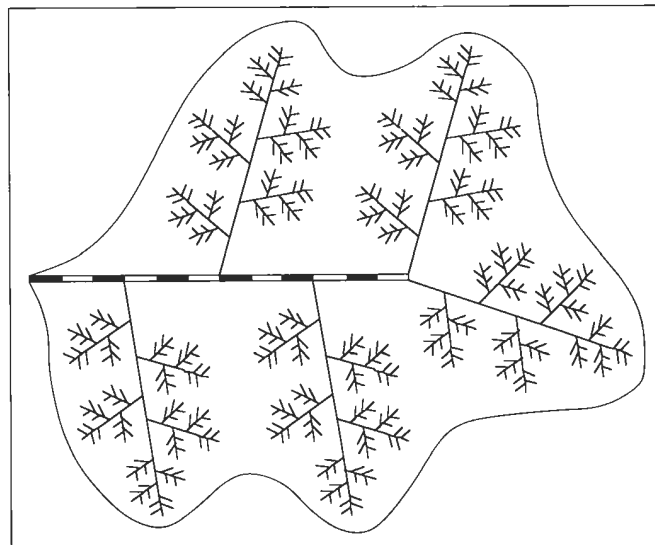


Figure 1—Modeled hypothetical 10,000-ha fifth-order watershed.

at a rate of 1 percent each year. These cutting patterns were repeated in succeeding centuries, rebuilding one-third of the road network every 100 years. Each fifth-order watershed was composed of five 200-ha fourth-order tributaries. The model predicted changes to twelve 1-km-long reaches of the fifth-order channel.

Rainfall is one of the primary causes of erosion in forested steeplands. Caine (1980) presented a relationship between rainfall intensity and duration that seemed to describe a “threshold” of worldwide occurrence of landslides. Rice and others (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 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 decline quickly (Ziemer 1981). In studies conducted in coastal Oregon (Ziemer 1976, unpublished data), root biomass approached zero approximately 20 years after cutting (*fig. 3*). Roots from the regenerating forest begin to grow soon after the area is cut, and root biomass recovers after some 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 8 to 10 years after 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.

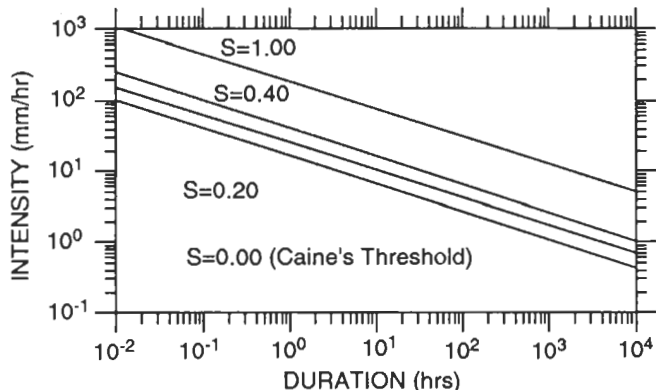


Figure 2—Storm severity (S) as a function of the duration and intensity of rainfall.

The rate of erosion from roads decreases rapidly after construction (fig. 5), based on data reported by Lewis and Rice (1990). Once a road is constructed, the erosion rate remains higher than that on hillslopes without roads. As with erosion of harvested areas, the rate of road erosion at any time after construction increases with storms of progressively greater severity.

Once erosion occurs on the watershed, the sediment is routed in the model 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 and others (1991a). Eventually, the sediment arrives at a modeled 1-km stream reach 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 algorithms for the tributary sediment delivery so that the parameters produced a watershed in an approximately steady state. Once a steady-state condition was attained, the logging strategies were applied. The effect of these logging strategies was 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

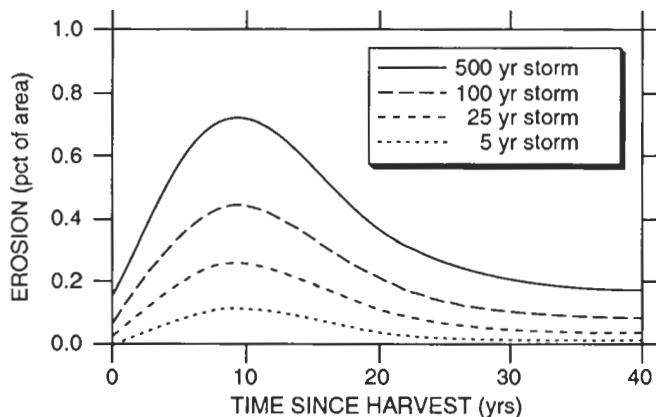


Figure 4—Relationship between erosion from harvested areas resulting from changes in soil reinforcement by roots following logging and time since harvest as affected by storm frequency (from Ziemer and others 1991a).

