Invited paper presented at the EPA/USFS Technical Workshop on Sediments
Feb. 3-7, 1992, Corvallis, OR. Pp. 81-87.

Sediment Monitoring: Reality and Hope

Lee H. MacDonald
Department of Earth Resources
Colorado State University
Fort Collins, Colorado

Introduction and Overview

Water quality regulation in the United States is largely based on the maintenance and enhancement of the designated beneficial uses of water. The Clean Water Act's overall goals and amendments are couched in terms such as "swimmable," "fishable," and "the propagation of aquatic life." The policies and mechanisms to achieve these goals — water quality standards, best management practices (BMPs), antidegradation, and total maximum daily loads (TMDLs) — all relate back to this concept of the designated beneficial use (U.S. Environ. Prot. Agency, 1988). Monitoring is essential for the effective implementation of each of these policies and pollution control mechanisms (MacDonald et al. 1991).

In most of the western United States and Canada, coldwater fisheries are regarded as the designated use most sensitive to forest management activities. Public concern over the effects of forestry on streams and fish has triggered a series of intensive research projects to evaluate forestry-fisheries interactions, such as the Alsea study in Oregon and Carnation Creek in British Columbia (Moring, 1975; Chamberlin, 1988). These and other studies have not resolved what is often a highly charged and emotional debate. From a scientific view, confirmation of the effects of forestry on aquatic ecosystems requires:

- documentation of a change in the physical habitat (e.g., temperature, turbidity, bed material particle size, amount of cover, and pool depth) and
- a link between the changes in physical habitat and the designated use of concern (e.g., coldwater fish populations or "biological integrity").

In the last five years, several publications have reviewed these interactions between land management activities and aquatic ecosystems (Salo and Cundy, 1987; Chapman and McLeod, 1987; MacDonald et al. 1991; Meehan, 1991; Reid, 1991). At this time, there seems to be little point in generating another broad, state-of-knowledge report on forestry-fishery interactions, at least for the Pacific Northwest.

Monitoring Tools and Constraints

Lack of Criteria

The studies cited previously document how forest management activities can affect coldwater fisheries. However, we generally lack the sharp monitoring tools needed to regularly link on-the-ground management activities to coldwater fisheries or the biological integrity of aquatic ecosystems.

One major failing of the existing regulatory structure is that most water quality criteria are either insensitive or irrelevant to forest management activities. Of the 100 or so criteria discussed in the U.S. Environmental Protection Agency's (EPA) *Gold Book* (U.S. Environ. Prot. Agency, 1986), forest management activities generally affect no more than five or six criteria: dissolved oxygen

(DO), turbidity, suspended solids, color, temperature, and perhaps nitrate-nitrogen. Yet forestry activities are known to alter numerous other parameters that do not have EPA-specified criteria but do have great significance for aquatic and riparian ecosystems (MacDonald et al. 1991). Recent attempts to set criteria for parameters such as intergravel DO or embeddedness have been unsuccessful, primarily because of difficulty in establishing a consistent and technically sound basis for such criteria (Harvey, 1989).

Of the six criteria most likely to be affected by forest management activities, all but one or two are sediment-related. Turbidity, suspended solids, and color are expressions of the amount of fine sediment within the water column. Substandard concentrations of intergravel DO — at least in cool, lower-order forest streams — are most likely to result from deposition of fine sediment. Adverse changes in water temperature result primarily from a reduction in the riparian canopy, but the canopy can be altered either directly by forest harvest, or indirectly by changes in the balance between sediment load and discharge (Grant, 1988). Substantial increases in turbidity, suspended sediment concentrations, or the amount of bedload movement can usually be associated with adverse impacts on one or more designated beneficial uses (MacDonald et al. 1991).

Turbidity and Suspended Solids

Given these factors, the primary tools to regulate the effects of forestry activities on streams are the criteria for turbidity and suspended solids. Several western States have established specific criteria for these variables; for example, that turbidity should not increase by more than 10 or 20 percent above background. Such standards may be extremely difficult to enforce in areas with multiple and diffuse sources. Often, no undisturbed catchments are available to serve as controls and variability between sites is greater than the standard (see Carey, 1985).

