Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation
(Proceedings of the Vienna Symposium, August 1991) IAHS Publ. no. 203, 1991.

LONG-TERM SEDIMENTATION EFFECTS OF DIFFERENT PATTERNS OF TIMBER HARVESTING

R. R. ZIEMER, J. LEWIS, T. E. LISLE & R. M. RICE
U.S. Department of Agriculture, Forest Service, 1700 Bayview Dr., Arcata, CA 95521, USA

ABSTRACT It is impractical to address the long-term effect of forest management strategies on erosion, sedimentation, and the resultant damage to fish habitat experimentally because to do so would require studying large watersheds for a century or more. Monte Carlo simulations were conducted on three hypothetical 10 000 ha, fifth-order forested watersheds. One watershed was left undisturbed, one was completely clearcut and roaded in a decade, and one was cut at the rate of 1% each year. Each cutting strategy was repeated in succeeding centuries.

INTRODUCTION

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 years to over a century to mature. Consequently, the effect of repeated harvests could be estimated experimentally only in a study lasting several centuries. Even if a field-oriented approach were 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 also is appropriate because of the uncertainty concerning the spectrum of environmental conditions that could prevail during a period spanning centuries. 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.

A simulation's greatest weakness is that it is a simplification of nature and dependent upon the modeler's skill in programming natural processes accurately. Its strength is that it can represent the mean conditions of the area being modelled and that it can explore the effect of a spectrum of possible sequences of events. The results of a simulation need not be the victim of a unique series of meteorological events as a field study would be. 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 models can be tested.

What follows is a primitive simulation of the changes in stream bed conditions, and consequent effect on salmonid success, resulting from increased bedload transport associated with two logging strategies. It improves on the model reported by Ziemer *et al.* (1991) by relating storm size and fish spawning to season of the year and by modelling spawning success as functions of the depth of scour and fill.

THE MODELLED ENVIRONMENT

Our model simulates conditions found in 10 000-ha coastal watersheds of Oregon and California between 37°N and 45°N latitude. These watersheds have an average elevation of 300 to 500 m and extend about 30 km inland from the Pacific 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 *(Pitea sitchensis* (Bong.) Carr.) and Douglas-fir in the north. A more complete description of the area and mathematical functions used in the model can be found in Ziemer et al. (1991).

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, California. The data included the duration and total rainfall of 108 storms that produced more than 50 mm of precipitation. Smaller storms in this region have low geomorphic impacts.

An average of 6 storms were selected for each simulated year. Each storm was given a date and precipitation depth according to the distributions shc Fig. **1. The** duration of each storm was generated by adding a random error to the duration predicted by its regression on precipitation depth. The erosion potential of a storm was based on its "severity" (Rice ***et al.,*** 1982), a function of duration and average intensity of precipitation.

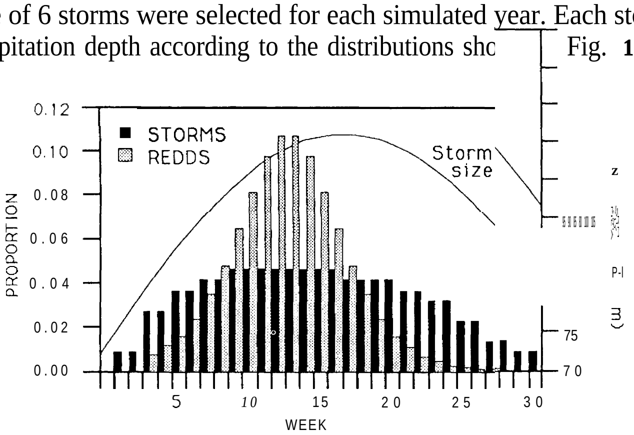

FIG. 1 Proportion of storms and redds occurring during the salmon spawning period. The line shows the annual variation in storm size.

Erosion

Only the effect of landslide erosion was considered. This limited scope was chosen because, in the coastal environment being modelled, landslides are the most important process by which logging causes erosion and sedimentation damage to fish habitat. In addition to their quantitative importance, mass movements are more likely to yield particles of a size that will affect stream bed stability than will surface, rill, or gully erosion.

