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SEDIMENT DYNAMICS IN TYPE 4 AND 5 WATERS,

A REVIEW AND SYNTHESIS

By

Ann MacDonald and Kerry W. Ritland

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The primary author of this report is Ms. Anne MacDonald. Mr. Ritland is the author of the section on water quality in Type 4 and 5 Waters. Additional technical and editorial review was provided by Mr. Gary Bigham and Ms. Carol Newlin, with assistance from Ms. Jane Sexton, Ms. Joyce Lundstrom and Mr. Scott Veggeberg. Graphics were produced by Mr. Kevin Hayes.

EXECUTIVE SUMMARY

Type 4 and 5 Waters, as defined in the Washington Forest Practices Rules and Regulations (WAC 222-16-030), are small headwater streams that cannot support significant populations of fish, are not used as developed water supplies, and are not specifically targeted for protection of downstream water quality. PTI Environmental Services reviewed existing literature and interviewed regional experts regarding the status of sediment dynamics of Type 4 and 5 Waters, specifically those occurring in headwater portions of drainage basins, for the Sediment, Hydrology and Mass Wasting Steering Committee of the Timber, Fish, and Wildlife (TFW) Cooperative Monitoring, Evaluation and Research (CMER) Committee. Field managers and other TFW participants were queried through a questionnaire and workshop regarding regional variations in sediment dynamics and the effects of forest practices on these streams. These streams are important because they are the major link between hillslopes and the downstream waters in which the state and its citizens have a legally established vital interest. Sediment dynamics in these small channels are difficult to understand, requiring a thorough integration of local and discontinuous hillslope and fluvial processes. Much is known about the general patterns and magnitudes of sediment input to and sediment production from small channels. Less is known about the range of actual fluvial transport mechanisms in these channels. Storage and transport processes within the channel are both fluvial and nonfluvial in nature. Understanding these processes is important, because predicting sediment loads in larger channels requires quantifying the stochastic nature of sediment supply input from upstream. This report summarizes existing information on sediment dynamics in headwater channels and notes information and baseline data gaps that must be resolved within the TFW process.

Sediment input from mass wasting, rilling or gullying, soil creep, dry ravel, or bioturbation begin the process of delivering sediment to Type 4 and 5 Waters. Regional variations in input processes and magnitudes under unlogged conditions can be large due to variations in geology and disturbance history. Observed differences in sediment dynamics in small channels, however, are often the result of discrete episodes of mass wasting rather than continuous sediment delivery.

Slumps and earthflows can be regionally or locally important forms of mass wasting. The failure surface for most of these types of mass movements is below the soil-rock boundary. Therefore, the local variation in their spatial frequency is primarily a function of bedrock geology. Many of these failures are centuries old, move on the order of 10 cm to 10 meters per year, and have lags of about a month to a few years in their response to destabilizing factors. Sediment is typically delivered to channels by debris avalanching off the toe of the slide. Presently no data are available on these features to assess their initiation mechanisms or their impact on sediment delivery to Type 4 and 5 Waters in the state, even though they have been widely reported in western Washington.

Rapid translational failures are the most frequent form of mass wasting in the Pacific northwest. Termed debris slides or debris avalanches, they are generally small, shallow failures brought on by excess pore pressure along a discrete surface that is roughly parallel to the ground slope. The failed mass retains little of the original coherence of the original soil mass. Undercutting of the slope toe by fluvial erosion or loss of apparent soil cohesion from a decrease in root strength can contribute to debris avalanching. Therefore, these failures occur in undisturbed watersheds at the toe of a slope adjacent to a stream, and in what are widely referred to as unchannelized valleys or colluvial hollows. Unchannelized valleys are the bedrock depressions above the channel head that concentrate subsurface stormflow, and are flushed by debris avalanching/sliding with a recurrence interval of several thousand years per valley in the Pacific northwest. Predicting the probability of these types of failure (i.e., site-specific threshold conditions) will require a significant investment in the acquisition of baseline soil, geology, and sub-surface hydrologic data.

Creep, treefall, and other bioturbation rates are on the order of a few millimeters of sediment per year, yet amount to 15 to 35 percent of the average annual sediment yield in small forested basins west of the Cascades. This proportion is probably of similar magnitude in eastern Washington. Surface erosion, rilling, and dry ravel are virtually unknown in undisturbed forest lands west of the Cascade crest. The shallow infiltration capacity of forest soils exceeds rainfall intensity for storms common in the Pacific northwest, preventing unchannelized (overland) water flow over the ground surface. Some non-harvested areas in eastern Washington forests may be subject to surface runoff and erosion in the highest intensity fall rainstorms, but none have been reported in the literature. Few data are available to document the rates and magnitudes of these processes in Washington, particularly during and after the initiation of harvest activities.

There are also few descriptions of channel morphology and inferred sediment transport processes available for the smallest of these channels. In larger Type 4 and 5 Waters, sediment transport by streamflow is rapid for fine materials that move as suspended load, and typically episodic for larger particles that move as bedload from one obstruction (logjam or boulder dam) to the next in a cascading fashion. No published data on streamflow transport rates in headwater channels were found, but rates appear to be low relative to those for hillslope input in western Washington. These channels are catastrophically flushed by debris flows or debris-dam breaks at recurrence intervals of 1,500 years in first order channels, delivering sediment instantaneously downstream to fish-bearing waters. The relations between hydraulics sediment transport, and channel morphology in these headwater channels must be addressed in greater depth in order to effectively manage these stream corridors.

Consistently demonstrated effects of forest practices on sediment dynamics in Type 4 and 5 Waters can be traced to road building, road use, yarding, and removal of vegetation from hillslopes. Roads are far more significant at generating chronic transportable sediment, which is more quickly available to headwater channels, than vegetation removal alone. Much of this eroded sediment is silt and clay, which moves rapidly out of small stream channel networks. Disrupted drainage can lead to severe erosion of saturated fill areas, and in turn to mass wasting. The magnitude of the increased sediment load is sensitive to construction, maintenance, and storm history. Recent studies in the northwest put the road-related increase in sediment yield from <2 to 50 times background yields. Earlier studies showed sediment yield increased several hundred times, but those magnitudes were a function of outdated construction practices coupled with major storms. The connection between road layout and construction methods and downstream observed effects must be better established, particularly in eastern Washington.

LOD is a major component of small streams in forested watersheds. Stream size and LOD loading are inversely correlated. Movement of LOD is by flotation of small pieces during high flows or by debris flows; the latter are required to mobilize the largest pieces. Debris stability in turn controls the residence time of associated sediment storage sites, which can be stable for a few years (eastern Washington) to tens of years. Most woody material introduced to channels during timber harvest is slash. Small pieces are more mobile and caulk larger debris accumulations, making the resulting jam more susceptible to catastrophic failure. Subsequent long-term additions of debris to streams draining logged watersheds are likely to be from early successional tree species, which in the northwest consist of hardwoods such as alder, followed by early maturing conifers. Jams from second growth appear shorter-lived than jams in undisturbed channels, although this may not be geomorphically significant. It is important to note that as yet no data exist in the literature which evaluate buffer strips as long-term sources of LOD along lowest order channels. To some variable extent, debris jams buffer fluvial sediment transport through disturbed basins, which have high sediment loads per unit area for several years following logging and road building activities. Issues of long-term LOD recruitment, LOD-influenced sediment routing, and appropriateness of channel clearance must all be addressed.

Vegetation removal, road building, and surface yarding can alter the hydrologic system of small watersheds by increasing streamflow or flood peaks. Depending upon local hydrologic factors, road building and surface yarding can also influence runoff to the extent that some of the watershed is rendered impermeable. This effect is increasingly important with increasing basin area in roads and skid trails. In rain-dominated watersheds, increases in runoff alone do not appear to be generally near the magnitude required to increase total geomorphic work. The frequency of moderate runoff events can increase for a period of time (<5 years) after harvest. Studies of snowfall-dominated systems, however, point to two very different and important conclusions. First, altered snowmelt dynamics between clearcuts and forested land are responsible for increases in peak flows, while decreased summer evapotranspiration increases low flow and total annual yield conditions. Second, increases in peak flows of 20 percent could be sufficient to entrain more of the fluvial sediment load. Research on the geomorphic effectiveness of alteration in the timing of runoff, and of increased peak flows (absent other impacts) is necessary.

Interest in the chemical quality of small streams is focused around nutrient cycling and on entry and persistence of man-made organic chemicals (i.e., insecticides, herbicides, and fertilizers) applied to forests. There are no documented problems of adverse water quality resulting from timber harvest and slash treatment or from pesticide and fertilizer application. A comprehensive body of literature indicates that clearcutting, slash burning, and fertilizing normally result in a temporary increase in nitrate concentration, but concentrations remain well below water quality standards and return to normal following revegetation. Secondary peaks of nitrate following fall rains occur but do not pose a water quality hazard. Direct application of chemicals to surface water can be limited by maintaining a buffer strip along flowing streams as is currently required.

An important aspect of developing a research strategy for Type 4 and 5 Waters is to assess the problems that land managers involved in TFW have encountered in addressing issues related to headwater streams. A questionnaire was used to acquire information from TFW participants regarding the topics addressed above. Sediment dynamics were found to be similar within four areas: lowlands and steeplands on the west slope of the Cascades, and lowlands and steeplands on the east slope. These regions did not entirely coincide with either DNR regional boundaries or the simplified forest ecosystem boundaries used for analysis. Mass wasting dominated sediment input on the steeplands and in the western Washington lowlands. Sediment storage was associated with obstructions in all small channels, regardless of geographic locale. Primary timber harvest impacts were associated with roads statewide, although road-related mass wasting in northeastern Washington was not noted. LOD clearance and recruitment following clearcutting were important topics in small channels. Water quantity appeared to be altered to some degree statewide by timber harvest activities, although the magnitude and geomorphic effectiveness of this impact is not known at all. Most respondents believed that the Forest Practices Rules have significantly reduced impacts associated with timber harvest. However, there are no data that confirm or rebut this belief. Finally, TFW was viewed as a useful forum for increasing communication, although it offered no significant changes to regulation of small channels.

From this information, the SHAM Committee has developed a research strategy to address the numerous remaining issues surrounding Type 4 and 5 Waters in a way that will be useful to managers. Tools are required to assist screening permit applications, and managers must be able to determine potential hazards and associated risks relative to forest harvest. SHAM's research agenda includes:

- Compilation of baseline data on sedimentation and management effects
- Acquisition of descriptive information on channel morphology, sediment, and fluvial sediment transport and storage processes in Type 4 and 5 Waters
- Additional data on initiation of mass wasting, particularly related to management activities, and with attention to channel recovery
- Study of recruitment and export patterns for LOD and floatable debris and management activities
- Documentation of alterations to flood hydrographs from management, and the geomorphic responses of small channels, with special focus on rain-on-snow events
- Study of other region-specific issues, such as grazing impact in eastern Washington.

INTRODUCTION

The Timber, Fish, and Wildlife (TFW) program is a natural resource management agreement negotiated between representatives of Indian tribes, state agencies, the timber industry, and environmental groups in the state of Washington. This agreement, which has led to a comprehensive and enforceable accord on managing forested lands in the state, is guided by the principle of adaptive management. Crucial to this management process is the combination of interdisciplinary scientific study and intergroup cooperation to advance the knowledge and improve the site-specific management of natural resources. PTI Environmental Services has reviewed existing literature and interviewed regional experts regarding the status of sediment dynamics of Type 4 and 5 Waters, specifically those occurring in headwater portions of drainage basins, for the Sediment, Hydrology and Mass Wasting Steering Committee of the TFW Cooperative Monitoring, Evaluation and Research (CMER) Committee. We also queried field managers and other TFW participants through a lengthy questionnaire and workshop regarding the statewide regional variations in sediment dynamics of headwater basins, and the effects of forest practices on these streams.

Type 4 and 5 Waters, as defined in the Washington Forest Practices Rules and Regulations (WAC 222-16-030), are small headwater streams that cannot support significant populations of fish, are not used as developed water supplies, and are not specifically targeted for protection of downstream water quality. Although other types of channels or bodies of water can be classed as Type 4 or 5 Waters, headwater channels and associated unchannelized swales and depressions are the focus of this report.

By regulatory definition, Type 5 Waters include both flowing streams less than 2 feet wide and areas of perennial or intermittent seepage. (Type 5 Waters may also be bogs or ponds. However, sediment dynamics associated with standing water are not addressed in this report.) Type 4 Waters are larger than Type 5 but inaccessible or otherwise too small to provide significant fish habitat. An upper limit on the size of Type 4 Waters is 5 feet wide between the ordinary high water marks if accessible to anadromous fish or 10 feet wide if available only to residents, with a gradient of <12 percent and a minimum summer flow of 0.3 ft^3/sec. Type 4 and 5 Waters correspond to zero order, first order, second order, and small third order streams (Strahler 1957; Dietrich et al. 1987). Such streams generally have high gradients, contain significant woody debris, and may exhibit intermittent or ephemeral flow patterns. (Note that the Washington state stream typing system ranks channels in the opposite direction from that used in the geomorphic stream ordering system. Thus, Type 5 Waters represent the lowest stream orders, while Type 1 Waters represent the highest stream orders.)

As TFW seeks to balance the preservation of natural resources and maintain a viable timber industry, appropriate management of Type 4 and 5 Waters has become a serious issue. Type 4 and 5 Waters are arguably the most difficult elements of a forested landscape to reconcile with present timber harvest practices. These streams are important because they are the major link between hillslopes and the downstream waters in which the state and its citizens have a legally established vital interest. They are also particularly vulnerable to natural disturbances and forest management activities because of their large numbers and their proximity to sensitive hillslope processes that may be affected by forest practices. As a result, disturbance of Type 4 and 5 Waters is nearly impossible to avoid during road construction and yarding activities. Hence, local disturbance of low-order channels is a predictable impact of both timber harvest and post-harvest silvicultural activities.

Understanding sediment dynamics in these small channels is also difficult, requiring a thorough integration of local and discontinuous hillslope and fluvial processes. Larger channels (third and fourth order, or equivalents to Type 3 Waters) are better understood for several reasons. They are extensively studied in relation to their value to anadromous fish, they are more physically accessible, and they are more like alluvial channels in character and therefore more regular in morphology. Fully alluvial channels (fifth order and larger, or equivalents to Type 1 and 2 Waters) flow through relatively uniform sediments deposited by fluvial processes. Such channels exhibit consistent spacing of pools and riffles (5-7 times the channel width), and they have generally more predictable sediment transport rates. In contrast, Type 4 and 5 channels are dominated by discontinuities in the geologic materials over which they flow and by vegetation, including large organic debris (LOD) (Swanson 1981). Type 5 Waters in particular represent a crucial link between the processes of downslope soil movement and the drainage network. The lateral extent of these streams can fluctuate over geologically short periods of time in response to natural and manmade basin disturbance.

FOREST PRACTICES RULES AND REGULATIONS APPLIED TO TYPE 4 AND 5 WATERS

Present activities associated with timber harvest in and around Type 4 and 5 Waters vary in accordance with existing regulations due to local physical condition of headwater channels and local forest practice. Washington Forest Practices Rules and Regulations require the following, at a minimum:

- Buffering of Type 4 Waters from road sedimentation (WAC 222-24-025 and -030) and landing sidecast (WAC 222-30-020.3e)

- Buffering of both Type 4 and 5 Waters from the inadvertent application of chemicals (e.g., herbicides, fertilizers; WAC 222-24-050, WAC 222-38-020.5)

- Minimizing skidding across Type 4 Waters (WAC 222-30-070).

Furthermore, these regulations seek to maintain the preharvest pattern of LOD by requiring slash to be removed and other pre-existing wood to remain (WAC 222-30-060, -070, and -100). Guidelines for slash and debris removal suggest that significant stream clearance (including removal of pre-existing wood) should be undertaken only in channels with very steep slopes (60 percent; 31 degree) and channels where both the danger of debris flows and the risk to downstream waters is considered high.

Additionally, the TFW agreement provides for protection of Type 4 and 5 Waters through site-specific conditions on forest practice permits. A commonly used condition is the specification of a riparian leave area on a Type 4 Water to "protect public resources" (WAC 222-30-020.5). Environmental checklists are required to comply with the Washington State Environmental Policy Act for road construction in slide-prone areas drained directly by a Type 4 Water (WAC 222-16-040.1e).

Finally, Type 4 and 5 Waters judged to be unstable (or otherwise highly sensitive) receive field review by Washington Department of Natural Resources (DNR) field personnel and, if necessary, by interdisciplinary teams of specialists. Specific forest practice actions are developed to limit impacts from these waters based on recommendations from these individuals. Controversy exists over site-specific management in and around Type 4 and 5 Waters because they are afforded substantially less protection than Type 1, 2, and 3 Waters. For this reason, research to better understand sediment dynamics in these small channels is a high priority of the CMER Committee.

ORGANIZATION OF THIS REPORT

Specific topics of interest have been identified by CMER that relate directly to sediment processes in small streams and the effect of forest practices on these processes. This report is organized in the following manner to address these topics. The first section following this introduction describes the methods used to compile information on both regional sediment dynamics in headwater channels of forested watersheds, and the specific patterns of sediment routing and related management issues of concern to TFW participants. The next section presents the results of the literature review and discussions with regional researchers. This section specifically addresses the following issues:

- Sediment input to Type 4 and 5 Waters under undisturbed forest conditions
- Sediment transport and routing in these channels by fluvial processes and debris flows, also under undisturbed forest conditions
- Effects of forest practices on sediment dynamics in Type 4 and 5 Waters
- Dynamics of large organic debris in Type 4 and 5 Waters, including the effects of forest management
- Changes in water quantity and routing following timber harvest
- Effects of forest practices on water quality in Type 4 and 5 Waters.