In general, turbidity is probably more useful than the concentration of suspended solids because the latter is known to vary with depth and location across the stream cross section (Allen and Peterson, 1981; Edwards and Glysson, 1988). These complications in measuring suspended solids may not be too severe in lower-order, turbulent mountain streams, but the concentration of suspended solids also varies with discharge, timing of the sample within a storm hydrograph, and the interval between storm events (Walling and Webb, 1981; Williams, 1989).

The relationship between suspended solids and these other factors are rarely consistent (Ketcheson, 1986), and this inconsistency, when combined with the range of natural sediment-producing events, results in a high degree of variability within storms and between years (Sullivan, 1985; Rieger and Olive, 1986). Documentation of a statistically significant change in sediment concentrations or annual sediment load as a result of management activities requires a substantial commitment of human resources and a safe location for sampling high flow events. Using automated pump samplers can reduce staff time, but the problems associated with nozzle placement and design may hinder data interpretation (Thomas, 1985). The quality of data from automated samplers can be improved by using flow-weighted rather than time-proportional sampling (Thomas, 1985, 1988), but it is unrealistic to expect detection of a 10 or 20 percent change in the annual suspended sediment load (see Ketcheson, 1986).

It is much more feasible to detect a 10 to 20 percent increase above background when single sites are being monitored during relatively constant or low flows. For example, small changes in turbidity or suspended solids because of bridge construction, gravel mining, or similar activities can be detected more easily when background levels are very low. In such cases, the typical monitoring design is a direct comparison of upstream and downstream locations; however, it should be noted that the lack of replication limits the extent to which cause-and-effect can be statistically inferred (Hurlbert, 1982). Previous experience, professional judgement, and qualitative observations might indicate that a particular activity is causing the observed change, but upstream-downstream comparisons are subject to exactly the same statistical limitations as paired watershed experiments (MacDonald et al. 1991).

Bedload

Problems of spatial and temporal variability are even more severe in the case of bedload monitoring. Research has repeatedly demonstrated — at least for gravel-bedded streams that are prime fish habitat — that bedload movement is

- highly variable over very short time periods (Gomez et al. 1989),
- often relatively rare (King, 1989), and
- poorly correlated with discharge (Carey, 1985; Sidle, 1988).

The accuracy of the most common bedload sampling technique — Helley-Smith samplers with a 7.6-cm square opening — varies with the particle-size distribution of the material being transported (Emmett, 1980). This, together with the spatial and temportal variability of bedload movement, means that standard bedload sampling techniques cannot be assumed to accurately measure bedload movement (Hubbell, 1987). Hence, most attempts to gather reliable, quantitative data on total bedload transport or sediment yield must be regarded with considerable skepticism (Gomez et al. 1990).

How do forest management activities affect sediment production?

↓

How is this sediment production routed into the stream channel?

↓

How is an increased sediment load routed through the stream system?

↓

How does the change in sediment affect channel structure and stability?

↓

How do the changes in sediment and channel morphology affect the designated beneficial uses of concern?

Figure 1.—Suggested procedure for evaluating effects of forest management activities on sediment, stream channels, and aquatic ecosystems (adapted from Grant, 1987).

Alternative Monitoring Strategies

Channel Morphology

Problems with directly monitoring sediment production and yield, when combined with the limited resources available for most monitoring projects, suggest that surrogate measures should be considered. The basic concepts of fluvial geomorphology imply that selected channel measurements could both indicate and partially explain changes in the balance between runoff and sediment as a result of management activities. Grant (1987) suggested that effects of forest harvest on peak flows could be evaluated in a physically meaningful way by relating peak flow increases to the movement of bed material and thence to channel structure and channel stability. An adaptation of his logic to sediment monitoring is presented as Figure 1. Each of these links must be addressed if a monitoring project is to provide definitive results and be used to guide future management activities.

Although the logic of Figure 1 is clear, the selection of variables for monitoring forest management effects on coldwater fisheries is still problematic (MacDonald et al. 1991). Different national forests are attempting to use a variety of variables, including pool-riffle ratios, embeddedness, pool volumes, and channel cross-sections. In the Panhandle National Forest a riffle armor stability index is being tested (Kapesser, 1992). These efforts are hampered by the absence of long-term data sets to indicate the background variability (Ziemer and Lisle, 1992) and the need to stratify streams for comparison purposes. My personal view is that no one variable can directly link management activities to changes in stream channel morphology; in most cases, at least two interrelated measurements will be needed to understand the physical processes causing change. Because different stream types will respond in different ways, or perhaps not at all, a process-based understanding is necessary to infer the cause-and-effect link required for effective management decisions.