Loss of root strength was assumed to be the principal factor predisposing clearcut areas to accelerated landslide erosion (Ziemer, 198la). The volume of erosion from harvest areas was based on storm severity and relative root reinforcement (Ziemer, 198lb), with the maximum erosion occurring about 9 years after logging. Road erosion volume was also a function of storm severity, declining from a maximum on newly constructed roads to a relatively low constant value about 15 years later. The erosion functions were constrained to fit the mass erosion data of Lewis & Rice (1990).

Tributary Sediment Transport

The modelled 10 000-ha watershed consisted of 12 one-km main-channel reaches fed by five identical fourth-order tributaries. Two tributaries fed the fifth-order main channel at the top of reach 1, while the other tributaries joined the main channel between reaches 3 and 4, 6 and 7, and 9 and 10. 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. Channel widths were fixed according to common hydraulic geometry parameters (Carlston, 1969), and varied from 20 m in reach 1 to 28 m in reach 12. Overbank flow was not modelled in these rectangular channels.

Each tributary had a base flow of 0.14 $m^3 s^{-1}$. In addition, storm runoff was generated by delivering all rainfall from the tributaries to the main channel as one cycle of a sine wave. Rainfall interception and other transmission losses due to logging were considered to be negligible since, in the region being modelled, almost all of the important runoff occurs after the watersheds have been recharged in the fall. Flows entering the main channel were routed to the watershed's mouth using the Muskingum flood routing technique (Linsley *et al.*, 1982) with a 10-minute iteration interval. During landslide-producing storms, 20% of the eroded material was delivered to the main channel and the other 80% was stored in the tributaries. 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, During all storms, whether or not they were large enough to cause landslides, sediment was also exported from the five tributaries as a function of water discharge and the amount of sediment stored in the tributaries.

Bed Dynamics

Channel aggradation or degradation results when the bed load transport into a reach differs from transport out of the reach. Bedload transport was modelled using the Meyer-Peter &Muller (1948) formula, as a function of excess shear stress. Critical shear stress was derived from Shields' (1936) criterion for bed material entrainment, using D_{50} as a grain-size parameter. Depth and discharge were related using a form of Hey's (1979) friction equation. 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. At each iteration of the simulation, D_{50} was adjusted for changes in bed elevation due to bedload transport in the previous iteration.

Effect of scour and fill on egg survival

The construction of redds and deposition of salmon eggs throughout the winter (Fig. I) was patterned on unpublished data gathered in northern California by Six Rivers National Forest and California Department of Fish and Game.

Salmon eggs buried in the streambed can be destroyed by scour or smothered by fine sediment in spawning gravel. During scour and fill, a layer can develop to the depth of maximum scour whose fine-sediment concentration is commonly equal to that of the original bed material before spawning. The simulation models egg mortality from removal of eggs by scour and from increases in fine-sediment concentration caused by scour and fill of gravel overlying incubating eggs. Simulated changes in average bed elevation during storms were usually only a few centimeters and very rarely exceeded 10 cm. Burial depth of salmon eggs, by contrast, is commonly 30 cm or more. Local ranges of scour and fill, however, greatly exceed the average in a reach due to the migration of bedforms (Whiting *et al.*, 1988) and growth and erosion of bars (Jackson & Beschta, 1982). Lisle (1989), for example, measured annual changes in local bed elevation of more than 40 cm in three streams, even though the mean bed elevations remained constant.

Local scour and fill, y_2, was modelled as 4 times the range of mean bed elevations, y_m, during 9-week incubation periods (Fig. 2). To compute the fraction of eggs removed by scour, the depth of burial, yt, was assumed to follow the distribution measured for coho salmon on the Queen Charlotte Islands, British Columbia (Tripp & Poulin, 1986). The proportion of eggs lost was equal to the proportion of eggs buried shallower than y_2.