The remaining section of the report describes regional characteristics of Type 4 and 5 Waters and the watersheds which they drain, sediment dynamics in these channels, and the effects of forest practices on these channels, as determined by a questionnaire distributed to TFW participants and other interested parties. This final section also presents management tools and information needs of land managers with respect to sediment in Type 4 and 5 Waters, and research recommendations by the SHAM Committee and PTI Environmental Services.

METHODS

The primary objective of this project is to synthesize the present understanding of small stream sediment dynamics, regional variations of processes controlling sediment dynamics specific to Washington state, and the contribution of various forest practices to these processes. These tasks were accomplished through a review of published and unpublished information, interviews with experts in forest geomorphology, and a questionnaire and follow-up interview with personnel currently involved in forest management in Washington state.

REVIEW OF EXISTING INFORMATION

To review and synthesize literature on sediment dynamics of low-order stream channels draining coniferous forests, PTI Environmental Services' internal library information was reviewed to construct search algorithms for bibliographic databases. Using five databases (GeoRef, Water Resources Abstracts, National Technical Information Service, Dissertation Abstracts, and Conference Papers Index), citations to relevant publications by current researchers specializing in forest geomorphology were obtained. This provided a means of evaluating the relative merits of these databases. Based on these searches, two databases, Water Resources Abstracts and GeoRef, were found sufficient for complete coverage of specific search algorithms. These two databases were then searched, concentrating on the topics of water quality, mass wasting, LOD, water quantity, forest practices, and sediment production in small, forested channels. The search algorithms were specifically designed to uncover sources of information specific to Type 4 and 5 Waters. The PTI internal library was used to gain a broader view of forest geomorphology. All available citations referring to coniferous forests of the western United States were investigated, recognizing that studies of these processes have occurred throughout the region and may not be directly applicable to Washington. Each study reviewed herein is deemed to be at least indirectly applicable based on one of the following factors: 1) the climate and forest regime of the study area are similar to those of one or more regions of Washington, or 2) the study database is extensive enough to allow comparison of processes occurring in Type 4 and 5 Waters with processes occurring in larger river systems. Specific climatic, geologic, and physiographic information is available for numerous long-term study sites outside the state (e.g., H.J. Andrews Experimental Forest and Alsea River watershed in Oregon, Redwood National Park in California, and the U.S. Forest Service Idaho Batholith study area). In fact, only 10 percent of the citations given in this report are based upon studies in Washington state; 29 percent are from Oregon, and the remainder are from Idaho, British Columbia, northern California, or pertain to general topics or methods (Beschta, R.L., 31 May 1989, written communication). However, such information has not yet been compiled for regions within the state of Washington in sufficient detail for determination of the specific applicability of studies from outside the state. In addition, during the course of this review, several examples of gray literature (reports prepared under contract to specific organizations but not released to the public) and unanalyzed data were discovered. However, because of the short project schedule, few of these could be evaluated.

The experts in west coast forest geomorphology listed in Table 1 were interviewed by telephone or in person. Roughly half of these individuals had studied channels small enough to be equivalent to Type 4 or 5 Waters. Lee Benda, Tom Dunne, Gordon Grant, Bob Beschta, Stan Gregory, Mike Church, Walt Megahan, Bill Weaver, Leslie Reid and Bill Dietrich are actively studying small channels and have ongoing research projects which TFW should remain abreast of. Although Peter Lewis of the B.C. Ministry of the Environment could not be reached for an interview, he is also likely to have a useful perspective on the issue of sediment dynamics in headwater streams.

Using this approach, a great deal of existing information applicable to small streams was found on three specific topics: 1) zero order basins (colluvial hollows or swales) and the transition from unchannelized to channelized hillslopes (Dietrich et al. 1987), 2) debris flows, and 3) paired basin studies between "managed" (e.g., timber harvest, roads) and unmanaged watersheds, with sediment and water flow data collected on second through fourth order streams (equivalents of Type 4 and 3 Waters). Less well understood are the mechanisms of fluvial transport in small channels, although current research by Gordon Grant (13 March 1989, personal communication) and Mike Church (10 April 1989, personal communication) may improve this situation. The fate of LOD is also moderately understood. Only Bilby (1984), Duncan et al. (1987), and Keller et al. (1982) present data from streams draining second growth forests where a large relict component is not obvious. Finally, little direct information was found on water quality in small channels. The information available was generally restricted to sediment (discussed below), temperature (the subject of a separate study within TFW), or nutrients (the subject of another TFW study). For example, no data were found examining the effectiveness of the buffer strip requirement in the application of forest chemicals adjacent to Type 4 and 5 Waters.

ADMINISTRATION OF THE QUESTIONNAIRE

The objective of this task was first to summarize regional differences in the sediment dynamics of Type 4 and 5 Waters of Washington, building on interviews of DNR personnel from regional offices and TFW interdisciplinary team members operating in each of the ecoregions.

TABLE 1. LOCAL AND REGIONAL EXPERTS CONSULTED

Name	Institutional Affiliation
Mr. Lee Benda	University of Washington
Dr. Robert Beschta	Oregon State University
Dr. Robert Bilby	Weyerhaeuser Company
Mr. Matt Brunengo	Washington Department of Natural Resources
Mr. Ken Buss	USFS Mt. Baker-Snoqualmie National Forest
Dr. Michael Church	University of British Columbia
Dr. William Dietrich	University of California, Berkeley
Mr. Stan Duncan	Weyerhaeuser Company
Dr. Thomas Dunne	University of Washington
Mr. William Fowler	USFS - Wenatchee National Forest [retired]
Dr. Jerry Franklin	University of Washington
Dr. Gordon Grant	USFS Forestry Sciences Laboratory, Corvallis
Dr. Stan Gregory	Oregon State University
Dr. Dennis Harr	USFS Forestry Sciences Laboratory[a]/University of Washington
Dr. Harvey Kelsey	Western Washington University
Mr. George Lienkaemper	USFS Forestry Sciences Laboratory, Corvallis
Dr. Thomas Lisle	USFS Redwood Sciences Laboratory
Ms. Mary Ann Madej	Redwood National Park
Dr. Walt Megahan	USFS Intermountain Forest and Range Exp. Station, Boise
Mr. Roger Nichols	USFS Mt. Baker-Snoqualmie National Forest
Ms. Susan Perkins	University of Washington
Dr. John Pitlick	USGS Cascades Volcanoes Observatory[b]
Ms. Leslie Reid	USFS Redwood Sciences Laboratory
Dr. James Sedell	USFS Forestry Sciences Laboratory
Dr. Kathleen Sullivan	Weyerhaeuser Company
Dr. Fred Swanson	USFS Forestry Sciences Laboratory, Corvallis
Dr. William Weaver	Redwood National Park
Mr. Rick Wooten	USFS Gifford Pinchot National Forest

[a] USFS - USDA Forest Service.

[b] USGS - U.S. Geological Survey.

Next, information was sought regarding the perceived impacts of forest practices on Type 4 and 5 Waters, with the focus on the issues and questions posed in the literature review and on downstream impacts of forest practices in Type 4 and 5 Waters. To ensure uniformity of topical coverage, a questionnaire was prepared after partial completion of the literature review to solicit this information from TFW participants in each of the seven DNR regions. Those individuals with significant experience in more than one ecoregion were queried further to ascertain perceived contrasts between ecoregions. In order to summarize the salient characteristics of the ecoregions themselves, the first portion of the questionnaire focused on the climatic, physiographic, and dendrological characteristics of the state-regulated forest land base. Additional questions regarding actual forest practices were included. The second portion of the questionnaire examined the experience, observations, and perceptions of sediment dynamics related to the issues outlined in the discussion above. The next part of the questionnaire queried respondents about the effects of timber harvest practices on sediment dynamics, water quality (exclusive of total suspended sediment), woody debris loading, and mass wasting. The remainder of the questionnaire was devoted to information needs and management tools. The questionnaire was either distributed by regional TFW contacts or sent by PTI Environmental Services to TFW participants to solicit their ideas prior to interviewing. A separate mailing was made to Washington Forest Protection Association (WFPA) members who were not already named on the distribution/interview list, to ensure adequate industry participation. The Washington Environmental Council and U.S. Forest Service also circulated additional questionnaires to their staff. A copy of the questionnaire is provided in Appendix A.

Anne MacDonald of PTI Environmental Services met with TFW participants to discuss the questionnaire at regional meetings in the Northeast, Southeast, Northwest, South Puget Sound and Olympic DNR regions during the week of April 3, 1989. The purpose of the questionnaire was explained as a first attempt to find out what is known about small channels. When possible, participants filled out the questionnaires at those meetings. Otherwise, they were asked to return them by mail. Response rate was estimated to be about 25 percent but was not calculated exactly because of the unknown number of questionnaires circulated by non-PTI personnel. Responses appeared high for those regions where a meeting was scheduled and lower for the other two regions (Southwest and Central).

INTERIM REVIEW OF PROGRESS

Responses to the questionnaires received through 17 May, as well as the results of the literature review, were presented by PTI to participants at a workshop held in Ellensburg 18 May, 1989. Members of the SHAM channel morphology group also presented a tentative research agenda for studies in Type 4 and 5 Waters, based upon information gaps identified in the literature review and by questionnaire respondents. In attendance were a range of TFW cooperators, representing the four major constituencies. This provided an independent check on the validity of the questionnaire, and enabled participants to more fully explore their particular topics of interest relative to Type 4 and 5 Waters. The workshop was also a forum by which other CMER committees could coordinate their research agendas on Type 4 and 5 Waters with those of the SHAM committee.

SEDIMENT DYNAMICS IN TYPE 4 AND 5 WATERS: REVIEW OF EXISTING INFORMATION

Type 4 and 5 Waters form a crucial and direct link between soil moving on hillslopes and sediment moving in larger alluvial and semi-alluvial river channels. This link is direct because it is unbuffered by the presence of an extensive floodplain or a large absolute amount of within-channel sediment storage (Reid, L., 6 April 1989, personal communication). Hillslopes are governed by a body of processes that balance soil matrix strength (cohesion from roots and mineralogy, and internal friction) and downslope forces (weight of the soil mass less pore pressure normal to the failure plane, and slope angle). Sediment transported in alluvial river channels is governed by the resisting forces of sediment particle moment of inertia (a function of particle size and packing) and hydraulic roughness vs. the shear stress of water exerted on the channel bed and banks. Forest geomorphologists have benefited from the efforts of the geotechnical and hydraulic engineering communities, expended on behalf of understanding these systems. Because Type 4 and 5 Waters form the interface between two fundamentally different environments, they are both difficult and crucial to understand.

A review of available literature and queries of experts in forest geomorphology of the western United States shows that a great deal is known about the general patterns and magnitudes of sediment input to and sediment production from small channels. Less is known about the range of actual fluvial transport mechanisms in these channels, although ongoing research shows promise for integrating the pieces that are known. Input processes from hillslopes will be examined by expanding upon the recent thorough review by Swanson et al. (1987b). Storage and transport processes within the channel are both fluvial and nonfluvial in nature. Understanding sediment and other exports from these headwater channels is important to understanding sediment transport in larger, fish-bearing streams. Predicting sediment loads in larger semi-alluvial stream channels requires understanding the stochastic nature of fluctuations in both the sediment transport capacity and the sediment supply available for transport.

Sediment input transport and storage processes in undisturbed forests, as well as supporting details on the effects of forest practices on sedimentation, LOD dynamics, water quantity, and water quality are discussed in this section. For ease of comparison among studies and regions, units of measurement are as consistent as possible within each section. For instance, sediment yields are given in t/km^2/yr and LOD loading is given in m^3/m^2 of stream channel. This occasionally required converting volume data to mass (using an arbitrary density of 1.6 t/m^3 for in-channel sediment) or making assumptions about channel width (5-10 meters in third order channels, depending upon information supplied by the author of each article). If insufficient data were given to allow the final estimate to be within an order of magnitude, no figures for these quantities are listed in this report and readers are urged to consult the source.

SEDIMENT INPUT TO TYPE 4 AND 5 WATERS

Sediment input from mass wasting, rilling or gullying, soil creep, treethrow and other forms of bioturbation, or dry ravel begins the process of delivering sediment to Type 4 and 5 Waters. Geomorphologists use sediment budgets (Table 2) to account separately for quantities of sediment delivered to a reach of stream channel (or other portion of a watershed), for storage in the channel reach, and for output from the channel reach (Dietrich et al. 1982). Although ideally based upon measurements of each process within the study watershed over a homogeneous period of record, most sediment budgets require inference of rates of processes with long recurrence intervals or the application of regionally valid rates determined elsewhere. Sediment budgets constructed in this manner are described as synthetic. Within the uncertainties of measurements and extrapolation of individual rates, these budgets allow comparisons in magnitudes of residence time among major classes of input processes as well as among regions. Regionally representative sediment budgets given in Table 2 exemplify these contrasts: the very wet, glaciated, tectonically active Queen Charlotte Islands have sediment yields an order of magnitude greater than the drier, snowmelt-dominated, granitic terrain of central Idaho, while parts of western Oregon and Washington are intermediate. This difference is due to significant mass wasting occurring in the watersheds studied in the Queen Charlotte Islands (vs. no mass wasting reported in the Idaho watersheds) and to greater rates of soil creep in the deeper and more cohesive soils found in the Queen Charlottes.

Swanson et al. (1987b) have provided the most thorough recent review of sediment input processes from mass wasting on disturbed and undisturbed land, although they have not specifically dealt with input to headwater channels. The important parts of their paper are summarized as follows. First, as noted above, regional variations in input processes and magnitudes under unlogged conditions can be large due to variations in climate and geology. Disturbance by fire and severe storms is regionally significant though often difficult to quantify because of long recurrence intervals. Observed differences in sediment dynamics in small channels, however, are often the result of discrete episodes of mass wasting rather than continuous sediment delivery by soil creep or other more continuous processes. For instance, surface erosion and dry ravel are virtually unknown in undisturbed forest lands west of the Cascade crest, although they may develop locally after logging or road construction particularly on steep (>50 percent) slopes (Swanson et al. 1987b). Second, headwater channels and seeps equivalent to Type 4 and 5 Waters are the most direct conduits to larger channels for sediment delivered to the channel by small-scale events, because they make up a large proportion of the stream network in any watershed. Therefore, the pattern

TABLE 2. SEDIMENT BUDGETS FOR SMALL, OLD-GROWTH WATERSHEDS IN THE PACIFIC NORTHWEST

	Queen Charlotte Islands British Columbia[a]	Clearwater River Olympic Peninsula, WA[b]	Watershed (WS) 10 Cascade Range, OR[c]	Idaho Batholith Central Idaho[d]
Forest Type	Sitka spruce, western redcedar	western hemlock, silver fir	Douglas-fir	Douglas-fir, ponderosa pine, grand and subalpine firs
Geology	Triassic sedimentary and volcanic	Miocene sedimentary	Tertiary volcanics, volcaniclastics	Cretaceous granitics
Drainage Area	1.4 km^2	10 km^2	0.1 km^2	1.26 km^2 (average)
Hillslope Sediment Delivered to Streams (t/km^2/yr):				
Mass wasting	34-53	38	60	no data
Soil creep/treethrow	34-88	29/9	11/1	no data
Slope wash/ravel	4-15	0	5	no data
Gullying (slide scars)	4-8	0	0	no data
Other (bioturbation, etc.)	–	4	0	no data
Total	76-164	80	77	> 7-22 (probably slope wash, creep, and dry ravel)
Fluvial Erosion (t/km^2/yr):				
Stream banks	19-99	46 (72% from 1st and 2nd order channels)	6	< 3-10
Total (t/km^2/yr):	95-263	126	83	10-32

[a] Roberts and Church (1986); synthetic, based upon regional rates, aerial photography 1936-1967, and field measurements.

[b] Reid (1981); synthetic, based upon field measurements 1977-1979, geologic and dendrochronologic interpretation, regional rates.

[c] Swanson et al. (1982); synthetic, from process measurements in H.J. Andrews with 2-25 yr periods of record, 1957-1982.

[d] Megahan (1982); based on measurements 1973-1978.

of background sediment delivery by continuous processes (e.g., soil creep) is more important in these channels than in larger ones. The following paragraphs provide details of specific processes and patterns of sediment input to headwater channels.

Soil Creep, Bioturbation, Surface Erosion, and Dry Ravel

The processes of soil creep, bioturbation, surface erosion, and dry ravel are continuous or nearly continuous in time and space on hillslopes. Soil creep and dry ravel both move soil downslope nonbiogenically, under the influence of gravity. Dry ravel is restricted to nonplastic movement of discrete soil and rock particles in the absence of significant water. Surface erosion, which is restricted to disturbed sites in forested environments, occurs as soil particles are moved downslope by the action of unchannelized water flow. Finally, bioturbation reflects soil mixing and downslope movement due to treethrow, animal burrowing, and other biologic processes. Creep, treefall, and other bioturbation rates are on the order of a few millimeters of sediment per year (Dietrich et al. 1982; Lehre 1987; Benda 1988). Rates of soil transfer are difficult to measure directly. Creep can be measured over a decade or more by monitoring the deformation of some (generally vertical) datum buried within the soil, such as an inclinometer tube (Lehre 1987). Sediments transported by surface erosion, dry ravel, or treethrow can be collected over a discrete time period. Individual measurements can then be extrapolated to similar locations in watersheds and integrated over the area and period of record. Representative rates for these processes are often calculated in sediment budgets by subtracting from storage + output all discrete input locations, or calculated from deposition rates into unchannelized valleys. Creep and bioturbation together amount to 15-35 percent of the average annual sediment yield in small, forested basins west of the Cascades, and could be of similar magnitude on the east side (Table 2).