Monitoring channel morphology has several advantages over the direct measurement of sediment concentrations or sediment flux. Most measurements can be made annually, which can greatly reduce costs. Measurements often can be made during low-flow months when access is less difficult and more field assistance is available. Finally, changes in channel morphology can more easily be related to the designated use of coldwater fisheries. For example, an increase in percent fines — as was documented on the South Fork of the Salmon River (Megahan et al. 1980) — can be related to the quality of spawning habitat. A reduction in residual pool depth or the amount of large woody debris can be directly related to the amount of cover and quality of rearing habitat (MacDonald et al. 1991).

One disadvantage of monitoring channel morphology is the disruption caused by extreme natural events, such as large floods and debris flows (Benda, 1990). A procedure is needed for comparing the impact of these highly disruptive but rare events to the more continuous impact of management acitivities. A second disadvantage of monitoring channel morphology is that severe impairment may already be occurring by the time adverse changes are detected. Since full recovery could take years or decades, there is a strong need for accurate predictive tools.

Unfortunately, much of the knowledge regarding the use of channel measurements for monitoring is scattered throughout the literature or available only as unpublished reports from different agencies. MacDonald et al. (1991) summarizes some of the key literature, but much more experience exists, and this could help guide future work. It may be worthwhile to convene a special working group to: (1) compile and synthesize this information, and (2) make recommendations for monitoring projects and future research.

Biomonitoring

A second alternative to directly measuring sediment is to monitor the stream biota. Current EPA regulations require States to adopt qualitative biologic criteria. A longer-term objective is to develop quantitative biologic criteria.

In terms of procedures, the most straightforward approach — monitoring coldwater fishes — is not an easy task. Among other problems, coldwater fish are highly mobile, difficult to count, and subject to a variety of external factors over which researchers often have little control or accurate knowledge. Fishing pressure, hydroelectric dams, mixing of hatchery and wild stock, and ocean mortality all hamper the establishment of a direct link between fish populations and forest management activities. EPA's Rapid Bioassessment Protocols establish procedures that assess from two to five levels of impairment based on fish or macroinvertebrate sampling (U.S. Environ. Prot. Agency, 1989), but these procedures need to be adapted and validated for different areas and stream types (MacDonald et al. 1991). Overall, biomonitoring is an area of active research and controversy, but also one with some promise (Cullen, 1990).

Scale Considerations

A critical concern in sediment monitoring is the location of sampling sites within the stream network, as this can greatly affect the results. Preliminary work (MacDonald, 1989) demonstrated the effects of dilution on the percent change in annual water yield and sediment concentrations according to stream order (Figs. 2, 3). These simulations applied real data to a hypothetical fifth-order basin where first-order catchments were clear-cut on an 80-year cycle. Results showed that the magnitude of change, and hence the likelihood of detecting change, varied by several orders of magnitude depending upon where the measurements were made.