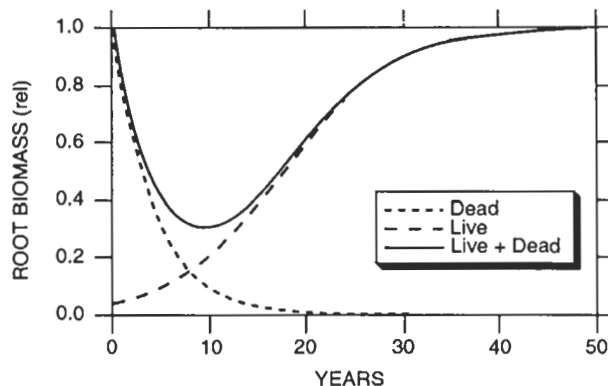


Figure 3—Change in live, dead, and total root biomass as a function of time following logging (from Ziemer, 1976, unpublished data).

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 were concerned about survival of salmon eggs in redds, small changes in bed elevation might be of less concern than those greater than some magnitude, perhaps 0.10 m.

The amounts of erosion, of sediment transport, and of change in bed elevation are 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 0.3 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 1.0 and 1.3 m. In the logged watersheds, the bed elevation increased from 1.0 to about 2.0 m during the first 100 years, and then established a new equilibrium bed elevation of about 2.2 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.

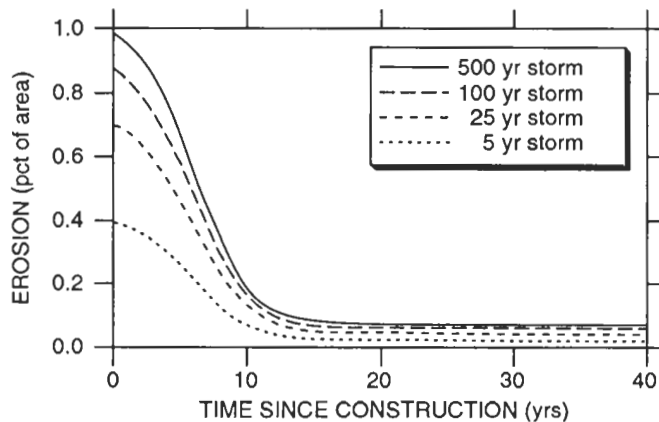


Figure 5—Relationship between erosion from roads and time since construction as affected by storm frequency (from Ziemer and others 1991a).

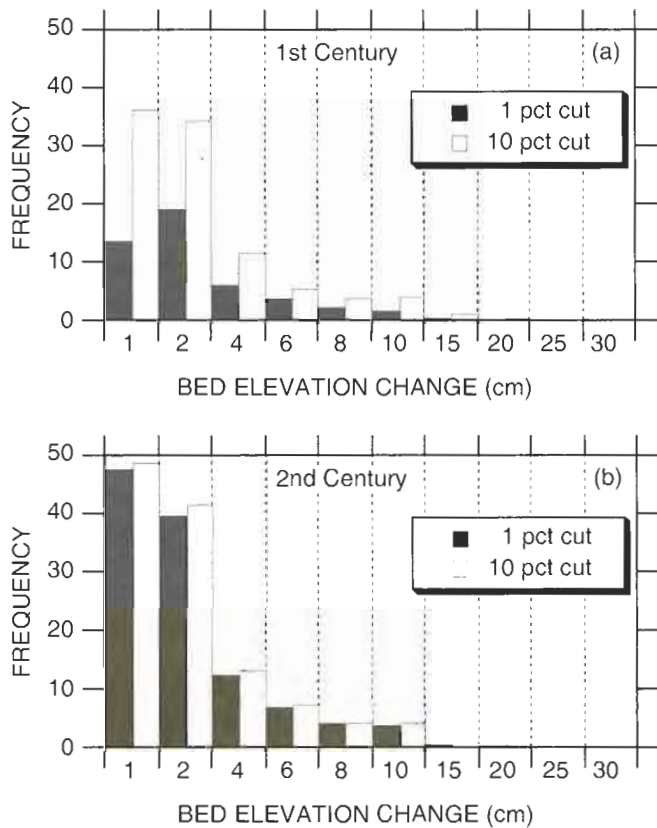


Figure 6—The distribution of the number of within-storm changes in bed elevation, in excess of that occurring in the uncut watershed, during (a) the first 100-year period and (b) the second 100-year period (Ziemer and others 1991a).