Surface erosion, as noted above, is almost nonexistent in undisturbed, forested landscapes. The shallow infiltration capacity of forest soils exceeds rainfall intensity for storms common in the Pacific northwest, preventing unchannelized (overland) water flow over the ground surface. Adequate drainage of forest soil depends on the presence of voids in the soil (also known as soil pipes or macropores). Voids in turn depend on some form of soil cohesion to persist.

Some undisturbed areas in eastern Washington forests may be subject to surface runoff and erosion in the highest intensity fall rainstorms, but none have been reported in the literature. (Intense rainfall onto frozen ground can also produce overland flow and surface erosion. This process has been reported as common in the Rockies but has not been singled out as an important process in Washington.) Dry ravel, the sliding and falling of individual, loose soil particles and small rock fragments, has been reported related to disturbed ground in eastern Washington (Helvey 1980) and Idaho (Megahan 1982). Again, these processes can be expected to deliver sediment to stream channels on the order of millimeters per channel length per year, but they are the dominant source of sediment to headwater channels in the absence of mass wasting.

Slumps and Earthflows

Slumps (discrete rotational failures) and earthflows (continuously deforming translational failures) can be regionally or locally important forms of mass wasting (Swanson et al. 1987b). Swanston et al. (1988) report that combined, slumps and earthflows constitute 10-30 percent of mountainous landscapes in the Pacific northwest. The failure surface for most of these types of mass movements is below the soil-rock boundary. Therefore, the local variation in their spatial frequency is primarily a function of bedrock geology. Many of these failures are centuries old, move 0.1-10 meters per year, and have lags of about a month to a few years in their response to destabilizing factors such as erosion of the toe by fluvial processes or alteration of the water balance within them. Sediment is typically delivered to stream channels (regardless of order) by debris avalanching off the toe of the slide mass (Swanson et al. 1987b). Data regarding styles and rates of sediment delivery to channels from earthflows are available from the Cascades and Coast Range of Oregon (Hicks and Lienkaemper 1983; Pyles et al. 1987; Swanson et al. 1987a). For example, the Lookout Creek earthflow has moved at an average annual rate of 8.9 cm/yr over the 1974-1986 time period (Pyles et al. 1987), with measured local movement rates ranging from a low of less than 1 cm/yr during the 1976-1977 drought to 21 cm/yr during the 1981-1982 season. These rates correspond to seasons of minimum (1049 mm) and maximum (2496 mm) precipitation during the period of record (Swanson et al. 1987a). Since these earthflows have been subject to either fluvial erosion of the toe by a third order or larger channel or by human disturbance, it is not known whether these movement rates represent suitable approximations of sediment delivery to headwater channels. Furthermore, no data are available on these features to assess their impact on sediment delivery to Type 4 and 5 Waters in the state, although these features are present in Washington.

Rapid Translational Failures

Rapid translational failures are a common form of mass wasting in the Pacific northwest. Variously termed debris slides or debris avalanches, they are generally small (<100 m^3), shallow slope failures brought on by excess pore pressure along a discrete surface. The failure surface itself is commonly parallel or subparallel to the ground slope, and the failed mass retains little of the original coherence of the original soil mass. Undercutting of the slope toe by fluvial erosion or loss of apparent soil cohesion from a decrease in root strength can contribute to debris avalanching. Unfortunately, while these types of failures are very common in the Pacific northwest, they are rarely identified separately in landslide inventories of undisturbed lands. An exception is several studies by Swanson and coworkers in Oregon (Swanson et al. 1987b). Swanson et al. (1981) found that avalanches averaged 54 m^3 and resulted in a soil transfer rate of 45 $t/km^2/yr$ in the Mapleton Ranger District of Siuslaw National Forest in the Oregon Coast Range. Watersheds in this region are highly dissected and developed in Tyee Sandstone. Swanson and Lienkaemper (1985) found a similar soil transfer rate in the central Oregon Cascades (underlain by volcanic flows, breccias, and tuffs) from larger individual failures with lower spatial frequency. Finally, Swanson et al. (1987b) report a figure based upon work by Schulz (1980), who reported a transfer rate of only 6 $t/km^2/yr$ in the Bull Run watershed east of Portland. Swanson et al. (1987b) note that differences in slide size and spatial or temporal frequency are attributable to bedrock geology and geomorphic history. Similar data have not been developed for Washington.

Areas prone to these translational failures should be relatively easy to predict in a gross fashion since they are amenable to simple infinite slope analyses (Sidle 1987) using a program such as Level I Stability Analysis (LISA). Such analysis requires calculation of the ratio of soil strength (cohesion, apparent root cohesion, angle of internal friction) to driving force, which is a function of slope and pore water pressure on the failure plane. If this value is less than or equal to one, an area is unstable. In order to implement LISA, the USDA Forest Service and Bureau of Land Management are developing representative values for soil data as a function of bedrock and geomorphic setting (Wooten, R., 21 March 1989, personal communication). Site-specific values of hillslope angle are also relatively easy to obtain from topographic data or direct field measurement. Assessing actual pore water pressures given input precipitation is the most difficult part of the prediction process, because of seasonal variation in precipitation intensity and soil and bedrock inhomogeneities. This problem is illustrated by the experience of Sidle and Swanston (1986) who report the development of perched water tables at the bedrock-till contact during heavy, early-season rains in southeastern Alaska. Soil macropores are well developed in this location, allowing efficient translocation of incoming precipitation.

The likeliest places for such failures to occur in undisturbed watersheds are at the toe of a slope adjacent to a stream, where fluvial undercutting of the toe can oversteepen the slope, and in what are widely referred to as unchannelized valleys. In the first case, changes in local slope angle relative to soil strength govern the probability of failure. This appears to be the primary mechanism by which fluvial erosion influences hillslope processes in small watersheds, although this point is not made explicitly in the literature reviewed for this project. In the second case, concentration of pore water is the most important failure trigger.

Unchannelized valleys (also termed headwalls, swales, colluvial hollows, or zero order basins) are the bedrock depressions above the channel head that collect colluvium over centuries, localize bedrock weathering, and also concentrate subsurface stormflow. For purposes of TFW in

Washington, they are Type 5 Waters if they show signs of intermittent seepage or are located immediately above a Type 5 stream. Dietrich et. al. (1987) have recently reviewed the pertinent literature (about half of which they are responsible for). The key points are summarized here. First, regardless of their name, hollows are extensions of the drainage network that extend nearly to the drainage divide. There is an inverse logarithmic relationship between the average hollow gradient and the source area, which varies regionally as a function of precipitation intensity, and root and soil cohesion. For instance, a hollow gradient of 50 percent corresponds to source areas of 1,000-15,000 m^2 in Marin County, California; 7,000-15,000 m^2 in the southern Sierra Nevada; 2,000-7,000 m^2 in Japan; and 5,000-40,000 m^2 in the Oregon Coast Range (Dietrich et al. 1987).

Hollows are filled with colluvium delivered by creep or ravel and periodically are purged by debris avalanching or sliding. The failure recurrence interval is generally several hundred to well over a thousand years in the Pacific northwest; 7,000 years in Redwood National Park (Marron 1985); 5,000-6,000 years in the Oregon Coast Range (Benda and Dunne 1987); 600(?) years elsewhere in the Siuslaw basin of western Oregon (Swanson and Roach 1985); and 8,300-8,600 years in the Clearwater River basin of western Washington (Reneau et al. 1989). (All recurrence intervals listed here except that of Swanson and Roach (1985) are based upon ^{14}C dates on colluvial fills. Differing methods of calculation may explain this apparent discrepancy.) Lee Benda believes that the clustering in age of failures points to a disturbance plus climatic trigger (Benda, L., 31 March 1981, personal communication.) Initial failure concentrates at the channel head, due to pore water effects exceeding soil strength of a critically oversteepened mass. Observed failure surfaces are nearly always between the base of rooting in the soil mantle and the bedrock surface (Dietrich et al. 1987; Reneau et al. 1989). For this reason, vegetation type controls both the size of the hollow and the minimum size of the failure (i.e., deeper rooted vegetation leads to larger failures). Once the initial (small) mass has failed and soil and vegetation has been removed, the bare soil is prone to rilling and may eventually be drained by a headward-propagating channel. Subsequently, failure by debris avalanching can propagate headward toward the divide until all available soil and colluvium are removed from the hollow, with a resulting extension of the limit of channelized flow. Sediment excavated in this manner from the hollow is delivered directly to the fluvial system. In addition, sediment delivery to the hollow will be accelerated over the mean rate as long as oversteepened hollow sides are present estimated to be on the order of 10's of years. This will be most noticeable until hollow margins are revegetated. Over several hundred to a few thousand years, however, infilling rates may either accelerate or decelerate in response to climate and other basin factors (Reneau et al. 1989). The effect on sediment routing such failures have if they become debris flows is discussed below.

Conclusions

Within small watersheds in the Pacific northwest, episodic mass wasting events and continuous soil creep, bioturbation, ravel, and surface erosion jointly deliver sediment to headwater channels. In the absence of human activity in these watersheds, mass wasting processes deliver approximately 50-80 percent of the hillslope sediment production to the stream channel. Limited data applicable to drier conditions typical of eastern Washington suggest that mass wasting is less significant there. Within the landscape, unchannelized valleys at the head of stream channels and channel margins are the most consistent pathway for soil weathered from bedrock to be transported to larger channels. Other areas of significant instability are existing slumps and earthflows, which are generally localized in a specific geologic setting.

The absolute values of annual sediment yield reported in Table 2 are representative of at least the more erodible portions of the Pacific northwest, and with the exception of the data from Idaho they include a sufficiently long period of measurement or geologic inference to account for episodic events. Other values of sediment yield for undisturbed watersheds reported from the Pacific northwest include: 6-8 $t/km^2/yr$ (Sullivan et al. 1987b) on Hard and Ware creeks, third order basins developed on resistant volcanics in the upper Deschutes River of the southwestern Cascades (based on daily measured sediment loads for 4 years prior to significant management, and not directly including any mass wasting events); and 39 $t/km^2/yr$ (Benda and Dunne 1987) in second order watersheds developed on competent sandstones in the Oregon Coast Range (based on geologic inference over a 6000-year period). These latter two values are 10-30 percent lower than those reported in Table 2 and represent significantly different approaches to calculating sediment budgets. It is important, therefore, when comparing sediment yields and sediment budgets, to recognize that discrepancies may be related to regional or local variations in process rates as well as methods of measuring those rates.

SEDIMENT STORAGE AND FLUVIAL TRANSPORT IN TYPE 4 AND 5 WATERS

Understanding the dynamics of stream channels similar to Type 4 and 5 Waters is the last major topic in watershed evolution models to be addressed by the forest geomorphology community. Consequently, there are few descriptions of channel morphology (i.e., ratios of width to depth, slope, planform or map-view pattern, pattern of sediment storage and distribution) and inferred sediment transport processes available for the smallest channels. Indeed, there has been little explicit elaboration on headwater channels since Hack and Goodlett (1960, p. 7) described first order channels in the forested Appalachians as,

> . . . bordered directly by the side slopes, or by a gentler slope called the foot slope . . . In the stream channel, intermittent flows of water prevent the growth of trees and shrubs. The channel bottom is armored with coarse rock fragments . . . the foot slopes contain remnants of old channelways, preserved like terraces. In places they consist of detritus derived from the side slope above and which has accumulated next to the channel because of a long period of lateral cutting on the opposite side of the channel. Foot slopes are not present along the entire valley. In small valleys the side slope commonly abuts directly on the channel.

Most researchers concerned with forest geomorphology in the northwest, having at least casually observed these channels, have a conceptual model of the morphology of small channels as completely dominated by the discontinuities in their valleys (wholly nonalluvial; Swanson 1981). As noted above, this contrasts with the better understood gradation from slightly larger channels, which are locally capable of adjusting their slope and channel morphology but are still constrained to some degree by discontinuities in their stream valleys (here termed semi-alluvial). Very large rivers, which can fully adjust as they meander through floodplains composed wholly of their own deposits (alluvial channels), are best understood in terms of predicting channel dimensions and pattern relative to discharge and sediment loads. Thresholds between these types of channels, each with *inferred* characteristic sediment transport processes, are just now becoming explicitly recognized, and terminology is not yet standardized. The following discussion is based upon the authors' view of this collective conceptual model, although its applicability to the smallest and steepest of Type 4 and 5 Waters has not been established.

Two primary themes emerge from the literature on sediment transport within headwater channels. First, due to generally flashy runoff (short-duration peaks separated by little or no flow), fluvial sediment transport is rapid for fine materials that move as suspended load and typically episodic for larger particles that move as bedload. Routing of larger particles through the system is governed by the number and size of obstructions or pools and by the volume of available storage behind these structural features. In small watersheds in the northwest, bedload export makes up roughly 40-70 percent of the total fluvial export: 38 percent in Caspar Creek, northwestern California (Reid 1981); 46 ± 10 percent in the H.J. Andrews watersheds (Fredrikson 1970; Swanson et al. 1982; Swanson et al. 1987a); and 70 percent in the Idaho Batholith watersheds (Megahan et al. 1986). It is important to note this partitioning of sediment transport for several reasons. First, these values are much larger than the 5 to 15 percent value commonly reported for larger semi-alluvial and alluvial channels (Nolan and Janda 1981). Second, when studying these channels under low flow conditions, one observes the results of bedload deposition (and therefore transport) to a much greater degree than suspended load deposition.

Data relating to these observations have been generated either in flumes and undisturbed channels or as a result of studies aimed at understanding forest management effects. The former are discussed in this section; the latter are discussed in the section on forest practices.

The second major theme in sediment transport in small channels is catastrophic transport of bedload sediment. This occurs in the form of debris flows arising from external hillslope failures and traveling within channels as inertial slurry flows (Pierson and Costa 1987), and dam breaks originating within channels and traveling as hyperconcentrated streamflows are major long-term processes in headwater channels in the Pacific northwest. Sediment routing by this mechanism is discussed as well.

Sediment Storage and Transport Associated with Obstructions and Steps

It is useful to begin a discussion of sediment storage and transport with a description of major morphologic characteristics of small channels, as sediment transport processes generally are inferred from the observed distribution of channel-forming elements. One of the major features in river channels regardless of scale is pools. Their location relative to other channel and valley features forms a starting point for any discussion of channel morphology. The locations of pools in mountain streams are fixed by large roughness elements such as bedrock outcrops, sharp bends in the stream course, LOD and boulder jams, or cobble-boulder steps in a step-pool sequence. Pools form from repeated scour in the vicinity of these roughness elements (Swanson 1981; Lisle 1986). An irregular and low pool-to-pool spacing (<5-7 channel widths between pools) in headwater streams is indicative of their nonalluvial character. Transient sediment storage is the last major element of headwater channels and is also almost exclusively related to discrete roughness elements. Together, these elements form a sequence of storage compartments, steps, and plunge pools that are developed to some varying but as yet undescribed degree. In the literature, then, these channels are described in one of three ways: 1) as sluices, with few or no pools, obstructions, or sediment storage (Keller and Swanson 1979; Kaufman 1987); 2) as a stepped-bed where logs and boulders fully obstruct the channel and are randomly located (Keller and Swanson 1979; Heede 1981; Marston 1982); or 3) as step-pool systems, where the steps are small boulders and cobbles arranged as transverse ribs and may be ordered features with a characteristic spacing (Bowman 1977; Whittaker and Jaeggi 1982).

Fluvial (streamflow) erosion and deposition patterns in stepped-bed headwater channels can be understood as the result of the expenditure of energy on the streambed and banks by flowing water in the form of work (Beschta and Platts 1986). In steep mountain streams, channel obstructions such as logjams, boulder jams, and to a lesser extent rock steps, act as local base levels. They produce stretches of the channel where water surface slope, representing potential energy loss per unit length of channel, is locally decreased above the jam and increased over the jam relative to the mean. Generally, a pool and/or ponded sediment is present above the jam, and a plunge or scour pool is found under or downstream of the jam, depending upon the porosity of the jam to sediment. In mobile streambeds, pools reach maximum depth just as the flow overtops the obstruction (Beschta 1983). Finally, at high to moderate discharges, pools are characterized by very turbulent flow capable of keeping a great deal of sand and finer sediment in suspension. This turbulence dissipates additional stream energy. Thus, a significant amount of a stream's potential energy can be dissipated at debris-created steps or falls that occupy a relatively small proportion of the total stream length. The remaining portion of total energy is dissipated by other irregularities in the bed and banks or is available to transport sediment.

As an example of the significance of this localized energy dissipation, up to 70 percent of the elevation (potential energy) loss within the first and second order stream reaches in northwestern California (primarily the northern Redwood Creek basin) surveyed by Keller et al. (in press) was controlled by LOD. This form of debris control of energy distribution along the channel was most pronounced in headwater reaches and decreased with increasing drainage area. In undisturbed basins, debris-stored sediment (vs. other types of stored sediment) was strongly and positively correlated with channel slope, indicating the importance of debris in providing storage sites in steep channels, as well as the locally high production of sediment associated with steep valley slopes (Keller et al. in press). Farther south in the Redwood Creek basin, Pitlick (1982) found that organic debris was responsible for storing a substantial portion of all sediment stored in tributary channels. This portion ranged from 39 percent in streams draining Douglas-fir-dominated forest to 74 percent in basins originally forested with redwood. Data of Marston (1982) show a much smaller rate of energy dissipation (<10 percent) for small streams in the Oregon Coast Range, while Swanson et al. (1976) report values in the range of 30-50 percent.