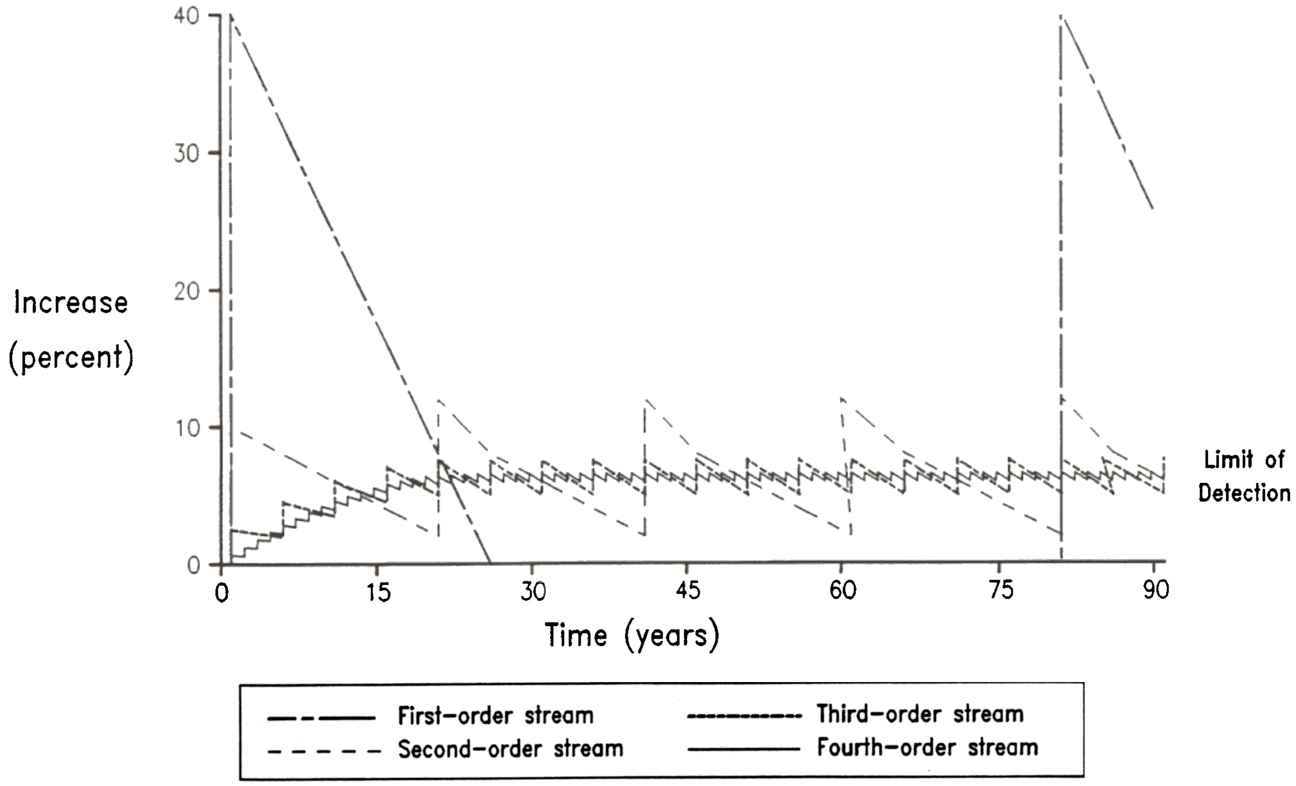

Figure 2.—Modeled increase in annual water yield by stream order because of clear-cutting.