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 and others 1991b). During the first century, the 10 percent logging strategy produced a much greater egg loss for the first 50 years than did the 1 percent strategy (*fig. 8*). But during the last half of the first century, there was little difference between the 10 percent and 1 percent strategies. The 10 percent strategy required the watershed to be completely logged in the first 10 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 percent strategy, while the watershed following the 10 percent 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 percent strategy than the 1 percent strategy (*fig. 9*). Both watersheds entered the second century having been completely logged and roaded. There was substantially less difference between the two strategies during the second century. During the first half of the second century, the 10 percent strategy produced more egg loss, whereas during the second half, the 1 percent strategy produced more egg loss.

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 represents only that of the first century of the simulations. The simulations suggest that at least one 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 predictions by the model. However, without a long-term steady-state perspective, comparisons of the environmental costs among alternative land management strategies will be incorrect.

Another problem making any long-term evaluation nearly impossible is that water discharge is measured only in the larger and more important rivers. Very few small upland streams are gauged. The length of record for rivers and streams in the western United States is usually less than 100 years, and records less than 30 years long are most common. And, for those rivers having the good fortune to be gauged, the condition of none of the watersheds could be considered to be static over time—even those in National Parks where development is restricted. Even pristine forests change in density and compo-

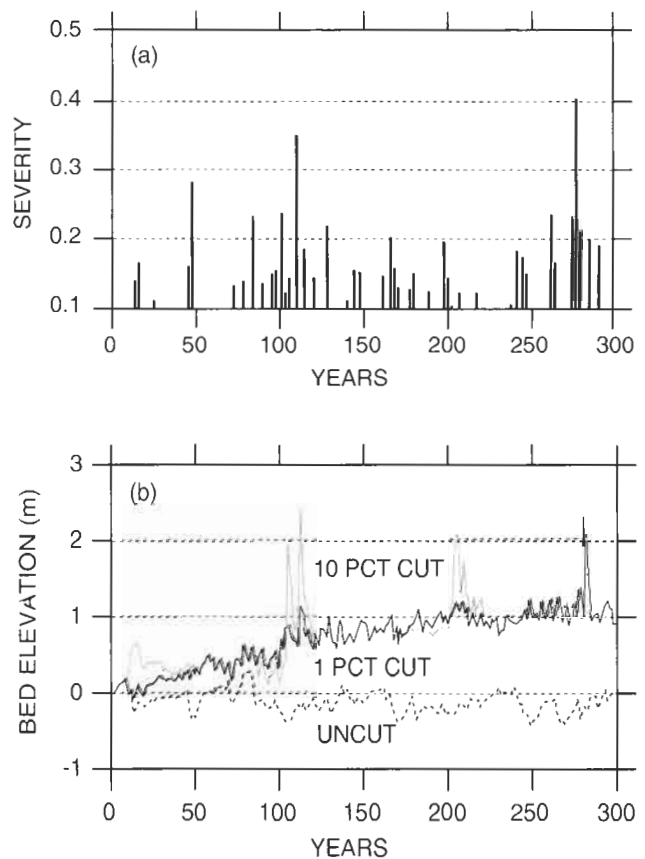


Figure 7—Distribution and magnitude of (a) severe storms and (b) bed elevation in the uncut, 1 percent cut, and 10 percent cut watersheds during a single 300-year simulation.