Studies by Megahan and Nowlin (1976) and Megahan (1982) in the Idaho Batholith, Swanson and Lienkaemper (1978) in the Oregon Cascades, Benda and Dunne (1987) in the Oregon Cascades, Reid (1981) on the Olympic Peninsula, and Tally (1980) in Redwood National Park suggested that annual total sediment yields in small, undisturbed forested watersheds are from 3 to 30 percent of the sediment stored in channels, implying a residence time of 3 to 33 years for in-channel sediment. (Note that residence times of sediment within the active high-flow channel of Redwood Creek range from 9 to 50 years. No comparable data were found for semi-alluvial channels in the Pacific northwest, or for a large river with lower bedload transport than Redwood Creek.) This ratio of storage to yield should not be interpreted to mean that the sediment storage compartments associated with LOD effectively trapped *all* of the bedload moving into a particular reach. In fact, the upper horizons of debris-stored sediment was shown by Tally (1980) to be more mobile than riffle/step gravel. This suggests that debris-stored sediment is stratified into a basal layer of semipermanent storage (which is deposited immediately after the formation of a logjam or step and is physically retained) and an upper layer of transient sediment storage. The semipermanent component can remain stored until the jam deteriorates in some way (Mosley 1981). Benda and Dunne (1987), working in the Oregon Coast Range, found little textural difference between colluvial sediment deposits in unchannelized valleys and sediments stored in first and second order channels (average drainage areas of 0.07 km^2 and 0.26 km^2, respectively). This finding suggested little of the fluvial transport of selected particle size classes observed by Tally (1980). The different degrees to which sediment stored by obstructions is apparently fluvially transported in these two studies may be attributable to differences in study locations or the focus of the studies. Differences in the study locations include those of stream size (drainage basins on which Tally collected these data ranged from 1 to 10 km^2), bedrock geology (more fine-grained clastic sedimentary rocks are found in northern California), climate, forest type, or some combination of these variables. Discrepancies such as these highlight the necessity of basic descriptive work in these channels.

Finally, no published data from direct field studies of actual sediment transport rates in headwater channels were found, and recent reviews of channel processes in mountain streams are generally more concerned with channels that are slightly larger than those of interest here (Lisle 1987; Sullivan et al. 1987a). Publication of discrete transport rate data is important because it allows correlation of bedload and suspended sediment transport rates with streamflow and basin characteristics. Gordon Grant is currently analyzing data from H.J. Andrews watersheds in this light (Grant, G., 9 March 1989, personal communication).

Still, a conceptual picture of the episodic nature of sediment transport in stepped-bed or step-pool channels can be tentatively brought upstream, with the details remaining to be tested by current research (Grant, G., 9 March 1989, personal communication; Church, M., 10 April 1989, personal communication). Sediment is either eroded from the channel bed by flows exceeding a critical discharge or is supplied by erosion of channel banks or adjacent hillslopes in a more catastrophic fashion. It is transported downstream under normal fluvial processes which are adjusted to the relatively low ratio of depth to grain size (relative roughness) of stationary particles within the channel. This process continues until the particles reach an area of low shear stress, at which point they are deposited. This area of low shear stress is commonly a pool behind an obstruction (Mosley 1981; Whittaker 1987; Grant, G., 9 March 1989, personal communication). MacDonald (unpublished data) calculated that the storage compartment behind a 0.5-meter high by 6-meter wide step in a moderate gradient (1.4 percent), third order channel could have filled with 10 to 20 hours of bedload transport at bankfull discharge. This episodic filling of successive storage compartments continues in a cascading fashion downstream until the flow drops below the threshold required for movement or all pools above obstructions and steps have reached their storage capacities.

If sediment continues to be available and discharge remains sufficient for transport, transport rate increases rapidly because obstructions to flow no longer exist. At this stage, even plunge pools can fill with sediment (MacDonald, A., unpublished data; Grant, G., 9 March 1989, personal communication). Sediment and water availability are both crucial. Landslides that enter the channel and are not transported downstream can provide a steady supply of sediment for a number of years. This supply is large at first and then declines rapidly to a much lower but persistent input until the deposit is gone or stabilized by vegetation (Perkins in press). The scale of the diminution (decay) of the deposit is related to the deposit size, grain sizes present, and size of the channel. Third through fifth order channels in the Deschutes and Chehalis basins of southwestern Washington provided 1000 to 2500 m^3/yr to downstream waters over a period including moderately high flows (8 to 50 year return period), resulting in 20-80 percent removal of the slide mass in less than 7 years following the breach of any LOD jam present (Perkins in press). The applicability of this model to smaller channels has not yet been evaluated. However, Perkins (in press) suggests that it may be possible to estimate erosion of discrete landslide deposits on a regional basis to get widely applicable values for the decay constant. These values could then be used to evaluate the capability of other channels to recover from similar depositional events.

Sediment can also be eroded from the channel bed. Eroded sediment is usually the finer fraction of previously stored sediment (sand and pebbles) that is entrained by streamflow or the result of debris jam failure (Tally 1980; Mosley 1981; Sidle 1988). Sediment transported on an annual basis usually follows a pattern of seasonal and within-storm cycling in suspended sediment transport noted by VanSickle and Beschta (1983). Suspended sediment concentrations are generally higher for a given flow early in the season and on the rising limb of each storm hydrograph.

In a small channel in a forested watershed in southeastern Alaska, Sidle (1988) documented this sporadic behavior of bedload transport over a 6-year period. His study reach had a gradient of less than 1 percent and would probably be equivalent to a Type 3 Water. The channel was much steeper immediately upstream of his study reach, and LOD was responsible for sediment storage. Therefore, he was probably measuring sediment transport as it occurred in several Type 4 and 5 Waters with only minor buffering. He noted that while 33 storms in the period produced sufficient peak discharges to entrain fine material (<1 mm), discharges at or above 70 percent of bankfull discharge produced significant transport and entrained coarse bedload (>8 mm). Over a short reach of channel, significant scour and fill were occurring (totaling -2.3 meters to +5.1 meters over the period). Finally, transport rate was determined to be a function of instantaneous discharge, peak discharge of the previous storm (usually a negative correlation) and cumulative flow above the entrainment threshold. These latter two terms were not significant in all years.

In many respects, the step-pool channel type is more enigmatic than the stepped-bed channel. Problems of non-uniform sediment supply and grain size, and flashy discharge, are present in these streams as well. Step-pool channels are characteristic of sediment-poor systems. The steps may be formed by boulders, cobbles, or bedrock, and they are also best modeled from a sediment transport perspective as a series of weirs or the cascading system described above, governed by sediment supply limitations (Whittaker 1987; Grant, G., 9 March 1989, personal communication). In fact, channels with LOD-dominated steps may still have riffle, boulder, or rock steps. Therefore, the conceptual model of sediment transport described above should be applicable to these streams as well, although they may be morphologically distinct from the stepped bed channel. (Confusion between nomenclature regarding these two channel types exists in the literature. However, *step-pool* is not used to describe steps made of woody debris.) The origin of the steps are enigmatic, as they seem to be features relict from previous very high discharge events that had very heterogeneous bed material in transit (Whittaker and Jaeggi 1982). Their apparent regularity of spacing (not actually documented) has led Koster (1978) to propose an antidune origin for them. Gordon Grant is working along the same lines (Grant, G., 9 March 1989, personal communication). The steps themselves are apparently destabilized at discharges greater than bankfull, which is the threshold discharge usually associated with mobilization of sediment from riffles and point bars in alluvial channels. Gordon Grant estimates this to be 130 to 140 percent of bankfull discharge based upon flume data, but has not verified this. To date, all measurements or models of bedload transport in such systems have relied upon flume data making them suspect until field data can be obtained. Both Gordon Grant (personal communication, 9 March 1989) and Mike Church (personal communication, 10 April 1989) plan or have already begun to extend their work in this direction.

The above discussion suggests that deterministic modeling of bedload transport in headwater streams is a long way off (Whittaker 1987). Simple empirical equations for fluvial erosion using easily measured field data (slope, depth, and relative grain size) which are calibrated to similar field situations, such as Bathurst's (1987) or Milhous' (1987) represent the state of the art. Calculation of long-term sediment yield by fluvial erosion in headwater channels will probably require some form of simulation modeling similar to LISA or that of Benda (described later in this report) to account for the stochastic nature of sediment supply and the required magnitudes of streamflow. Even this form of modeling will require a better understanding of fluvial sediment transport mechanics in small channels than is currently available. One major weakness in understanding sediment transport in very small channels is quantifying the effects of composite large roughness elements. A hydraulically unique form of flow resistance (termed spill resistance) is associated with roughness elements that form plunge pools. Since the relationship between this form of flow resistance, total available stream power, and sediment transport is not understood at this time, sediment transport theory developed for larger channels cannot yet be applied directly to headwater channels (Sullivan, K., 20 May 1989, written communication).

Sediment Routing in Type 4 and 5 Waters by Debris Flows

Debris flows, also regionally termed debris torrents, are a major component of the sediment transfer mechanism in forested watersheds in the Pacific northwest. They have been reported from all areas of western Washington or Oregon, from the Entiat basin in the northeastern Cascades (Helvey 1980), and from the Yakima River basin in the southeastern Cascades (Brunengo, M., 18 May 1989, written communication). Debris flows are most commonly reported as beginning as debris avalanches/slides on hillslopes prior to moving into small channels. Dam-break torrents/floods are often confused in the literature with debris flows (and both are called debris torrents). Dam-break torrents begin as in-channel failures of sediment obstructed by LOD accumulations. They can originate as hillslope failures also but must come to rest temporarily in the channel where the sediment becomes fully saturated. The distinction between debris flows and dam-break torrents once mobilized is based upon material properties of the sediment. Stiffer debris flows cannot move on surfaces with gradients less than approximately 3.5 degrees, while dam-break torrents are more fluid and can move for many kilometers down channels of relatively low slope (Benda, L., 25 May 1989, personal communication). Dam-break torrents, which are poorly documented and understood, are not necessarily as recognizable on aerial photographs or in the field several years (perhaps 20) after their occurrence, and seem to be more characteristic of the larger semi-alluvial channels than headwater channels. Therefore, they have not been inventoried or investigated in the Pacific northwest, although they are thought to be a significant problem in the northwest Cascades (Nichols, R., 20 March 1989, personal communication). Benda, Zhang and Dunne have research in progress on dam-break torrents in the northwestern Cascades and the Oregon Coast Range but are not sufficiently advanced to comment on their results (Benda, L., 26 May 1989, written communication). Therefore, the following discussion is restricted to debris flows.

Debris flows are a potential consequence of every streamside landslide in the Pacific northwest, although the percentage of slides that become debris flows is not established unambiguously by independent inventory anywhere in the region. Consequently, the calculation of debris flow recurrence interval by Benda and Dunne (1987) of one every approximately 1,500 years per first order channel in western Oregon is at present an order-of-magnitude estimate. When the eastern half of Washington or Oregon is inventoried, there is likely to be a major increase in recurrence interval relative to the western slope of the Cascades. Furthermore, debris flows are significant for Type 4 and 5 Waters in that they are locally a major sediment transporting mechanism linking hillslopes with fish-bearing streams (Benda and Dunne 1987). Through debris flows, disturbance on 1 percent of the hillslope can translate into sedimentation effects in 10 percent of the channel network of low order basins (Swanson and Lienkaemper 1978). In terms of volume, while the initiating landslides in the Oregon Coast Range deliver around 11 $t/km^2/yr$ to a first order stream, the total sediment flushed by debris flows (through second order channels) averages 39 $t/km^2/yr$ (Benda and Dunne 1987).

While many investigators have been interested in the occurrence of debris flows, only Benda and Dunne (1987), Benda, et al. (in preparation), and Benda and Dunne (in preparation) have developed the details of routing these features through a forested watershed. Using the unglaciated and debris-flow-prone areas of the central Oregon Coast Ranges underlain by Tyee Sandstone as a test case, Benda and Dunne (1987) found that first and second order channels stored 90 percent of the sediment delivered to them from hillslopes, with the remainder exported as fluvially transported suspended sediment and bedload. (Compare this with the Swanson et al. 1982 estimated sediment storage of 80 percent of annual yield in the Oregon Cascades.) These channels are flushed out during debris flows at recurrence intervals of 1/1500 years (first order channel) to 1/750 years (second order channel), assuming independence of failure. Deposits of sediment below the channel bed in these low order channels exhibited little sorting, having a greater similarity to colluvial deposits on adjacent hillslopes than to clearly fluvial deposits downstream.

Once debris flows are moving (for several kilometers, and at speeds up to 25 m/s), material can be scoured from the first and second order channels. Eventually, this scouring occurs to bedrock, but several failures may be necessary for this to occur (Nichols, R., 20 March 1989, personal communication). In the Oregon Coast Range study area, flows erode to bedrock if the channel slope is greater than 10 percent. The deposit stops when it reaches a critical lower angle of slope, below which viscous forces in the sediment slurry again dominate. This critical gradient was between 3.5 and 4.4 degrees. Flows stopped on steeper slopes if the low order tributary joined a higher order (third or fourth) channel at a planform angle greater than 70 degrees. A consequence of the model is the realization that 10 percent fines (silt and clay) are required to produce a debris flow rather than hyperconcentrated streamflow. This result helps to explain why debris flows are uncommon east of the Cascades on soils developed in granitic rock. Benda et al. (in press) have developed a model to predict runout length and scour potential of coarse sediment in steep headwater channels from estimates of soil properties or field measurements of depositional slopes and tributary junction angles. This model can be applied to debris flow hazard assessment.

Benda and Dunne (in preparation) are now using the data obtained in the Coast Range to derive a long-term sediment routing model employing debris flows for this location. The model combines a stochastic driver (with rainfall and fire components) with the deterministic failure and debris flow model to examine trends in sediment delivery to low order channels. This will allow a better definition of recurrence intervals and sediment routing characteristics, as independence of failure need not be assumed. Based upon data from reservoir sedimentation surveys and dendrochronologic surveys of debris flow fans, Benda and Dunne (in preparation) have determined that 7 percent of the basin area fails every 400 years, and that this material can be moved along with background sediment to third through fifth order channels in 125 years, leaving channels in a sediment-impoverished state for 275 years. This model will be linked to observed distributions of aquatic habitat and salmonid species by Lee Benda, Fred Everest, Jim Sedell, and Gordon Reeves at the USDA Forestry Sciences Laboratory in Corvallis (Benda, L., 31 March 1989, personal communication). The sediment routing cycle predicted by Benda and Dunne (1987) seems to agree well with fish species distribution data (coho midway through the cycle, when moderately high sediment loads make riffles that hold up large pools). However, fish biologists are left with the difficult task of determining where a channel is on the cycle. Benda (31 March 1989, personal communication) suggests that adding sediment in sediment-poor systems may be a viable fisheries management technique to maintain existing population distributions, if the sediment is husbanded once it is in the channels.

Conclusions

Sediment storage and transport from headwater basins has a strong stochastic component that has complicated the understanding of these channels. A significant amount of sediment storage is available in these channels. Volumes on the order of 10 to 100 times the average annual output remain in small channels for long periods of time, filling successive storage compartments. Background, chronic sediment inputs move relatively quickly but episodically through a cascading system once storage compartments are full. Debris flows serve to reset this system, flushing out the stored sediment and delivering it catastrophically downstream to fish-bearing waters. For semi-alluvial streams in the Oregon Coast Range, a 125-year period of sediment richness followed by approximately 275 years of sediment depletion has been proposed (Benda and Dunne, in preparation). Upcoming research by Benda will test these hypotheses in the northwest Cascades (Benda, L., 31 March 1989, personal communication). In addition, both Gordon Grant with Richard Iverson (Grant, G., 9 March 1989, personal communication) and William Dietrich and Kathleen Sullivan (Dietrich, W., 6 April 1989, personal communication) are making plans to instrument a headwater channel and induce or monitor a debris flow.

EFFECTS OF FOREST PRACTICES ON SEDIMENT DYNAMICS

Due to a long-standing need to better manage forest lands in the Pacific northwest, most of the information on sediment dynamics in small channels (Type 5 to Type 3) has come from field efforts to compare sediment yield from "managed" basins (some combination of roaded and harvested) with those from unmanaged basins. These studies help to understand background erosion processes (discussed above) as well as the accelerated erosion that has led to the problems TFW is working to mitigate. Because such studies are crucial to the debate that resulted in the formation of TFW, they are examined here in significant detail. The following conditions confound the results of these studies (Swanson et al. 1987b):

- A relatively short perspective on and record of actual sediment fluxes
- The need to put extreme meteorologic events in perspective
- An elongated lag between changes in management techniques and the demonstration of their effects, combined with an investment in sites that are no longer representative of forest practices.

Over the past 20 years, the only consistently demonstrated effects of forest practices on sediment dynamics in Type 4 and 5 Waters can be traced to road building, road use during and after harvest activities and associated skidding of logs during yarding, and removal of vegetation from hillslopes. Generally, roads are far more significant than vegetation removal in generating transportable sediment that quickly becomes available to headwater channels. Even recent studies of road construction (to post mid-1970s requirements) and use suggest that roading is a chronic source of increased sediment, although the magnitude of the effect is sensitive to road construction and maintenance techniques, the location and density of skid trails, site-specific antecedent conditions, and the area's storm type and sequence. The influence of vegetation change alone on changes in sediment input to streams is not as well documented because of the less frequent occurrence of landslides in general and the difficulty of isolating road effects in most situations. The alteration of channel sediment storage and routing patterns following timber harvest and associated activities is only touched on here because of insufficient available information, although this issue is presently of greatest concern to TFW.