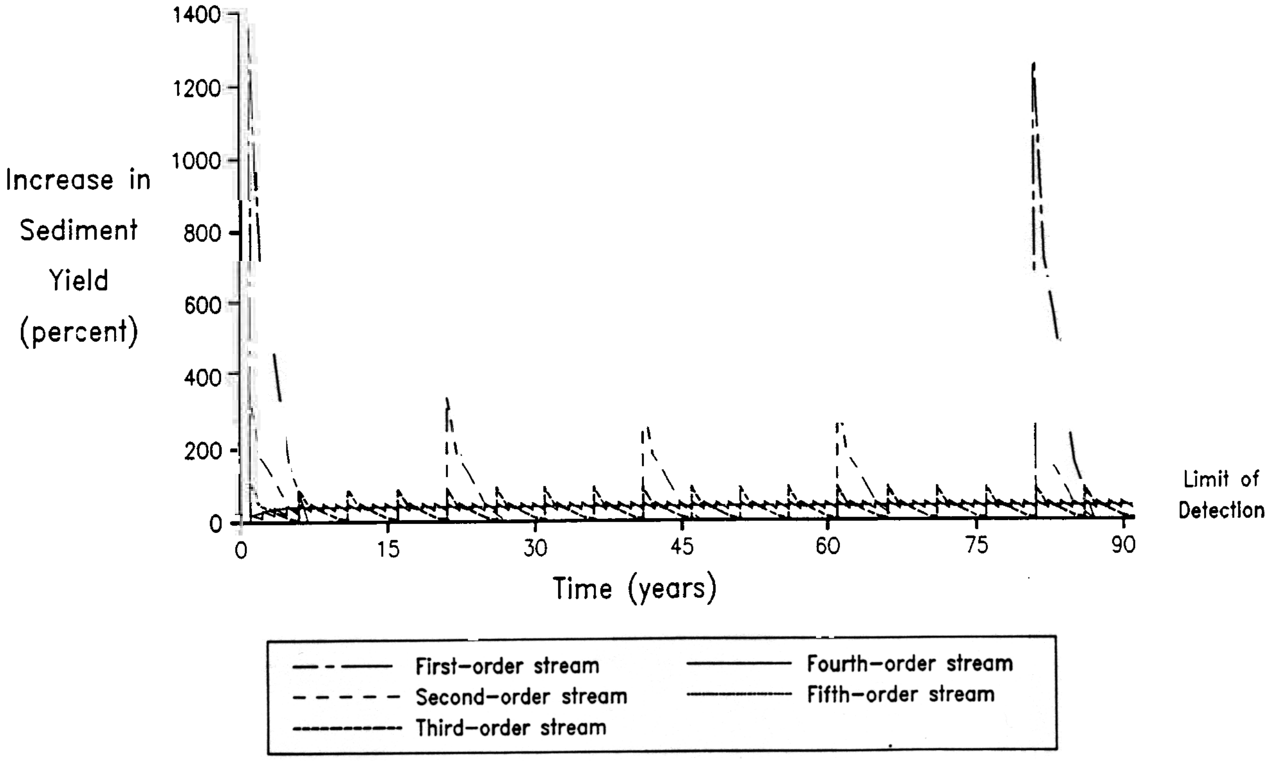

Figure 3.—Modeled increase in sediment yield by stream order because of clear-cutting and road building. Dispersion and storage are not considered.

Sediment storage is another important factor that is highly scale-dependent and must be explicitly considered when designing monitoring projects. Generally, many times more sediment is stored within the stream channel than is delivered as sediment yield at the basin outlet (Megahan, 1982). This storage effect further diminishes the effects of upstream management activities on downstream sediment concentrations and creates a time lag of uncertain length between sediment production and sediment yield. Given the short duration of most monitoring projects, these considerations again suggest that results will be highly dependent on the sampling location within the stream network.

The ability to detect a change in sediment concentrations is also a function of the natural variability and measurement uncertainty. In theory, natural variability should decline in the downstream direction, and this tendency may partially compensate for the dilution and storage effects mentioned above. Measurement uncertainty is a fourth factor that affects the ability to detect change. These four factors, when combined with a specific sampling scheme, will determine the minimum detectable effect (Fig. 4). A quantitative understanding of each of these four factors is basic to monitoring sediment concentrations and sediment flux, but a rigorous, quantitative analysis has not yet been conducted. Evaluation of the minimum detectable effect for sediment monitoring should therefore be a high priority for research.

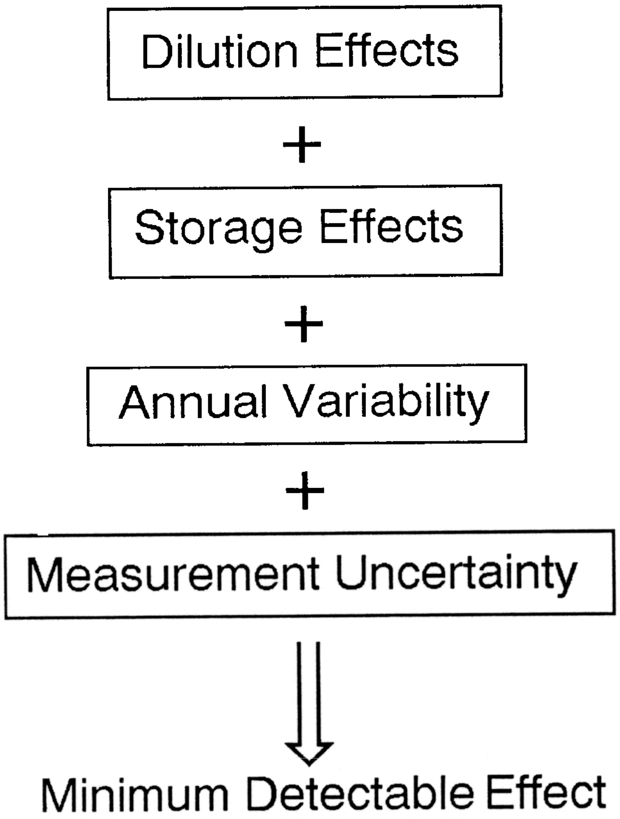

Figure 4.—Considerations of scale and uncertainty in sediment monitoring.