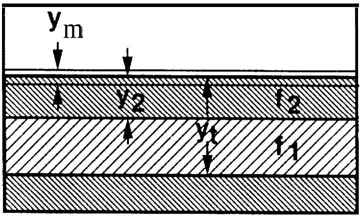

FIG. 2 *A schematic representation of the influence of scour and fill on the fraction of fine sediment in salmon redds, calculated by Eq. (1).*

To compute the mortality of the remaining eggs from increases in fine sediment, an initial fraction of fines, f_1, was assumed to be in the gravel after spawning and a second fraction, f_2, was in the material deposited as the bed filled over the depth y_2. The overall fraction of fines (F) in gravel overlying the eggs was

$$F=\{f_2 y_2 + f_1 (y_t - y_2)]/y_t \qquad (1)$$

The fraction f_1 was assigned 0.1, a typical value for salmon redds, and f_2 was assigned 0.4, a typical value for potential spawning gravels that have not been spawned upon (Kondolf, 1988). In this computation yt was given a value of 0.29 m, which is the median value of burial depth. Eqn. 1 then simplifies to

$$F = 1.034\ y_2 + 0.1 \qquad (2)$$

Egg mortality during each 9-week incubation period was a function of F, determined for the Queen Charlottes (Tripp & Poulin, 1986).

THE SIMULATIONS

The model was run in an undisturbed watershed condition for 500 years 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 two different timber harvesting strategies. Each strategy was based on clearcut logging and a 100-year cutting cycle.

In one strategy five widely dispersed 20-ha first-order basins were clearcut each year. This represents logging 1% of the watershed each year. One percent of the total road network was constructed during each year of the first century. During subsequent centuries, 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. The second logging strategy called for logging to begin in the headwaters of the watershed and progress downstream at a rate of 1000 ha $year^{-1}$. That is, the entire drainage would be logged in the first 10 years of each century, followed by 90 years 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 decade of subsequent centuries, 3.3% of the road was rebuilt each year. The effect of these logging strategies, in excess of natural variability, was recorded in terms of egg mortality resulting from scour and fill.

The model did not allow any logging-related streamflow increases because studies at Caspar Creek (Ziemer, 1981c, Wright, 1985) 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-year simulations. The simulations were terminated at 200 years because earlier, longer simulations had shown that there was little change in the pattern of disturbance effects after the second century.

RESULTS AND DISCUSSION

Relative loss of salmon eggs was defined as the average difference in egg survival between any two management strategies as a proportion of egg survival in the undisturbed watershed. Egg loss was averaged for each strategy over all 12 reaches and ten 200-year simulations. Each logging strategy was compared to the undisturbed watershed (Figs. 3a and 3b). Relative egg loss in the 1% dispersed logging strategy increased throughout the first century, and remained fairly constant in the second century. In the I0% progressive strategy, relative egg loss peaked from years 5 to 25 of each century, gradually recovering by the end of each century to a level determined principally by residual erosion from the road system. Mortality caused by removal of eggs by bed scour was an insignificant proportion of all losses. Differences between the 10% progressive logging and the 1% dispersed logging strategies were much greater in the first century than in the second century (Fig. 4). The 10% progressive logging strategy produced significantly more egg loss than did the 1% strategy during the first 75 years of the first century and the first 50 years of the second century. During the remainder of each century, the 10% strategy produced less egg loss than did the 1% strategy. However, the temporary large increases in egg mortality following the concentrated 10% progressive logging greatly increase its potential impact on fish populations.