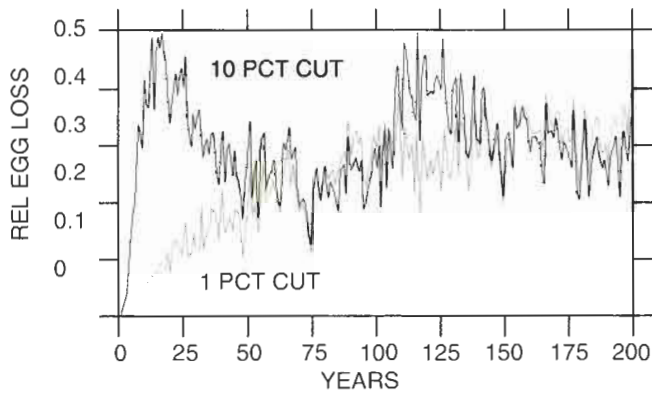


Figure 8—Comparison of relative salmon egg loss between logging strategies. Relative egg loss for a logging strategy is the difference in egg survival in the uncut watershed minus that in the treated watershed divided by the survival in the uncut watershed (Ziemer and others 1991b).

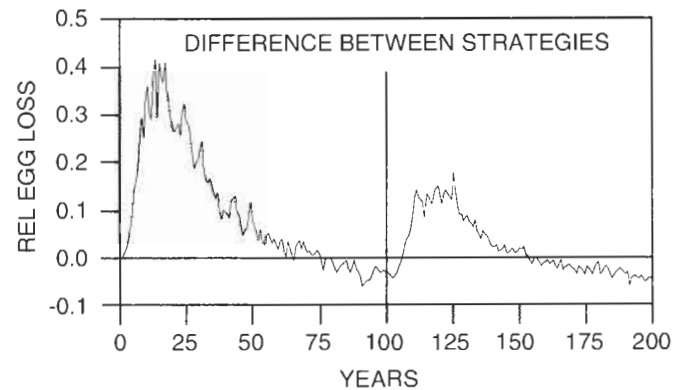


Figure 9—The difference in relative salmon egg loss between the 10 percent and 1 percent logging strategies (Ziemer and others 1991b).

sition as natural ecological processes, including insects, disease, wildfire, and old age, work their influence over time.

In the tropics, these problems are compounded many fold. It is difficult to find good streamflow records of virtually any length, and the number of gauged streams is decreasing in many areas. For example, in the portion of the Caroline Islands that now comprise the Federated States of Micronesia, streamflow was monitored on at least a daily basis at 34 stations in 1970. This number had been reduced to 16 stations by 1989. And, by 1991, nearly all of these stations had been discontinued.

Consequently, the basic data necessary to measure any long-term change in streamflow or sediment transport are missing—whether the suggested change is the result of a cumulative effect of land management or a shift in the world's climate.

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, data on rainfall threshold (Caine 1980) and storm severity (Rice and others 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.

References

- Caine, Nel. 1980. The rainfall intensity-duration control of shallow landslides and debris flows. *Geografiska Annaler* 62A (1-2): 23-27.
- Lewis, J.; Rice, R.M. 1990. Estimating erosion risk on forest lands using improved methods of discriminant analysis. *Water Resources Research* 26 (8): 1721-1733.
- Office of the Federal Register. 1989. Council of Environmental Quality. In: Protection of the environment, 40. Part 70 to end. Revised as of July 1, 1971. Washington, DC; p. 649.
- Rice, R.M.; Ziemer, R.R.; Hankin, S.C. 1982. Slope stability effects of fuel management strategies—inferences from Monte Carlo simulations. In: Conrad, C.E.; Oechel, W.C., eds. *Proc. symp. on dynamics and management of Mediterranean-type ecosystems*; 1981 June 22-26; San Diego, CA. Gen. Tech. Rep. PSW-58. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 365-371.
- Ziemer, R.R. 1981. Roots and the stability of forested slopes. In: Davies, T.R.H.; Pearce, A.J., eds. *Erosion and sediment transport in Pacific Rim steeplands (Proc. Christchurch Symp.)*; 1981 January 25-31; Christchurch, N.Z. Publ. 132. Wallingford, UK: International Association of Hydrologic Sciences; 343-361.
- Ziemer, R.R.; Lewis, J.; Rice, R.M.; Lisle, T.E. 1991a. Modeling the cumulative effects of forest management strategies. *Journal of Environmental Quality* 20(1): 36-42.
- Ziemer, R.R.; Lewis, J.; Lisle, T.E.; Rice, R.M. 1991b. Long-term sedimentation effects of different patterns of timber harvesting. In: Peters, N.E.; Walling, D.E., eds. *Sediment and stream water quality in a changing environment: trends and explanation (Proc. Vienna Symp.)*; 1991 August 11-24. Vienna, Austria. Publ. 205. Wallingford, UK: International Association of Hydrologic Sciences; 143-150.