Summary

At present, relatively few State-established criteria have been developed that are useful for monitoring the effects of forestry activities on streams. Direct monitoring of changes in suspended sediment and bedload is difficult because of high natural variability over time and space, but the implications of these factors for detecting change seem not to have been explicitly considered in regulations or most monitoring plans. There is a strong need to quantitatively investigate the implications of dilution, storage, variability, and measurement error with regard to the detection of change and location of monitoring sites.

Alternatives to the direct monitoring of sediment include biomonitoring and measurements of channel morphology. Advantages of the latter approach include reduced sampling frequency and the ability to infer management-induced changes in discharge and sediment yield from the observations of channel morphology. Changes in channel morphology can then be linked to the designated use of coldwater fisheries in a physically realistic manner. Biomonitoring is more easily related to the designated beneficial use, but it may be more difficult to link the observed changes to specific management activities. Considerable experience will be needed to determine the best approach for either alternative. Simple, universally applicable procedures will remain the Holy Grail of monitoring.

ACKNOWLEDGMENTS: The author is grateful to U.S. Environmental Protection Agency for sponsoring his participation in the meeting and to Walt Megahan and my colleagues at Colorado State University (John Stednick, Stan Schumm, and Ellen Wohl) for their comments on an earlier version of this paper.

References

Allen, P.B. and D.V. Petersen. 1981. A study of the variability of suspended sediment measurements. Pages 203-11 *in* Erosion and Sediment Transport Measurement. Publ. No. 133. Int. Ass. Hydrol. Sci., Wallingford, UK.

Benda, L. 1990. The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA. Earth Surf. Proc. Landforms 15:457-66.

Carey, W.P. 1985. Variability in measured bedload-transport rates. Water Resour. Bull. 21(1):39-48.

Chamberlin, T.W., ed. 1988. Proc. Applying 15 Years of Carnation Creek Results, Nanaimo, British Columbia. Carnation Creek Steering Comm., Pac. Biol. Sta., BC, Can.

Chapman, D.W. and K.P. McLeod. 1987. Development of Criteria for Fine Sediment in the Northern Rockies Ecoregion. EPA 910/9-87-162. Water Div., U.S. Environ. Prot. Agency, Region 10, Seattle, WA.

Cullen, P. 1991. Biomonitoring and environmental assessment. Environ. Monitor. Assess. 14:107-14.

Edwards, T.G. and G.D. Glysson. 1988. Field Methods for Measurement of Fluvial Sediment. U.S. Geo. Surv. Open File Rep. 86-531. U.S. Dep. Int., Reston, VA.

Emmett, W.W. 1980. A Field Calibration of the Sediment-trapping Characteristics of the Helley-Smith Bedload Sampler. Prof. Pap. 1139. U.S. Geol. Surv., Reston, VA.

Gomez, B., R.L. Naff, and D.W. Hubbell. 1989. Temporal variations in bedload transport rates associated with the migration of bedforms. Earth Surf. Proc. Landforms 14:135-56.

Gomez, B., D.W. Hubbell, and H.H. Stevens, Jr. 1990. At-a-point bedload sampling in the presence of dunes. Water Resour. Res. 26(11):2717-31.

Grant, G.E. 1987. Assessing effects of peak flow increases on stream channels—a rational approach. Pages 142-49 *in* Proc. Calif. Watershed Manage. Conf. Rep. No. 11. Wildland Resour. Center, Univ. Calif., Berkeley.

———. 1988. The RAPID Technique: A New Method for Evaluating Downstream Effects of Forest Practices on Riparian Zones. Gen. Tech. Rep. PNW-220. Forest Serv., U.S. Dep. Agric., Washington, DC.

Harvey, G. 1989. Technical Review of Sediment Criteria. Water Qual. Bur., Idaho Dep. Health Welfare, Boise, ID.

Hubbell, D.W. 1987. Bedload sampling and analysis. Pages 89-120 *in* C.R. Thorne et al. eds. Sediment Transport in Gravel-bed Rivers. John Wiley & Sons, NY.

Hurlbert, S.H. 1984. Pseudoreplication and the design of ecological field experiments. Ecol. Monogr. 54:187-211.

Kapesser, G. 1992. Riffle armor stability index. Unpubl. paper. Panhandle Natl. Forest, Coeur d'Alene, ID.

Ketcheson, G.L. 1986. Sediment Rating Equations: An Evaluation for Streams in the Idaho Batholith. Gen. Tech. Rep. INT-213. Forest Serv., U.S. Dep. Agric., Washington, DC.