Effects of Logging Roads and Skid Trails on Sediment Delivery to Headwater Channels

Sediment is generated adjacent to logging roads from several sources: the road surface itself (Reid and Dunne 1984; Duncan et al. 1987); the often unvegetated cut bank (Megahan et al. 1983); and drainage ditches, stream crossings, and soil failure of cut and fill material (Hagans and Weaver 1987). The sediment can be dislocated either directly by rainfall and sheetwash upon a surface of low permeability, resulting in sheetwash or rill erosion (Johnson and Beschta 1980), or indirectly by altering the stability of a soil mass through altered drainage regimes or loading. The literature on this topic falls into two groups. Several studies report an aggregate effect of road construction in a watershed (commonly with vegetation removal effects present but not deemed significant) by changes in suspended sediment output (Fredriksen 1970; Swanson et al. 1987b; Beschta 1978; Sullivan 1985; Roberts and Church 1986; Anderson and Potts 1987). Other studies analyze the sediment contribution from specific processes but may or may not relate the discrete processes into an overall small basin sediment budget (Megahan et al. 1983, 1986; Reid and Dunne 1984; Megahan et al. 1986; Hagans and Weaver 1987).

Basin-wide Studies—Whole basin studies comparing roaded and unroaded watersheds (or portions thereof) are useful for demonstrating the magnitude of the chronic change in sediment yield in basins disturbed by timber harvesting, although site-specific effects of harvest practices and internal watershed adjustments are commonly masked in these cases (Table 3). The studies of Beschta (1978), Nolan and Janda (1981), and Roberts and Church (1986) illustrate the effects of timber harvest methods no longer allowed in Washington, Oregon, or California (e.g., the lack of protection to fish-bearing channels) during a period that included several high magnitude, low frequency storms. All of these studies apply to measurements made in basins drained by channels equivalent to Type 3 Waters in regions typical of western Washington. They do, however, also include any effect of upslope and upstream buffering of sediment output by headwater equivalents of Type 4 and 5 Waters and therefore present a minimum contrast between streams draining managed and unmanaged lands. The study by Sullivan (1985) integrates over a larger area the effects of a similar extent of disturbance under more recent forest practices, also on the western Pacific slope. Anderson and Potts (1987) cover a shorter pre- and post-logging time period than the other studies but present data from a Type 5 equivalent watershed in western Montana.

The most extreme increases in sediment yield from a small basin were reported by Fredriksen (1970) and Swanson et al. (1987a) for two second order, approximately 100 ha watersheds in the H.J. Andrews Experimental Forest located in the western Cascades of Oregon. One site, WS-3, was 6 percent roaded in 1959. Annual sediment yield was increased up to 36 times that of the control basin over the following 4 years. A debris flow in the 1964 storm in the year after timber harvest produced 2.4 t/km^2, or 135 times that of the control basin. Total post-logging yield averaged 90 times that of the control, indicating the importance of a debris flow on a small watershed. The other watershed has had a 14-year average increase of 12 times the control, due to increased debris avalanching unrelated to road building. Both of these watersheds are being compared to a control basin that was not influenced by mass wasting during the period of study.

Beschta (1978) reported significant increases in suspended sediment following treatment in the Alsea River watershed in the Oregon Coast Range. For 4 of 8 post-harvest years, increases were recorded in a 304-ha third order watershed that was 77 percent clearcut and 5 percent roaded. A 75-ha adjacent watershed, 21 percent patch cut and 4 percent roaded, had a significant increase in 3 of the 8 post-harvest years. The maximum increases in sediment concentration in the two watersheds were 5 and 2 times the expected yield, respectively. Total maximum annual yields were slightly greater due to measured increases in streamflow, increasing from 53 to 305 t/km^2/yr in the first watershed and from 97 to 262 t/km^2/yr in the second. By the eighth post-harvest year, annual

TABLE 3. SEDIMENT BUDGETS FOR SMALL WATERSHEDS FOLLOWING TIMBER HARVEST IN THE PACIFIC NORTHWEST

	Queen Charlotte Islands British Columbia[a]	Clearwater River Olympic Peninsula, WA[b]	Watershed (WS) 10 Cascade Range, OR[c]	Idaho Batholith Central Idaho[d]
Forest Type	Sitka spruce, western redcedar	western hemlock, silver fir	Douglas-fir	Douglas-fir, ponderosa pine, grand and sub-alpine firs
Geology	Triassic sedimentary and volcanic	Miocene sedimentary	Tertiary volcanics, volcaniclastics	Cretaceous granitics
Drainage Area	1.4 km^2	10 km^2	0.1 km^2	1.26 km^2 (average)
Road Density (km/km^2)	0.3	2.5	0	?
Hillslope Sediment Delivered to Streams (t/km^2/yr):				
Mass wasting	926-1480	136-235	126	17
Soil creep/treethrow	42-102	29/9	11/1	7-22 (total all 4 rows)
Slope wash/ravel	12-18	16	17	
Gullying (slide scars)	54-217	0	0	
Other (bioturbation, etc.)	0	4	0	
Road surface, backcut	6	65-74	0	49
Total	1040-1823	259-367	155	73-88
Fluvial Erosion (t/km^2/yr):				
Stream banks	223-463	29 (72% from 1st and 2nd order channels)	31	<3-10
Debris flow	–	26	494	0
Total (t/km^2/yr):	1263-2286	555	680	76-98
Total yield above background (t/km^2/yr):	469-1708	191-309	597	66

[a] Roberts and Church (1986); synthetic, based upon regional rates, aerial photography 1936-1967, and field measurements; 60 percent of sediment production from unlogged portion of the basin.

[b] Reid (1981); synthetic, based upon field measurements 1977-1979, geologic and dendrochronologic interpretation, regional rates.

[c] Swanson et al. (1982; 1987a); synthetic, from process measurements in H.J. Andrews with 2-25 yr periods of record, 1957-1986.

[d] Megahan (1982) and Megahan et al. 1986; based on measurements 1973-1978, 1980.

yields returned to near background. The data sets were truncated prior to storms in 1975, so a longer-term view of recovery is not possible. Increased early season flushing of sediment was also noted.

Sullivan et al. (1987b) tracked sediment output of two fourth order watersheds in the Deschutes River watershed, beginning with road construction and continuing through harvest in both basins. No control data were available to track sediment yield, and the baseline record consisted of 2-3 years prior to road construction. (Lack of control data and the short period of record prohibit the determination of climatic impact on sediment yield during the post-construction period of increased precipitation). Increases in sediment yield that could be attributed in part to road construction were observed. Yields rose from 6-8 $t/km^2/yr$ to a peak of 80-200 $t/km^2/yr$ in the last year of road construction. Sediment yield (though not turbidity) had decreased to near background concentrations by 1984. Interbasin variation was attributed primarily to differences in sediment delivery during road construction (with the higher yield coming from the basin in which road construction occurred in the winter) and required a very large fill in the stream channel. This basin was also underlain by more competent volcanic rock, on which steeper slopes and higher drainage densities had developed.

Synoptic measurements of suspended sediment in Redwood National Park over a 5-year period showed 1.6 to 10 times the expected discharge per unit area in harvested basins (Nolan and Janda 1981). Most important in this study was the apparently long recovery time. Suspended sediment output nearly doubled for a minimum of 10 years after harvest in the Lost Man Creek watershed.

Using aerial photography, Roberts and Church (1986) synthesized pre- and post-harvest sediment budgets for small watersheds with 10-20 percent harvested area in the Queen Charlotte Islands. Road-related sediment accounted for 1 to 14 percent by volume of the total sediment yield (which is on the order of 650-850 $t/km^2/yr$ after logging). All of this road sediment was assumed to be delivered to the stream channel. Interestingly, the contribution from roads was proportionally smallest in the smallest basin studied, which was the only basin likely to be drained by a channel equivalent to a Type 4 Water or smaller.

In the Middle Santiam River, Sullivan (1985) found no significant differences over a 10-year period between the annual sediment yields upstream and downstream of a 8 km^2 block of "intensely managed" land (4.4 percent roaded and 42 percent harvested by the end of the first decade), although temporary increases in sediment yield from individual landslides could be seen in continuous monitoring. Sullivan (1985) reported limited buffering in the Middle Santiam River itself (a fifth order channel) as well as in tributaries adjacent to areas where at least half of the logging occurred (Sullivan, K., 23 May 1989, personal communication). Primary credit for the lack of observed differences between the two stations is given to the bedrock composition of this portion of the watershed (dense andesitic flows that are relatively resistant to erosion). More erodible hydrothermally altered volcaniclastics in the same formation that dominates the H.J. Andrews Experimental Forest are found upstream of the upper monitoring station. This finding demonstrates the problem of trying to detect subtle changes in erosion regimes in the presence of high (or highly variable) background concentrations.

Anderson and Potts (1987), working in meta-sedimentary rocks of western Montana, show a strong first-year post-road construction flushing effect even with 20 to 40 meter wide buffer strips adjacent to stream channels. Annual suspended sediment yield was elevated 7 times above the background level the first year and twice the background level the second year after logging. Sediment yields were on the order of 0.005-1.4 t/km^2. Suspended sediment concentrations were initially high but declined quickly following the beginning of snowmelt runoff. A short period of record increases the difficulty of putting the results of this study into perspective, however.

Component Process Studies—Because of the extreme variability in the results of the basin-wide studies (due to the underlying variability in road construction and logging practices as well as in natural sediment yields), studies of erosion processes on individual components of a logging road have been replacing the studies described above in the published literature. (Results of long-term monitoring at established sites continues. However, there is a shift at these sites to better description of the details rather than aggregate results.) Too few of these discrete process studies exist in the published literature to allow deterministic modeling of sediment production from forest roads. Such studies are useful from a management perspective. These studies enable much better calculation of the marginal cost (construction + resource alteration) and benefit (in terms of dollars per unit sediment decrease) of a particular construction or maintenance practice, improve estimation of the short-term sediment delivery ratio for both bedload and suspended load to various scales of stream channels, and when combined with basin-wide studies, can be used in determining the temporarily and spatially cumulative effects of integrated harvest practices.

In an attempt to isolate the magnitude and mechanisms of delivery of sediment to stream channels from road construction alone, Megahan et al. (1986) developed a sediment budget during a recent June-November construction period. Four small basins were monitored on the Idaho Batholith: one control, two with standard U.S. Department of Agriculture Forest Service (USFS) roads, and one with upgraded erosion controls, including asphalt or crushed rock surfacing, fill compaction, mulching and revegetation, and culvert downspouts and energy dissipators. Total yield per unit area at the mouths of the roaded basins (equivalent to Type 3 and 4 Waters) were elevated 4 to 14 times above the control (0.6 t/km^2), varying between heavy and routine erosion control. Sediment eroded from the road averaged 1.1 t/km^2 for this 5-month period. This basin yield was buffered both by slope storage (85 percent) and tributary channel storage (8 percent). Continued monitoring is planned to assess the post-construction phase delivery of sediment and the effectiveness of the upgraded road. The authors noted that the total amount of local erosion was tied to the sequencing of road building relative to summer storms. Previous studies indicated that 80 percent of the road erosion occurred in the summer, while most runoff was due to snowmelt. Results of Sullivan et al. (1987b) in small watersheds in the southwestern Washington Cascades showed an even greater increase in annual sediment yield coinciding with road construction (10 to 30 times a similar background yield), but the results indicate that return to pre-disturbance sediment yields can occur within 3 years of construction.

Sediment can continue to be eroded from forest roads at relatively elevated rates after construction. Stream crossings are the obvious locations where road surface sediment is delivered to the channel, and they provide a chronic source of sediment from the fill prism (Sullivan et al. 1987b). Reid (1981) and Reid and Dunne (1984) used a composite sediment budget calibrated with extensive field data to examine sediment production from three major components of logging roads in the Clearwater River basin on the Olympic Peninsula: the backslope, the road tread, and road-related landslides. They found that road traffic heavily influences the supply of fine sediment that can be eroded from the tread surface, with a heavily trafficked dirt or gravel road contributing 1,000 times the sediment of an abandoned road and 130 times that of a road used only by light vehicles. In a hypothetical 10-km^2 basin, with 40 percent of the area logged and a road density of 2.5 km/km^2, cutslope erosion was insignificant, road surface erosion accounted for 47 $t/km^2/yr$ (17 percent), road-related landslides accounted for approximately 155 $t/km^2/yr$ (55 percent), and background erosion accounted for about 80 $t/km^2/yr$ (28 percent). The road surface and landslides contributed fine sediment (<2 mm) equally. More important, these figures represent sediment delivered to stream channels, with all of the sediment eroded from the road surface reaching a Type 4 or 5 Water. Sullivan (23 May 1989, personal communication) reported similar sediment yields from individual culverts in the upper Deschutes basin of southwestern Washington. However, at a basin-wide scale, the total contribution of road-use sediment was one-fourth to one-third as great.

The observation that roads, particularly poorly constructed ones, can be long-term contributors to sediment yield was documented by Megahan et al. (1983). This study estimated that a road constructed by the Civilian Conservation Corps in 1933 is producing sediment at a rate of approximately 320 $t/km^2/yr$. It is estimated that 3.6 $t/km^2/yr$ of that sediment is reaching the monitoring station at the outlet of a 1.06-km^2 basin in the Idaho Batholith.

Stream crossings and sidecast failures are the primary sources of catastrophic sediment delivery by roads to stream channels (Krag et al. 1986), although detailed data on the relevant processes are scarce (Beschta, R., 31 May 1989, written communication). Sullivan et al. (1987b) estimate that 50 percent of the landslide debris reaching small (first through third order) channels in the upper

Deschutes basin between 1975 and 1986 could be attributed to road fill failures. Two of the three slides were explicitly sidecast rather than stream crossing failures. The sediment budget by Reid (1981) cited above also documents the role of road-related mass wasting. Finally, Swanson et al. 1981 calculate that debris avalanching associated with roads in western Oregon, Washington, and British Columbia resulted in a soil transfer rate 50 to 300 times that of adjacent undisturbed lands. These results were calculated from studies covering varying portions of the period 1950-1980. This time period was characterized by several high recurrence interval storms and less stringent road construction and maintenance requirements. Present road-related soil transfer rates should be a lower portion of background rates due to climate and management changes in the interim. Failure of stream crossings in particular is an important management problem. However, conditions leading to failure and the detailed results of failure on stream channels in small basins are not explicitly discussed in the literature [with the exceptions of design guidance (U.S. EPA 1975) and studies in Redwood National Park discussed above].

Road-related increases in sediment yield are significant in cases where the road and skid trail network seriously disrupts the pre-existing drainage network. This condition was most common prior to establishment of regulations governing culvert spacing, when a large portion of the drainage from one first order basin could be diverted into an adjoining basin (Harr, D., 5 May 1989, written communication). Rice (1981) attempted to correlate erosion hazard rating with actual onsite erosion following tractor yarding of clearcut slopes and concluded that the best single explanatory variable was the degree of care taken by the bulldozer operator during this process. An extreme example of the effects of these practices was recently reviewed by Hagans and Weaver (1987) from studies in Redwood National Park. This study represents a maximum (or higher?) limit on expected erosion in the Pacific northwest. For the period 1954-1980, over the entire 107.7 km^2 of tractor-yarded lands in the lower Redwood Creek drainage, erosion of gullies (as road-drainage-induced extensions of the pre-logging drainage network) accounted for 665 $t/km^2/yr$ on average to eroded stream crossings which contributed 130 $t/km^2/yr$, surface erosion from roads at 72 $t/km^2/yr$ and streamside landslides that delivered 920 $t/km^2/yr$. Weaver et al. (1981) concluded that most of this accelerated erosion is attributable to four causes: lack of road maintenance (33 percent), stream diversions during tractor yarding (31 percent), insufficient numbers of culverts (15 percent), and construction on overly steep slopes (13 percent). Weaver (6 April 1989, personal communication) concluded that putting the roads to bed shortly after they are no longer needed can effectively eliminate this problem. Gullying as a discrete sediment source has not been quantified in Pacific northwest forests. The magnitude of the problem has not been as great elsewhere in the northwest due to less intensive roading and yarding, faster vegetative (and hence watershed) recovery, less intense precipitation, and more benign tectonic influences. Gullies are important, however, in that they represent an increased density of channels equivalent to Type 4 and 5 Waters following timber harvest.

In much of the northwest, the greatest danger associated with road failure is that the failed mass could become a debris flow. Instances of this have been noted in the literature (for example, Benda and Dunne 1987), but the exact source (i.e., road sidecast, stream crossing, or clearcut vs. timber-harvest-related) is rarely described. An exception is Swanson and Lienkaemper (1978), who describe the frequency of debris flow initiation by source area in the Cedar Creek drainage of the Oregon Coast Range for the period 1950-1976. Five debris flows began in undisturbed forest, eight began in clearcuts, and eight originated from roads. Following the model of Benda and Dunne (1987) for debris flow initiation, the failure of a saturated channel crossing would be most likely to result in a debris flow, where sufficient water and sediment are aligned directly with the stream channel. A failure of sidecast on a side slope, by contrast, is more likely to have a lower water content and a higher junction angle with a channel. Sullivan et al. (1987b) noted exceptions to this pattern in the upper Deschutes basin, where two of three timber-harvest-related debris flows originated from road fill not explicitly located at a stream crossing. Benda et al. (in preparation) have prepared a hazard map of the Knowles Creek watershed in the Oregon Coast Range that includes the prediction of relative initiation risks and the downstream effects of debris flow runout. The watershed is divided into four area classes: basins where debris flows will be deposited upstream of fish habitat, sediment-poor areas where debris flow sediments might improve fish habitat, areas with long runout where sediment would damage existing habitat, and areas where debris flows may become sediment-laden flood flows in the mainstream of Knowles Creek.