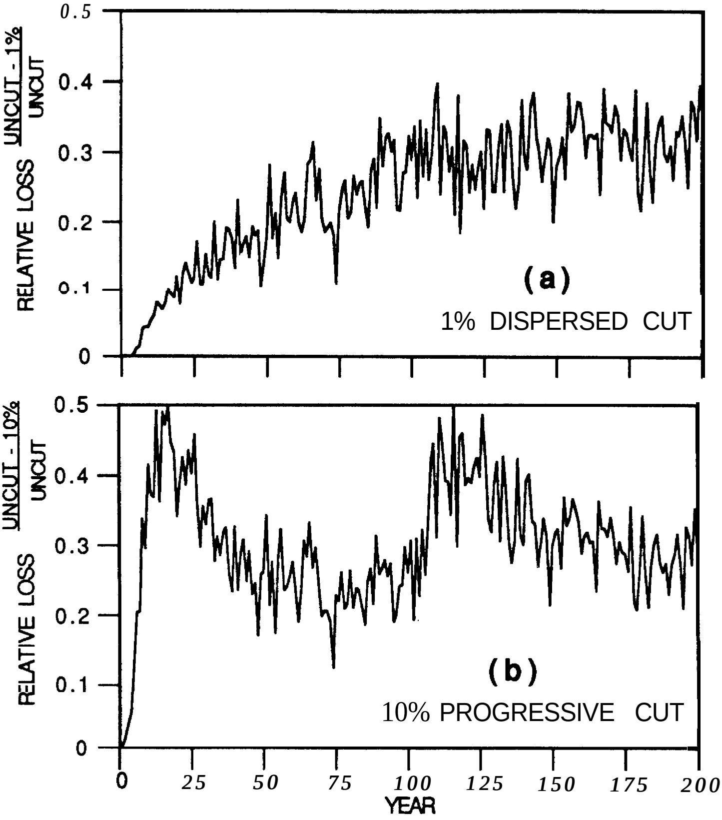

FIG. 3 *The difference in salmon egg survival between the (a) 1% dispersed and (b) 10% progressive logging strategy and the undisturbed watershed, as a proportion of the latter. The values are averaged over all 12 reaches and 10 simulations.*

The differences between strategies in the first century are related primarily to the rate of treatment. For the 10% strategy, the whole watershed was treated within the first 10 years, whereas the entire century was required to treat the watershed under the 1% strategy. Consequently, after the first 50 years only half of the 1% strategy watershed had been logged or roaded. After the first century, the road network and logging was complete under each strategy. Thereafter, comparisons are of completely "managed" watersheds representing different sequences of treatment. Watersheds in western North America have experienced varying amounts of logging since the mid-1800s. Logging in many watersheds did not begin until the 1950s. Consequently, the actual field conditions available to evaluate cumulative watershed effects typically represent those modelled here during only the first century. However, the second and subsequent centuries 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 whether designed experimental field data spanning Several centuries will ever be available to test such hypotheses.

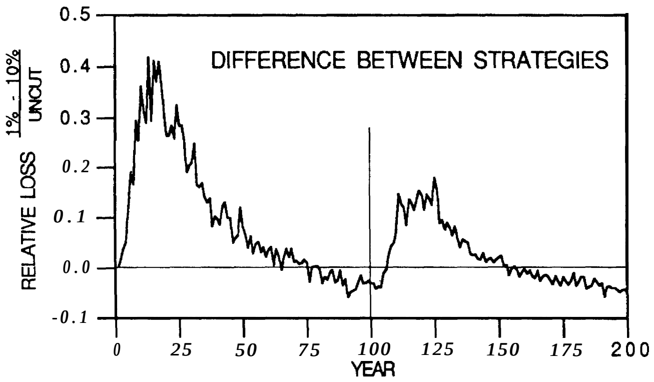

FIG. 4 *The difference in salmon egg survival between the 1% and 10% logging strategies, relative to egg survival in the undisturbed watershed. The values are averaged over all 12 reaches and 10 simulations.*

Some of the excess sediment produced during the first century was initially stored in the tributaries, resulting in increased delivery rates to the main channel during the second century. 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 observations may underestimate long-term cumulative watershed effects. Estimates of future impacts should consider the condition and changes in sediment storage in fourth-order and smaller streams, because routing of sediment from these channels will eventually affect main channels.

CONCLUSIONS

This Monte Carlo simulation of the effect of different forest management strategies leads to some rather disturbing hypotheses:

- 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 half a century.
- Current cumulative effects appraisals may overestimate the benefits of dispersion as a tactic to reduce sedimentation and fishery impacts. Differences between simulated management strategies were smaller in the second century of logging.
- Compared to the 1% logging strategy, the 10% strategy concentrates the timing of im-

pacts, temporarily increasing the potential damage to fish populations.

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

REFERENCES

Carlston, C.W. (1969) Downstream variations in the hydraulic geometry of streams: Special emphasis on mean velocity. *Am. J. Sci.* **267**:499-509.

Dietrich, W.E., Kirchner, J.W., Ikeda, H. & Iseya, F. (1989) Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. Nature, Lond. **340** (July 20,1989):215-217.