King, J.G. 1989. Streamflow Responses to Road Building and Harvesting: A Comparison with the Equivalent Clearcut Area Procedure. Res. Pap. INT-401. Forest Serv., U.S. Dep. Agric., Washington, DC.

MacDonald, L.H. 1989. Cumulative watershed effects: the implications of scale. Pap. presented 1989 Fall Meet., Am. Geo. Phys. Union (abstract in Eos 70(43):114-15).

MacDonald, L.H., A. Smart, and R.C. Wissmar. 1991. Monitoring Guidelines to Evaluate Effects of Forestry Activities on Streams in the Pacific Northwest and Alaska. EPA/910/9-91-001. NPS Sect., U.S. Environ. Prot. Agency, Region 10, Seattle, WA.

Meehan, W.R., ed. 1991. Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. Spec. Publ. 19. Am. Fish. Soc., Bethesda, MD.

Megahan, W.F. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho batholith. Pages 114-21 *in* F.J. Swanson et al. eds. Sediment Budgets and Routing in Forested Drainage Basins. Gen. Tech. Rep. PNW-141. Forest Serv., U.S. Dep. Agric., Portland, OR.

Megahan, W.F., W.S. Platts, and B. Kulesza, 1980. Riverbed improves over time: South Fork Salmon. Pages 380-95 *in* Symp. Watershed Manage. Am. Soc. Civil Eng., New York.

Moring, J.R. 1975. The Alsea Watershed Study: Effects of Logging on the Aquatic Resources of Three Headwater Streams of the Alsea River, Oregon. Fish. Res. Rep. 9. Oregon Dep. Fish Wildl., Portland, OR.

Reid, L. 1991. Research and Cumulative Watershed Effects. Draft manuscipt for Cal. Dep. Forest. Fire Prot. Redwood Sci. Lab., Forest Serv., U.S. Dep. Agric., Arcata, CA.

Rieger, W.A. and L.J. Olive. 1986. Sediment responses during storm events in small forested watersheds. Pages 490-98 *in* A.W. El-Shaarawi and R.E. Kwiatkowski, eds. Statistical Aspects of Water Quality Monitoring. Elsevier Publishing, NY.

Salo, E.O. and T.W. Cundy, eds. 1987. Streamside Management: Forestry and Fishery Interactions. Contrib. No. 57. Inst. Forest Resour., Univ. Washington, Seattle.

Sidle, R.C. 1988. Bed load transport regime of a small forest stream. Water Resour. Res. 24(2):207-18.

Sullivan, K. 1985. Long-term patterns of water quality in a managed watershed in Oregon: 1. Suspended sediment. Water Resour. Bull. 21(6):977-87.

Thomas, R.B. 1985. Measuring Suspended Sediment in Small Mountain Streams. Gen. Tech. Rep. PSW-83. Forest Serv., U.S. Dep. Agric., Washington, DC.

———. 1988. Measuring sediment yields of storms using PSALT. Pages 315-23 *in* Sediment Budgets. Publ. No. 174. Int. Ass. Hydrol. Sci., Wallingford, UK.

U.S. Environmental Protection Agency. 1986. Quality Criteria for Water. Off. Water Reg. Stand., Washington, DC.

———. 1988. Introduction to Water Quality Standards. EPA 440/5-88-089. Off. Water Reg. Stand., Washington, DC.

———. 1989. Rapid Bioassessment Protocols for Use in Streams and Rivers: Benthic Macroinvertebrates and Fish. EPA/444/4-89-001. Off. Water Reg. Stand., Washington, DC.

Walling, D.E. and B.W. Webb. 1981. The reliability of suspended sediment load data. Pages 177-94 *in* Erosion and Sediment Transport Measurement. Publ. No. 133. Int. Ass. Hydrol. Sci., Wallingford, UK.

Williams, G.P. 1989. Sediment concentration versus water discharge during single hydrologic events in rivers. J. Hydrol. 111:89-106.

Ziemer, R.R. and T.E. Lisle. 1992. Evaluating sediment production by activities related to forest uses — a Pacific Northwest perspective. *In* Proc. Tech. Workshop on Sediments, Corvallis, OR. U.S. Environ. Prot. Agency and Forest Serv., U.S. Dept. Agric., Washington, DC.