Failure of stream crossings commonly occur when culverts become plugged with sediment and organic debris, leading to overtopping. Undermining of the road fill by erosion at the culvert outlet also occurs but at an apparently lower frequency. Therefore, culvert (or bridge or ford) soundness (maintenance and design capacity) is an important risk factor in crossing failure. Piehl et al. (1988) addressed culvert flow capacity on small basins (≤ 1 km^2) in the central Oregon Coast Range; they computed the recurrence interval of the maximum actual and design flows that culverts could pass without overtopping. The magnitudes of peak flows of various return periods were calculated based upon the regional regression equations presented by Campbell and Sidle (1984). No loss in culvert capacity due to poor maintenance was noted on state of Oregon lands, a slight loss was noted on private lands, and greater (9 percent) loss was noted on federal lands. More important, more than 40 percent of all culverts on these small catchments were unable to adequately pass the 25-year peak flow as required under Oregon State Forest Practices Rules. However, actual sizing ranged from all culverts greatly exceeding the required capacity on the smallest watersheds (≤ 0.025 km^2) to 80 percent of the culverts underdesigned in the largest watershed class (0.25-1.0 km^2). Note that these are not large watersheds, and the culverts are not designed to withstand flood events on the scale of the 1964 flood. Further design guidance on other forms of stream crossings is available (U.S. EPA 1975).

Finally, it is useful to consider how much of observed road-related erosion can be considered avoidable, or subject to amelioration by better construction practices (increased culvert density and avoidance of unstable terrain being the most important). McCashion and Rice (1983) approached this question by surveying 550 km of roads in northwestern California in 1976. Most of these roads had been built in the previous 20 years. They classified avoidable erosion as that which can be reduced by better road design or minor realignment. Nearly 40 percent of the road-related erosion, or 118 t/km of road, fell into this category; allowance for major realignment would have increased this percentage. This represented only 24 percent of the total erosion affecting the road segments, however. An important consequence of this survey was the categorization of erosion processes. Of the average 491 metric tons of material eroded per kilometer of road, 0.8 metric tons was natural fluvial erosion, 15 metric tons was road related fluvial erosion (100 percent delivery to channels equivalent to Type 4 and 5 Waters), 129 metric tons was surface sloughing (virtually no delivery to headwater channels), and the remaining erosion was caused by landsliding (157 metric tons road related and 189 metric tons natural) with an unknown delivery ratio.

Effects of Forest Removal on Sediment Delivery

Following vegetation removal, two processes increase the availability of sediments to stream channels. First, the strength of the soil root matrix is decreased as tree stumps and roots die and disintegrate. The loss of tree roots decreases root-induced soil cohesion and the soil stabilizing arching and buttressing effects of the trunk and roots (Gray and Megahan 1980). Reinforced earth and pilings, respectively, are geotechnical engineering analogs of these effects. Second, loss of biomass leads to changes in soil moisture regime caused by decreased transpiration and locally decreased infiltration capacity from equipment compaction and drop in vegetation-induced porosity. Representative changes in the values of these parameters can be combined with stochastic meteorologic input to calculate relative risks of failures using the LISA program (Wooten, R., 21 March 1989, personal communication). However, a period of benign climate has prevented extensive model validation. Unfortunately, this model is not yet linked to a sediment delivery mechanism whereby the impact of hillslope failures on stream channels can be assessed.

When it occurs, the increase in sediment delivery from clearcuts can take the form of increased surface erosion (Swanson et al. 1987b), short-term acceleration of pre-existing earthflows (Swanston et al. 1988) or shallow landsliding (DeGraff 1979; Swanson et al. 1981, 1987b; Furbish and Rice 1981; Wolfe and Williams 1986). This landsliding is commonly adjacent to channel corridors, particularly in areas characterized by over-steepened inner gorges. Landslide debris is deposited directly in the channel and may become a debris flow if the conditions outlined by Benda et al. (in preparation; discussed previously) are met (Helvey 1980; Swanson et al. 1987b). Only the studies by Swanson et al. (1987a) and Helvey (1980) document both the elevation over background and recovery over time for these non-road related mass movements. Without the confounding effects of debris flows, the increase in sediment yield per unit area is still approximately 8 times the control (WS2) in WS1 at the H.J. Andrews (Swanson et al. 1987a). Debris flows in 1972 followed major forest fires in the Entiat basin in 1970; sediment yields in three small basins (4.7-5.6 km^2) were still 8-30 fold higher 6 years later. Note that these were measured at the mouths of basins that are at or near the transition from Type 4 to Type 3 Waters.

Sediment Storage and Transport In Type 4 and 5 Waters Following Timber Harvest

Only a few studies have successfully documented management-related changes in the magnitude of sediment storage in headwater channels and explored the extremes in both absolute magnitude and the increase above background of sediment delivery to the channel. In the severely overloaded system of Redwood Creek (sediment yield >1,000 $t/km^2/yr$), Pitlick (1982) documented storage of less than 20 percent of the landslide-delivered sediment in Type 5 to Type 3 tributaries, predominantly behind debris and boulder jams, only 10 years after timber harvest. In nearby basins, Keller et al. (1982) and MacDonald (unpublished) found that debris-stored sediment was more extensive in disturbed Types 3 and 4 tributaries, and that both debris-stored sediments and riffle sediments were of smaller caliber in these channels, indicating persistent effects more than 25 years after timber harvest. Any buffering capacity of the small tributaries was exceeded long ago.

Duncan et al. (1987) simulated the delivery of road sediment to Type 4 Waters by introducing known quantities of road surface sediment over a range of discharges. At flows approaching 50 percent of bankfull, storage of sediment in the <0.063 mm size class ceased, while less than 10 percent of the sediment in the 0.5-2 mm size class traveled the 95-124 meters to the tributary mouths. The total input volume was only 0.26-0.29 t/km^2, however. It is not likely that the limit of the buffering capacity has been reached in these channels.

As noted above, Megahan et al. (1986) measured changes in channel sediment storage during road construction in central Idaho. Channel storage was nearly equivalent to total yield, and both were approximately an order of magnitude less than the sediment remaining in storage on the hillslopes. At present transport rates, sediment liberated during road construction will not reach the channel for about 10 years. In a related study at the same location, Megahan (1982) noted a slight increase in sediment storage behind obstructions. This increase persisted for a year after logging since the obstructions were small and short lived due to erosion of stored sediment. Barring a catastrophic event, this system is at or slightly below the required buffer capacity.

Sediment budgets constructed by Swanson et al. (1987a) in the H.J. Andrews Experimental Forest allow an indirect comparison of net channel storage in WS9 (control) and WS10 (pre- and post-logging). WS9 is a net exporter of 0.23 $t/km^2/yr$, while WS10 stored 0.7 $t/km^2/yr$ prior to logging, and has exported 51.3 $t/km^2/yr$ in the 10 years since clearcut harvest without roads, primarily during a debris flow in 1986. Neglecting the debris flow, WS10 would nevertheless be a net exporter of 4.3 $t/km^2/yr$ of sediment following logging.

These studies suggest that small tributaries can in many instances buffer background fluvial contributions from forest roads, but they are quickly overwhelmed in the case of any significant landsliding. The buffering capacity reported has been in all cases due primarily to woody debris. Data from H.J. Andrews document the importance of having in-channel storage sites, particularly after logging, to maintain any buffering capacity. More extensive data collection is needed before an adequate estimate of buffering capacity can be developed.

Conclusions

Roads nearly always increase sediment yields in small watersheds, even with state of the art construction and erosion control practices. The effect is typically a short-term doubling of sediment yield (particularly suspended sediment); the sediment yield (particularly bedload) can rise even more catastrophically (25->100 times the average annual background yield) should a debris flow or a compressed period of intense storms occur. The contribution from roads alone, where road-related slope failures can be discounted, is on the order of 5 to 20 percent above background and is predominantly suspended sediment. The duration of this effect is not well established, but it probably remains at lower but elevated levels as long as the roads are in use. Sediment buffering by small channels may be sufficient in many locations, but the magnitude of this is not yet well established. The buffering effect is minimal with respect to silt and clay sized particles (suspended load), even at low (20 percent bankfull discharge) flows, but it increases significantly for the sand sized fraction of road sediments.

Mass wasting and severe gullying can also be associated with roads, though it can be somewhat avoided by better construction and avoiding existing mass movements. Where data exist, it appears that road related landslides are usually shallow and are more common in competent rock, indicating the importance to failure potential of steep slopes, rapid saturation of road fill, and low soil cohesion component (McCashion and Rice 1983; Sullivan et al. 1987b; Megahan et al. 1983). This suggests that vegetal erosion control on road rights-of-way could be very effective in reducing slides, depending upon local conditions (Gray and Megahan 1980).

Finally, the removal of vegetation from previously forested slopes may alter soil cohesion and moisture retaining properties to accelerate erosion from the hillside itself. However, this generally requires rapid input of water to the soil as well, whether from road runoff, a severe storm, or rapid snowmelt. Regrowth of vegetation is usually sufficiently rapid to avoid this situation. These studies taken together suggest that stabilization of road embankments, prevention of stream crossing failures, and proper dispersal of road drainage will bring sedimentation effects down to manageable levels in most instances.

Sediment eroded from hillslopes does not appear to be instantaneously translated to the trunk stream in the watershed; instead, it is temporarily stored in tributary channels. This excess sediment fills pools and other storage compartments, including those associated with woody debris accumulations. Much, but not all of it, moves out of the tributaries within the first decade or so after timber harvest. Some remains, however, both within and below the active channel. In northern California, bed material is generally finer in streams draining cutover basins (MacDonald, unpublished data), and the relative area of the wetted channel during summer low-flow is lower than in undisturbed basins. A significant amount of the sediment stored in all watersheds discussed here and by Keller and Tally (1979) and Tally (1980) was associated with woody debris, making LOD an important aspect of sediment dynamics in small basins following timber harvesting.

DYNAMICS OF LARGE ORGANIC DEBRIS IN TYPE 4 AND 5 WATERS

Large organic debris (all in-channel woody material > 10 cm in diameter) is a significant component of nearly all undisturbed headwater streams draining forested watersheds. LOD plays a crucial role in determining the morphologic and sediment routing characteristics of these channels. It is also responsible for much of the hydrologic variability and hence habitat diversity present in most streams of less than fifth order (Swanson et al. 1976; Keller and Swanson 1979; Tally 1980; Heede 1981; Cummins et al. 1984; Gregory et al. 1985; Bisson et al. 1987). In addition, LOD and associated smaller woody debris serve to retain organic material in headwater streams long enough for organic matter inputs to be processed for use by aquatic organisms (Speaker et al. 1984). The sediment routing properties of LOD have been discussed earlier; this section is devoted to the details of LOD distribution and stability in undisturbed and logged headwater channels, the effects of channel clearance in headwaters, and the role of debris in channel recovery. A thorough review of this topic as it relates to larger fish bearing channels was undertaken by Bisson et al. (1987). This section is designed to review those areas of our understanding deemed important in headwater or non-fish bearing streams. Measured values of debris loading (mass per unit channel area) found in the literature are summarized in Table 4.

TABLE 4. LARGE ORGANIC DEBRIS LOADING FOR SELECTED AREAS
(m^3 per m^2 of channel area)

Location	Forest Type	Stream Order				
		1st	2nd	3rd	4th	5th
New Hampshire (Bilby and Likens 1980)	second-growth northern hardwood	0.007	0.005	0.003	–	–
McKenzie River system, western Oregon (Keller and Swanson 1979; Lienkaemper and Swanson 1987)	old-growth Douglas-fir	0.087/ 0.050	0.076	0.057/ 0.034	–	0.023
Redwood Creek system, northwestern California (Keller and Tally 1979; Tally 1980)	old-growth redwood	–	0.195	0.134	0.039	–
Northwestern California Prairie Creek, Caspar Creek (Keller et al. in press)	second-growth redwood	–	0.120	0.147	–	–
Southeast Alaska (est. from Bryant 1980)	old-growth spruce, hemlock	–	–	–	0.010	–
	- second-growth	–	–	–	0.028/ 0.002	–
Queen Charlotte Islands, BC (est. from Hogan 1987)	old growth western hemlock, spruce, cedar	–	–	0.016	–	
	- second growth	–	–	0.009		
	- second growth and torrented	–	–	0.005		
Carnation Creek, Vancouver Island, BC (est. from Toews and Moore 1982)	old growth Douglas-fir, western hemlock	–	–	–	0.15	
	- following logging	–	–	–	0.11	
Olympic Peninsula (est. from Lestelle 1978)	old growth Douglas-fir, spruce	–	–	0.022	–	

Dynamics of In-Channel LOD In Undisturbed Headwater Channels

In general, there is an inverse relationship between the stream size (measured in terms of upstream drainage basin area) and debris loading. Small streams tend to have narrow valleys, steep valley slopes, and a relatively high frequency of small streamside landslides, all of which tend to increase the debris loading. Marston (1982) reported a peak in the frequency of log steps (not total debris loading) in third order streams, resulting from headward portions of streams typically having narrow, V-shaped valleys in which there is little likelihood of trees falling in and actually blocking the thalweg. Examination of Table 4, however, suggests that there is a great deal of spatial variability in the debris loading for any particular forest type. Where the density of large trees close to stream channels is relatively high, the debris loading is correspondingly higher. Tally (1980) indicated a good correlation ($r = 0.88$) between debris loading and frequency of large trees within 50 meters on either side of the channel in second through fourth order channels. Swanson and Lienkaemper (1978) noted that this relationship is less valid in very small (first and second order) streams due to minimal lateral migration of the channel. It is not appropriate, however, to assume that large trees always span small channels rather than lodge in the channel bed; even large trees can break upon falling or fall in such a way as to become significant to the channel morphology. Hogan (1987) is the only one to actually quantify this; he found 80 percent of the debris in small (second and third order) undisturbed channels in the Queen Charlotte Islands located on the stream bed rather than suspended above the channel.

LOD moves through the headwater stream system primarily by flotation of small pieces during high flows or by debris flows in very steep sections of stream channels (Swanson and Lienkaemper 1978; Keller and Tally 1979). Debris flow are particularly required to mobilize the largest pieces, and in fact are a major source of ready-made logjams in larger channels (James Sedell, 1 June 1989, personal communication). Because debris and associated stored sediment is flushed during debris flows, there is a desire locally to remove LOD from the steepest channels as a means of reducing sediment impacts to downstream reaches. Stability of wood is increased when the wood itself is rot and insect resistant (redwood, western redcedar, and to a lesser extent Douglas-fir), when it is as large as the bankfull width of the channel (Swanson et al. 1984), when it is buried in the channel bed, or when it is lodged into or on channel banks (Bisson et al. 1987).

Debris stability in turn controls the residence time of debris and associated sediment and organic material storage sites. Lienkaemper and Swanson (1987), working in Douglas-fir forested watersheds in the Oregon Cascades, report average turnover rates for LOD of 36, 83, and 52-68 years in first through third order channels respectively. In larger streams, flood discharges have been sufficient to float even the largest debris, and the residence time is therefore shorter (12 years in Lookout Creek, a fifth order channel; Lienkaemper and Swanson 1987). Debris sufficiently attached to the banks, however, may still contribute to the formation of large pools. Hogan (1987) reports residence time of debris in the Queen Charlotte Islands varies from 40 to more than 90 years. Residence times of log obstructions are lower in small (first through third order) channels in the Douglas-fir/ponderosa pine forest of the Idaho Batholith. By the end of a six-year study period, all but 5 percent of the log obstructions were ineffective at sediment storage. Nevertheless, logs were more permanent than other obstruction types (Megahan 1982). This puts a lower limit on the residence time of wood in these channels; whether this drastically lower residence time is an artifact of the short sampling period, to disturbance, or to the characteristics of the debris environment itself (species, size, or weathering factors) is not known.

Dynamics of In-Channel LOD in Disturbed Watersheds

Because of long residence times of LOD in Douglas-fir forests, a major component of post-harvest LOD will be that remaining in the channel. Prior to stringent forest practices regulations in Washington, Oregon and California in the early 1970's, logging debris was a major immediate and short-term addition that both lodged in headwater channels and floated to larger (third order and greater) channels. While 1 to 30 percent of the volume of debris in small channels in the redwoods of northwestern California could be attributed to boles with sawed ends, these were not the most numerous logging-introduced pieces. Most woody material introduced to channels during timber harvest was smaller slash, which was more abundant than LOD delivered by natural processes in the same size range (MacDonald unpublished data). Small pieces are more mobile and have a greater destabilizing effect on the channel than larger pieces because they caulk large, open, pre-existing debris accumulations (Froehlich 1973; Bryant 1980; Toews and Moore 1982), making the resulting jam more susceptible to catastrophic failure (Bryant 1980). Logjams resulting from pre-1970s timber harvesting practices led to widespread channel clearance, ostensibly to improve fish passage. As smaller and smaller channels were cleared (regardless of their ability to support fish afterward), the importance of LOD to headwater channel stability became more apparent.

Subsequent long term additions of debris to streams draining logged watersheds are likely to be from early successional tree species, which are smaller than climax species (Bilby and Likens 1980; Bryant 1980; Keller et al. in press; Bisson et al. 1987). In the northwest, hardwoods such as alder are the most common initial source of LOD, followed by early maturing conifers. These are less rot-resistant than western redcedar (or redwood in northwestern California), and are therefore shorter lived in the channel. Second-growth commercial timber is not a significant new component of LOD in streams until late in the harvest rotation, although blowdown from buffer strips and uncut snags will remain a potential source of new wood to the stream. It is important to note that as yet no data exist in the literature that evaluate buffer strips as long-term sources of LOD along the lowest order channels. What few studies are available deal with fish-bearing streams, and are themselves limited due to the relatively recent implementation of extensive streamside management zones (Swanson and Roach 1987; Bisson et al. 1987). Studies do suggest, however, that buffer strips can provide LOD early in the rotation cycle, prior to significant hardwood or second-growth input. This might be useful in as yet unidentified areas of the state where LOD residence time is low and there is reduced LOD relict from the pre-harvest period. Since small order channels are major sources of LOD to larger channels, the effectiveness of any leave areas on them and on downstream LOD loading should be monitored, particularly in response to large and regionally significant storms. Opportunities for such observation exist in areas where voluntary riparian leave areas have been placed on Type 4 and 5 Waters in Washington state and in headwall leave areas in Oregon.