Hey, R.D. (1979) Flow resistance in gravel-bed rivers. J. *Hydraul. Div. ASCE* **105** (HY4):365-379.

Jackson, W.L. & Beschta, R.L. (1982) A model of two-phase bedload transport in an Oregon Coast Range stream. *Earth Surf. Processes* **7**:517-527.

Kondolf, G.M. (1988) Salmonid spawning gravels: A geomorphic perspective on their size distribution, modification by spawning fish, and criteria for gravel quality. Ph.D. dissertation. The Johns Hopkins University, Baltimore, MD. 396 p.

Lewis, J. & Rice, R.M. (1990) Estimating erosion risk on forest lands using improved methods of discriminant analysis. *Wat. Resour. Res.* **26** (8):1721-1733.

Linsley, R.K. Jr., Kohler, M.A. & Paulhus, J.L.H. (1982) *Hydrology for Engineers.* 3rd ed. McGraw-Hill, New York, NY.

Lisle, T.E. (1989) Sediment transport and resulting deposition in spawning gravels, North Coastal California. *Wat. Resour. Res*. **25** (6):1303-1319.

Meyer-Peter, E. & Muller, R. (1948) Formulas for bed-load transport. p. 39-64. In: *Rept. 2nd Meeting Int. Assoc. Hydraul. Structures Res.,* Stockholm, Sweden.

Rice, R.M., Tilley, F.B. & Datzman, P.A. (1979) A watershed's response to logging and roads: South Fork of Caspar Creek, California, 1967-1976. *USDA-FS Res. Paper* **PSW-146**. Pacific Southwest Research Station, Berkeley, CA.

Rice, R.M., Ziemer, R.R. & Hankin, S.C. (1982) Slope stability effects of fuel management strategies--inferences from Monte Carlo simulations. p. 365-371. In: C.E. Conrad & W.C. Oechel (eds.) *Proc. Symp. on Dynamics and Management of Mediterranean-type Ecosystems,* San Diego, CA. 22-26 June 1981. USDA-FS Gen. Tech. Rept. **PSW-58**. Pacific Southwest Research Station, Berkeley, CA.

Rice, R.M., Pillsbury, N.H. & Schmidt, K.W. (1985) A risk analysis approach for using discriminant functions to manage logging-related landslides on granitic terrain. *For. Sci.* **31** (3):772-784.

Shields, A. (1936) Arwendung der Ahnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. *Mitteilungen der Preuss.* Versuchganst. fur Wasser, Erd, unt Schiffsbau, Heft 26. Berlin. 26 p.

Tripp, D.B. & Poulin, V.A. (1986) The effects of logging and mass wasting on salmonid spawning habitat in streams on the Queen Charlotte Islands. *Land Manage. Rept.* **50**. B.C. Min. For. Lands, Victoria, B.C.

Whiting, P.J., Dietrich, W.E., Leopold, L.B., Drake, T.G. & Shreve, R.L. (1988) Bedload sheets in heterogeneous sediment. Geology **16**: 105-108.

Wright, K.A. (1985) Changes in storm hydrographs after roadbuilding and selective logging on a coastal watershed in northern California. MSc thesis, Humboldt State Univ., Arcata, CA.

Ziemer, R.R. (1981a) The role of vegetation in the stability of forested slopes. In: *Proc. of the Int. Union of For. Res. Org.,* Div. I, XVII World Congress, 1981 September. Kyoto, Japan, p. 297-308.

Ziemer, R.R. (1981b) Roots and the stability of forested slopes. In: T.R.H. Davies & A.J. Pearce (eds.) *Erosion and Sediment Transport in Pacific Rim Steeplands.* IAHS. Publ. **132**:25-31.

Ziemer, R.R. (1981c) Stormflow response to roadbuilding and partial cutting in small streams of northern California. *Wat. Resour. Res.* **17** (4):907-917.

Ziemer, R.R., Lewis, J., Rice, R.M. & Lisle, T.E. (1991) Modeling the cumulative watershed effects of forest management strategies. J. *Environ. Qual.* **20**(1):36-42.