In evaluating existing and previous management on LOD loading, actual disturbance history from management and storms is significant. In second and third order channels that drain second growth watersheds in northwestern California, Keller et al. (1982) report lowest loading in a 90-year old clearcut where logs were sluiced downstream, intermediate loading in a low gradient channel immediately downstream from a 1968 clearcut, and highest loading within clearcuts from the 1954-1968 time period. Major floods occurred in this region in 1955, 1964, 1972 and 1975, and most of the jams in the basin with the highest LOD loading (Lost Man Creek) date from these events. Hogan (1987) noted a similar pattern, with larger and less frequently spaced debris jams in clearcut areas.

Effect of Debris Removal on Headwater Stream Channels

Early focus on LOD resulted from concerns over fish passage blockage by logjams, specifically the tendency for logging debris to accumulate in stream channels with an apparent increase in the frequency of impassable jams (Froehlich 1973; Baker 1979). Consequently, several studies in the last decade have evaluated the effects of debris jam removal on channel morphology (Beschta 1979; Pitlick 1982; Bilby 1984; MacDonald and Keller 1987) and the concomitant short-term changes in fish populations (Lestelle 1978; Baker 1979). All of these studies, with the exception of Pitlick's, were carried out in channels at the upstream range of salmonid habitat and may not be directly applicable to some Type 4 and 5 Waters. However, some reasonable extrapolations concerning the effect of debris removal on the smallest streams can be made.

All of the investigators cited above noted an immediate release of stored sediment once jams were removed or key logs were bucked. When tracked, the distance this sediment traveled was a function of channel gradient, flood flow patterns and the presence of jams below the manipulated reaches (Lestelle 1978; Baker 1979; MacDonald and Keller 1987). By the end of the first season, pool volume was either reduced or redistributed into larger and fewer pools, generally reducing the small scale variability that previously characterized these channels. Both Pitlick (1982) and MacDonald and Keller (1987) noted that the channel quickly stabilized around new obstructions or roughness elements including underlying debris jams, boulders, or bedrock. These studies, coupled with an appreciation for the cover value of LOD and the ability for adult salmonids to get through most jams at high flow, resulted in adjustments to forest practices to decrease channel clearing. Now, logging operators are instructed to leave pre-existing LOD in the channel and remove that introduced by logging operations.

The fact that woody debris jams can destabilize hillslopes by deflecting flows or failing catastrophically has led to guidelines for clearing loose woody debris and slash from steep Type 4 and 5 Waters when the potential for failure of hillsides or the jams are high, and expected downstream impacts of such failure are also high (Washington Forest Practices Board 1988). The destabilizing effect of LOD on hillslopes is well documented (Keller and Tally 1979; Pitlick 1982; Hogan 1987); in fact, Pitlick reports that from 10 (± 11) percent to 28 (± 18) percent of all landslide sediment in tributaries of Redwood Creek are due to LOD related slides. Pitlick reported complete clearing of a logjam in a high gradient (16 percent) channel (equivalent to a Type 4 Water) to alleviate erosion of the adjacent hillslopes. The jam resulted from a Humboldt crossing in which logs felled across the channel were cabled together to provide bridges for vehicles. Sediment had accumulated behind this jam and flow was being diverted into the adjacent steep hillslopes. Downstream and adjacent impacts of the clearing operation were reduced by removing 450 m^3 of sediment from the channel, laying back the adjacent hillslopes (650 m^3), and uncovering an underlying debris jam, which limited further channel lowering and provided local physical structure. Even with that, 430 m^3 of sediment was scoured from the site in the first winter following clearance, and an additional 50 m^3 was scoured in the second winter. Without the sediment excavation, nearly 1,600 m^3 of sediment would have been stored or transported downstream rather than the 480 m^3 that actually was released. (By comparison, Beschta (1979) documented the release of more than 5,000 m^3 channel clearance along 250 meters of a third order channel in the Oregon Coast Range with a gradient of 7 percent, while MacDonald and Keller (1987) report the redistribution of only 100 m^3 of sediment from clearing 100 meters along a third order channel in northwestern California with a gradient of 1.4 percent. The disparity between these latter figures is probably attributable in part to the difference in gradient.)

Based upon this information, clearing Type 4 and 5 channels should be done only in strict accordance with existing guidelines. The risk of a debris flow (rather than a simply a dam-break torrent/flood) and downstream hazard should be demonstrable and significant. However, the downstream impact of the clearing itself should be considered in any decision, assuming that all sediment stored behind the debris jam will be scoured within the first year. Downstream obstructions and bends which reduce the risk of damage from actual failure and possible debris flows also reduce the potential damage associated with debris jam removal. As the frequency of meteorologic forcing events, failure thresholds, and detailed routing processes are better understood, these sorts of relative risks of manipulation to the stream system can be assessed.

Recovery of Hydraulic Variability Following Major Disturbance

Major disturbance to the fluvial system, catastrophic or not, results in some loss of inherent system variability with respect to such parameters as substrate size, flow depth and flow velocity. As hydraulic variability is a necessary, though not sufficient, component of naturally functioning lotic ecosystems, such a loss adversely effects the biologic productivity of the system (Cummins et al. 1984). Steepland, nonalluvial streams flow through more heterogeneous materials than lowland alluvial rivers. While steepland streams are more frequently disrupted than lowland streams, by mass wasting, floods, or land use changes in the catchment, they also have available more raw material to recover the hydraulic variability lost by disturbance (Swanson 1981).

The recovery of streams following disturbances, such as timber harvest, is crucial to the maintenance of instream habitat. The concept has long been appreciated in the geomorphic community (Wolman and Gerson 1978), but it is difficult to evaluate appropriately, particularly in small channels (Beschta and Platts 1986; Pitlick 1988). Grant (1988) proposes a method that evaluates relative canopy opening as measured on aerial photos to document disturbance in forested watersheds, but this is of limited utility in headwater channels unless the photos are of sufficiently large scale (1:2000 or better). Both Kaufman (1987) and MacDonald (unpublished data) have proposed measures of "hydraulic variability" to begin the assessment of morphologic recovery. In steep headwater channels subject to debris flows, morphologic recovery equates with the ability of the channel to retain sediment and organic matter. These measures are based on deviance from a control undisturbed channel and revolve around either residual pool volume (Kaufman 1987), or pool volume + channel-stored sediment volume + pool/riffle ratio or spacing (MacDonald unpublished data). These and other recovery indices are related to restoration of salmonid habitat; ecological recovery of habitat in headwater channels has not been addressed in the literature, but it should be based upon recovery of organic material processing capabilities. The primary ecological role of these streams is to allow coarse particulate organic matter and small organic debris to be processed for downstream carbon and nutrient uptake (Bisson et al. 1987; Dr. Stanley Gregory, 10 April 1989 personal communication; Dr. James Sedell, 1 June 1989, personal communication).

Conclusions

Average residence time of LOD in headwater stream channels ranges from 36 to around 90 years, with that of individual pieces exceeding 100 years under natural conditions on the western Pacific slope of British Columbia, Washington and Oregon, and therefore influences the channel on a time scale that may be considered geologic (Swanson and Lienkaemper 1978; Lienkaemper and Swanson 1987; Hogan 1987; Bisson et al. 1987). What little information is available suggests that the residence time of LOD in small channels is shorter in drier forests (Megahan 1982), however, this should be better constrained with data. Larger pieces of LOD provide immediate structure to headwater channels following debris flows, but controversy exists over the actual size required for stability within the channel, to provide sufficient organic material retention, and to aid recovery (Speaker et al. 1984; Robert Bilby, 13 March 1989, personal communication; Stanley Gregory, 10 April 1989, personal communication). This is a topic for future investigation as understanding of organic matter processing dynamics and channel recovery processes become better developed.

The information obtained about LOD-dominated stream channels under natural conditions in northwestern California and Oregon suggests that debris should be a significant component of streams draining second-growth forests as well (Keller et al. in press). Since debris accumulations are effective barriers to sediment movement, they are expected to have an important role in routing sediment through disturbed basins, which have high sediment loads per unit area for several years following logging and road building activities (Nolan and Janda 1981). Tally et al. (1980) suggested that debris could buffer the impact of excessive sediment input from rapidly eroding hillsides prior to delivery to trunk streams, up to an ill-defined site specific threshold. Conversely, Pitlick (1982) noted debris causing locally significant increased sediment delivery to a trunk stream, negating any buffering, even though the debris was purposely introduced to the channel during logging operations. Subsequently, Keller et al. (in press), Kaufman (1987) and Hogan (1987) found that debris both buffers and induces sediment delivery from hillslopes in steep, logged basins, and that the crucial differences between old- and second growth watersheds are direct consequences of the disturbance history.

Major disturbance of watersheds in the Pacific northwest, such as timber harvesting, can result in significant long-term changes to the morphology of streams draining them. If present, these alterations are the product of three forest practice related impacts: persistent high sediment loads to the stream channels following disturbance of the catchment; disturbance to the channel by specific activities (channel crossings, yarding timber across the channel, etc.); and alteration of the type and reduction of the size of woody debris in the channel during timber harvest and for several decades thereafter. Debris jams from this smaller debris are likely to be shorter-lived and more prone to catastrophic failure than those in undisturbed streams (Keller et al. in press).

Therefore, retaining naturally occurring jams, rather than post-harvest stream clearance, provides the best chance of maintaining a relatively natural pattern of debris loading for the next century.

CHANGES IN WATER QUANTITY AND ROUTING FOLLOWING TIMBER HARVEST

Vegetation removal, road building, and surface yarding alter the hydrologic system of small watersheds in a number of subtle and pervasive ways. Reducing the vegetation decreases the amount of evapotranspiration, thereby increasing late summer soil moisture, translation of water through the soil system (Pearce et al. 1986), and autumn storm peaks (Harr 1976, 1987; Ziemer 1981). Depending upon local hydrologic factors, road building and surface yarding can also influence runoff to the extent that some of the watershed is rendered impermeable; this effect rises exponentially with increasing basin area in roads and skid trails. (Note that there is not a single threshold value, ex. 12 percent roads/skid trails, however (Harr 1987)). Runoff processes following timber harvests at high elevations, where transient snowpacks can accumulate, are slightly different that those at low elevations, adding yet another level of complexity (Berris and Harr 1987). The following studies focus on runoff alteration alone. To determine whether observed hydrologic changes have significant impacts on fluvial sediment transport in headwater channels, it is necessary to focus on whether the magnitude and frequency of streamflows have been elevated above a specific critical flow level. This threshold is not determined for any of the basins referred to in the cited references, but it is certainly the average annual peak (2.3 year return interval) or larger (Harr 1976).

Watersheds With Rainfall As the Dominant Form of Precipitation

In small watersheds below the transient snow line, changes in runoff are primarily the result of alteration of the drainage network and decreased infiltration capacity by roads and skid trails and by decreased evapotranspiration immediately after timber harvest. Ideally, increases in annual peak runoff will be related to the road network, particularly if the drainage network in a small watershed is disrupted (Harr 1976; Harr et al. 1979; Harr 1987 and 5 May 1989, written communication). A drop in infiltration capacity away from roads and skid trails in the southern Oregon Coast Range was insignificant in a study by Johnson and Beschta (1980), although it could be as high as 77 percent in coarse soils with highly disruptive yarding practices (Steinbrenner and Gessel 1955). The most consistent increases in flows following timber harvest are in the summer, fall, and early winter (July through December). Data of Harr (1979), Ziemer (1981), and Sullivan et al. (1987) demonstrate some or all of this phenomenon, which is linked to changes in the summer and fall soil moisture regime due to decreased evapotranspiration after vegetation removal. Data from Harr (1976) and Harr et al. (1979) show that at low elevations in the Oregon Coast Range and

Cascades, the loss of infiltration capacity due to roads coupled with vegetation removal occasionally increases large peak flows (5+ year recurrence intervals), increases average peak flow roughly 50 percent of the time, and nearly always increases annual water yield, for at least the first five to ten years post-harvest. Whether increases in the average or larger peak flows occurred was related to the magnitude of disturbance. Ninety to 100 percent clearcuts in the absence of roads, or 30 percent clearcut with 8 percent severely compacted gave rise to increased average annual floods but no change in larger peaks. Watersheds with higher percentages of compaction (12-15 percent) combined with clearcuts in excess of 25 percent showed increases in both peak flow categories. No basins with roads in the absence of harvest were included in the study to assess the effects of roads alone at these low elevations. Post-harvest slash treatment (e.g., tractor windrowing, and the effects of burning slash on soils with high clay content) has also been listed by Johnson and Beschta (1980) as contributing to lower infiltration capacity. However, the effects of these practices have not been independently assessed.

At low levels of disturbance, the effects of forest practices on total basin water yield are more ambiguous and site specific. Annual peak flow, and particularly larger floods, are not likely to be significantly increased (Harr 1976). At low elevations in northwestern California, Ziemer (1981) found no increase in flows capable of transporting sediment in a 4.2 km^2 watershed that was partially cut (with 67 percent of stand volume removed), and 15 percent of the watershed was rendered relatively impervious by roads and skid trails.

Influence of Snowmelt On Water Quantity Following Timber Harvest

Where snowfall makes up the majority of the precipitation, and where basins are both logged and clearcut, increases in annual peak flow and larger peak flows become more likely. This is true whether in the perennial or transient snow zone (Berris and Harr 1987). Berris and Harr (1987) documented preferential accumulation of snow and concentration of water equivalent in a clearcut plot relative to the adjacent forest, since vegetation intercepted snow in the forest plot, causing the snow to melt rapidly in the canopy. These processes seem to operate in the perennial snow zone as well (Cheng 1989) and account for higher discharge peaks following vegetation removal. Uniquely, in the transient snow zone, energy input during rainstorms was greater to the clearcut plot, allowing more rapid melt of a greater amount of stored water equivalent. This pattern is confirmed by a number of small watershed studies with several years of pre- and post-harvest data.

The increase in peak flows accompanying vegetation removal and road construction is most pronounced in areas of perennial rather than transient snowpacks, where annual peak flows are associated with snowmelt runoff. In central Idaho, Megahan (1983) reported an average increase in peak discharge of soil water from 30 to 40 percent, in part from interception of soil throughflow by road cuts. His instrumentation covered two 0.01 km^2 watershed segments. Cheng (1989) reports a 21 percent average increase in peak discharge, which occurs two weeks earlier in the year, following logging of a mixed ponderosa pine and Douglas-fir forest in the Okanogan of British Columbia. Troendle and King (1985) note that annual peak flows are elevated (around 20 percent) even 30 years after harvest in the Rockies, with a greater response during higher precipitation years.

At lower elevations, snowpacks are transient features and peak runoff events generally result from midwinter melt induced by warm rainstorms on a snowpack with a high antecedent water content. In the Oregon Cascades, Harr (1986) reports a post-harvest pattern for snow-related runoff events of increased peak flows and faster runoff, similar to that observed at higher elevations. Unlike Rothacher (1970), Harr separated out rainfall-only events from his analysis, significantly reducing the variance of the regression of flow in control vs. treated watersheds.

Peak flow does not always increase in the transient snow zone. Harr et al. (1982) noted an increase in annual water yield following harvest in two additional watersheds at H.J. Andrews Experimental Forest. One watershed was 100 percent clearcut and 9 percent roaded, while the other had 60 percent of the basal area removed in a shelterwood cut. No significant effects on peak flows were observed, although a significant drop in the number of summer low-flow days was observed in the post-logging period, particularly during the 1977 drought.

The data presented by Sullivan et al. (1987b) in the upper Deschutes River basin in southwestern Washington is another good example of the complexities that arise when trying to determine the combined hydrologic impacts of vegetation removal and roads. The data were obtained in two small (2.4 and 2.9 km^2) basins located at mid-elevation (both of which ranged from 450 to 1200 meters). These watersheds should be within the transient snow zone, although that is not explicitly noted in their report. They found both winter (January-March) and summer (July-September) average discharges increased in both basins over a 10 year period during logging and road building, while spring runoff increased only in the basin with substantial vegetation removal. Over the same period, winter precipitation rose 12 percent, fall and spring precipitation rose 4 and 8 percent respectively, and summer precipitation fell 73 percent relative to the long-term average, indicating that only the summer runoff increase was unambiguously a function of timber harvest activity. Winter increases in discharge in these two basins were attributed to climate and timber harvest activity, with relative responses between the two related to differences in management activities and bedrock geology. The greater increases in winter and summer runoff, and the drop in fall, occurred in the smaller of the two basins, which had a higher proportion of hard, jointed volcanic bedrock. Management activities evolved asynchronously in the two watersheds during the period of record, with 10 percent of the smaller basin (Hard Creek) cleared vs. 70 percent in the larger basin and approximately 2.4 percent in roads vs. 1.4 percent.

Peak flows in the two upper Deschutes basins fluctuated slightly relative to each other during the period. These fluctuations could not be tied directly to specific management activities. King and Tennyson (1984) conducted a short-term study of eight watersheds immediately after road building in higher elevations of north-central Idaho where snowfall is the dominant form of precipitation. Only two showed a statistically significant response to road construction and use; low to moderate flows were reduced in one and increased in the other. These two watersheds were equivalent in area, 0.86 and 0.84 km^2, respectively, in percent of basin area in roads, 4.3 and 3.9 percent, and in number of stream crossings, 3. They differed only in contributing area of the watershed above the road, 20 vs. 54 percent. These results indicate some of the complexities of basin response to road location details.

Conclusions

Where runoff is exclusively derived from precipitation falling as rain, increases associated with logging or roading do not appear to be near the magnitude required to increase total geomorphic work without significant basin disturbance from roads and skid trails. Alteration in the seasonal timing of flood peaks (including those less than the annual flood) may alter routing of fine sediment (sand, silt, and clay) through headwater channels to fish-bearing streams. This effect may or may not be detrimental to fish, depending upon local conditions (Everest et al. 1987). Studies of snowfall-dominated systems, however, point to two very different and important conclusions. First, the longevity of the effect and the relative insensitivity to amount of the watershed disturbed indicate that altered snowmelt dynamics between clearcuts and forested land are responsible for increases in peak flows, while decreased summer evapotranspiration is significant in increasing low flow and total annual yield conditions. Second, increases in peak flows of 20 percent could be sufficient to entrain more of the fluvial sediment load, assuming the bankfull discharge threshold observed by Sidle (1987) holds upstream. In areas not dominated by mass wasting, such as the Okanogan Highlands, this is potentially a significant alteration to the sediment routing system that should be more fully investigated with detailed measurements of fluvial sediment transport in headwater channels.

WATER QUALITY IN TYPE 4 AND 5 WATERS

Interest in the chemical quality of small streams is mainly focused around the cycling of nutrients between the terrestrial and hydrologic systems, and on entry and persistence of man-made organic chemicals (insecticides, herbicides, and fertilizers) applied to forests to control insects, eradicate unwanted vegetation, and increase productivity of timber crops. Relevant questions relating to impacts on the quality of water in small streams include the following:

- Do concentrations of chemicals increase in streams after forest practices are applied?
- Can these concentrations be toxic to organisms living in the stream?
- Are increased chemical concentrations in streams or losses from the forest ecosystem important to productivity in streams or forest sites?

From a sediment perspective, insecticides and herbicides are of primary concern because their mobility is largely a function of specific interactions with soil and sediment particles. In particular, mobility of these chemicals in the forest ecosystem depends on solubility, adsorption, and persistence characteristics, each of which vary widely between chemical types. Other chemicals, including nutrients, are essentially independent of most sediment processes. However, the same forest practices have direct effects on both sediment processes and water quality.

Nitrogen

Several studies have documented increases in nitrate nitrogen (NO_3-N) in nearby streams immediately following timber harvest. The rise in nitrate levels is attributed to interruption in nitrogen uptake and cycling by vegetation (i.e., removal of nitrate consuming vegetation), and by more rapid conversion of organic nitrogen to nitrates by slash burning (Hart et al. 1981). Nitrate levels are highest following timber harvest and decline to natural levels at rates depending on the return of vegetation, typically within 3 to 6 years (Brown 1979; Adams and Stack 1989).

The magnitude of nitrate increases in streams that drain harvested areas depends on soil, vegetation and climatic characteristics, and treatment of debris following timber harvest. Highest increases are found in clearcut watersheds where broadcast burning of slash followed harvest. Brown (1979) documented increased nitrate yields from 4 to 15 kg/ha in the Alsea basin of the Oregon Coast Range. In a nearby patch-cut basin, where 25 percent was logged and minimal burning occurred, nitrate levels were unchanged. This is attributed by Brown to the greater biomass of nitrogen-consuming vegetation remaining after harvest. In the Carnation Creek watershed on Vancouver Island, partial clearcutting and slash burning resulted in increased nitrate outflow, but total concentrations remained less than 1 mg/L (Scrivener 1982). In a small watershed with mixed conifers in southwest Oregon, Adams and Stack (1989) monitored water chemistry for several years in streams draining uncut, totally clearcut, patch clearcut, and shelterwood cut (50 percent of basal stem area removed) areas. This study concluded that clearcutting of complete catchments resulted in the highest nitrate losses, with a maximum concentration of 0.5 mg/L occurring two years after burning, or four years after cutting. The shelterwood and patch cut treatments showed very limited effects on water quality. In a study on the effects of various slash treatments on soil water nutrient levels in a lodgepole pine forest in western Wyoming, Hart et al. (1981) found that nitrate levels are increased from 2 to 100 times following harvest and three types of slash treatment, including chip mulching, broadcast burning, and windrow burning. Concentrations in nearby streams are inferred to be proportionate but much lower than the soil-water levels, which usually remained below 10 mg/L. Again, treatment of slash through burning resulted in the highest nitrate levels.

Nitrogen loss through erosional processes (i.e., sediment) was reported in the Entiat Experimental Forest in Eastern Washington following a 1970 wildfire (Helvey et al 1975). Total nitrogen losses increased from a pre-fire rate of 0.004 kg/ha/yr to 0.16 kg/ha/yr. Nutrient losses from soil were limited to the riparian zone, with debris flows facilitating most of the loss. Although nutrient loss from soil was greater than the solution (dissolved) nutrient loss, the decrease in site productivity and stability resulting from the nutrient loss was insignificant compared to the physical effects of channel scouring from debris flows, which were caused by the increased runoff rates following the fire. Solution losses are also probably more important because they represent available nutrients, rather than stable, inorganic forms of nitrogen present in the soil mass.

The impact of nitrogen loss from the forest ecosystem is not a water-quality issue when the concentrations are compared to standards and loss rates are compared to overall forest nutrient capital. Nitrate concentrations never approach a level where toxicity to aquatic life becomes a problem. The maximum concentration levels encountered under forest practice situations, several milligrams per liter over a short duration, is low compared to levels of hundreds to thousands of milligrams per liter required for freshwater fish mortality (U.S. EPA 1986), and the 10 mg/L federal drinking water criterion. From a nitrate budget viewpoint, Brown (1979) reported in the Alsea basin study that the 10 kg/ha short term nitrate loss from the terrestrial portion of the ecosystem is very small compared to the 20,000 kg/ha nitrogen capital in Douglas-fir forests in the Oregon Coast Range. In addition, nitrogen-fixing vegetation such as red alder, which rapidly invades low and mid-elevation clear-cuts following harvest, may quickly replenish any depletion caused by harvest. Adams and Stack (1989) also concluded that the peak increased nitrogen loss of 1-3 kg/ha from a clearcut and burned forest is relatively small compared to the expected total nitrogen soil reserve of several hundred kg/ha. This loss might be offset by nitrogen inputs from precipitation (about 2 kg/ha/yr) and biological fixation of gaseous nitrogen. Fredriksen et al. (1975) suggested that forest streams and lakes in western Washington characteristically contain low levels of nitrogen and other nutrients, with many waters considered deficient in nutrients, and that increases in nitrogen may gradually enhance stream productivity. Scrivener (1982) left open the possibility that the short-term loss in nitrates following timber harvest may be affecting nutrient requirements 30-40 years later in the forest succession, when nutrient demands are greater. The possibility that whole-tree harvest in short rotations may have greater impacts on nutrient removal was not evaluated and may require looking into research being performed on European forests. Fertilization serves to maintain long-term productivity by replenishing nutrients which are removed during harvest.

Phosphorus

Most studies have determined that phosphorus loss from the coniferous forest ecosystem and resulting stream-water concentrations are small or undetectable following all types of timber harvest, including clearcut with slash burning. Brown's (1979) study in the Alsea watershed showed unchanged total phosphate concentrations after various timber harvest methods. Concentrations were between 0.01 and 0.1 mg/L. Scrivener (1982) also reported no evidence of phosphorus loading in streams: post-harvest concentrations in Carnation Creek were typically very low (less than 0.001 mg/L PO_4-P). Brown et al. (1973) reported a small increase in inorganic phosphorus following slash burning in the H.J. Andrews Experimental Forest, where the maximum and mean concentrations reached 0.121 and 0.039 mg/L, respectively, in the year following burning. An explanation for this anomalous observation was not provided. Loss of available phosphorus associated with sediments was reported in the Entiat Experimental Forest following wildfire amounting to an increase from 0.001 kg/ha/yr to 0.014 kg/ha/yr. As detailed above with nitrogen, nutrient losses were insignificant compared to the physical impacts of the debris flows which caused the loss.

Given this information, it is apparent that forest practices have negligible impact on phosphorus loading in western Cascade streams. Effects on forests in eastern Washington are not well documented, but probably follow the same patterns. The phosphorus concentrations encountered in natural steams are, with few exceptions, lower than the recommended 0.05 mg/L total phosphorus concentration suggested for eutrophication control in receiving lake waters (U.S. EPA 1986). Short-term increases above this level, following logging and slash burning, are not likely to adversely impact downstream waters, since phosphorus tends to be a limiting nutrient in aquatic ecosystems. Any excess from natural sources will be utilized before causing chronic water quality problems.

Other Ionic Chemical Species

Other primary dissolved ionic species present in natural waters (including sodium, calcium, potassium, bicarbonate, silicate, among others) have also been studied to evaluate impacts of forest practices on in-stream concentrations and resulting loss from the forest ecosystem. Concentrations of these chemicals, generally decomposition products of bedrock and soils, can be grossly quantified using electrical conductance measurements. In cases where dissolved ions, including calcium, potassium, silicate, and bicarbonate, are supply-limited because they are geologically controlled, concentrations are negatively correlated with flow (Adams and Stack 1989). Scrivener (1982) measured significant increases in dissolved ions measured by conductivity in Carnation Creek following logging, suggesting losses from the forest ecosystem and increases in stream concentrations. Nothing could be said on the effects of such increases. Hart et al. (1981) determined that, for a lodgepole forest, natural stream-water concentrations of major cations are already higher than in the soil water under treated slash, meaning that none of the debris treatment options would have a notable effect on the concentration of these cations in stream water.

In no case was the loss of these chemicals from the forest ecosystem determined to be detrimental in any way to the nutrient or chemical balance in the forest ecosystem. Overall, water quality is never cited as a major concern because these chemicals have never constituted a water quality problem in natural forest streams.

Herbicides

Herbicides are used in forestry as a tool to control brush competing with Douglas-fir during the early stages of stand development. The specific chemical or combination of chemicals used, their formulation, and the rate and timing of application vary with the species to be controlled, the purpose of the application, the season, and the stage of stand development (Fredriksen et al. 1975).

Aerially applied herbicides are initially distributed to the air, intercepting vegetation, forest floor, and surface waters of the forest. The method of application and type of chemical used largely determines the amount of herbicide that ultimately enters forest streams. Routes of entry to streams include direct application or drift, in surface runoff, and in subsurface flow through the soil. Brown (1979) reported that from 20 to 80 percent of the herbicide is dispersed in the air prior to reaching the first intercepting surface, but these pre-1970 data may now be obsolete as more efficient application tools have been developed since that time. In a comprehensive review of several studies, Fredriksen et al. (1975) found that shortly after application some herbicide was found in most streams which flowed through or by treated areas. Peak concentrations occurred shortly after application, for durations in the order of hours, but residues typically did not persist for more than a few days. Herbicide residues were not detected in any study after several days had passed since application, and they were also not detected during the first major fall rainstorm. Herbicide contamination of small streams is therefore only found immediately after treatment, which implicates drift or direct application is the only significant source impacting small streams draining herbicide-treated forests. Brown (1979) confirmed that chronic entry of herbicides for long periods of application does not occur. This is primarily a result of the lack of overland flow on the forest floor. In western Oregon and Washington high soil infiltration makes overland flow uncommon. Herbicide use is more limited in drier climates where overland flow is more likely to occur. This is the only situation in which overland flow may become a dominant transport mechanism of herbicides to streams. Brown also stated that concentrations of 2,4-D, picloram, 2,4,5-T, and amitrole seldom exceed 0.1 mg/L in streams adjacent to carefully controlled forest spray operations.

The effects of herbicide residues, during or shortly after application, depend on both magnitude and duration of exposure. U.S. EPA (1977) gives a summary of recommended concentration maxima for herbicides and insecticides by specific chemical, supported by detailed toxicology references. Direct application and drift are minimized, but not totally eliminated, by the current Washington forest practices requirement that specifies a 50-foot buffer strip along all Type 4 and 5 Waters during application of all forest chemicals other than fertilizer, which requires a 25-foot buffer (WAC 222-38-20). An unpublished study reported in U.S. EPA (1977) presents data on the effect of buffer width on aerial herbicide application. The largest effect of the buffer strip in reducing overspray was in the first 50 feet of width, at which less than 5 percent of the target application was deposited. Beyond this width, additional reductions were minimal because the spray droplets were small enough to drift for a considerable distance. The effectiveness of a buffer strip under operational conditions was reported to be between one-third and one-half reduction in stream concentrations over that for non-buffered streams. The lower-than-expected control of chemicals in the stream is attributable to the difficulty of maintaining an even 100-foot strip along an irregular stream (U.S. EPA 1977). Fredriksen et al. (1975) indicated that maximum streamwater herbicide concentrations in excess of 0.05 mg/L should not occur, and average concentration over the first 24 hours after application is unlikely to exceed 0.01 mg/L when direct application to the stream is avoided. (More recent studies on the tolerance of aquatic organisms to specific herbicides were not obtained for this review, so discussion of acceptable surface-water herbicide concentrations is precluded).

Insecticides

Information collected on insecticides was limited to a 1971 discussion of forest chemicals reprinted in Brown (1979). Many of the insecticides discussed are no longer in use (e.g., DDT). More basic to the change in insecticide types is the reduction in pesticide use over the last decade as public agency and private policies have adapted to the realization that insects can develop tolerances and immunities to insecticides over time, requiring increasingly larger and expensive doses. Research on this particular subject has certainly overshadowed research into effects of insecticides on small streams. However, basic concepts on stream entry, fate, and toxicity to aquatic life of insecticides are similar to herbicides.

As with herbicides, insecticides are applied aerially and initially reach four components of the forest environment: air, intercepting vegetation, the forest floor, and surface waters. The most important mechanism of entry to the aquatic environment is direct application or drift of spray onto the water surface. As with herbicides, a substantial portion of the application can be lost to aerial dispersion prior to interception by vegetation. Careful selection of chemicals, spray equipment, and environmental conditions during application will minimize the potential for direct application and drift onto water.

Fertilizers

Operational fertilization of Douglas-fir forests in the Pacific northwest began in 1965. Nitrogen is the most common growth-limiting nutrient in this region, and all major timber types have responded to nitrogen fertilization. Granular urea (46 percent N) is used almost exclusively, with application rates of 370 to 493 kg urea/ha (150 to 200 lb N/acre) (Fredriksen et al. 1975).

Aerial fertilization has been documented in western Oregon and Washington forests to cause an almost immediate rise in nitrogen levels in streams, with lingering elevated levels lasting for several months. The greatest potential for entry to streams is through direct application to exposed surface water (Brown 1979). Brown (1979) and Fredriksen et al. (1975) detailed the effects of urea applied aerially at a rate of 224 kg urea-N/acre on the Coyote Creek basin of South Umpqua Experimental Forest in southwestern Oregon. Urea fertilizer is highly soluble in water. Once dissolved, it is rapidly hydrolyzed to the ammonium ion and then oxidized by bacteria to nitrite, which is then oxidized by other bacteria in a second step to nitrate. This sequence is reflected in streams draining the treated watershed: urea concentrations increased slowly and peaked at 1.4 mg/L 48 hours after application; ammonia-N reached a peak of 0.044 mg/L at the same time; and nitrate concentrations peaked in 72 hours at 0.17 mg/L and remained relatively high for 2 weeks. After 15 weeks, when nitrate levels returned to near normal, only 0.01 percent of the nitrogen applied to the watershed was found to have left the system via streams. A secondary nitrate peak, of the same magnitude as that which followed the initial application, occurred several months later at the onset of fall rains, probably resulting from leaching of soils. Ninety-two percent of the nitrogen lost from the system during the first year moved out during this secondary peak in the rainy season. All concentrations were much below toxic levels or drinking water standards. For comparison, nitrate levels in streams draining the fertilizer-treated patch-cut basin were considerably lower than nitrate levels emanating from an adjacent clearcut and slash-burned basin. The three-week average was 0.17 mg/L for the treated basin vs. 0.5 mg/L for the untreated clearcut basin. This fact implies that, in this instance, the fertilizer source of nitrate posed a lesser threat of water quality degradation than did normal timber harvest practices.

Aerial application of fertilizer has minimal drift or is not intercepted by the canopy, leaving the forest floor and surface waters as the primary receptors. High initial urea concentrations in streams are the result of direct fall into the surface waters. Drift of dust is largely controlled and limited due to the use of specially coated forest-grade urea granules. Thus, the amount of fertilizer entering streams can be minimized by avoiding larger streams during application. Fredriksen et al. (1975) noted that data from several studies show low initial concentrations of urea-N and ammonia-N when direct application to surface waters is intentionally avoided. Whether the 25-foot buffer strip requirement controls secondary nitrate peaks during the fall rainy season is inconclusive, although Fredriksen et al. (1975) noted that a secondary peak of nitrate was detected in every study in which sampling has continued long enough after fertilization.

TFW-related research on the subject of buffer strips and forest fertilizer is currently ongoing. This should provide a comprehensive evaluation of the effectiveness of buffer strips in maintaining acceptable water quality levels in Type 4 and 5 waters.

Another source of water quality degrading chemicals are leachates from forest organic matter and logs themselves. However, the concentration of leachates from organic matter (leaves, twigs, and needles) needed to produce toxic effects to fish was so high that oxygen depletion problems would occur first because of the high chemical oxygen demand (COD) of the material. The toxicity of leachate from logs and bark has been reported, but situations where this would occur are limited to logs that are being stored in relatively still water (U.S. EPA 1976).

Conclusions

The review of literature relating to water quality impacts of forest practices on Type 4 and 5 Waters indicates there are no documented problems of adverse water quality resulting from timber harvest and slash treatment, or from pesticide and fertilizer application. A comprehensive body of literature documents that clearcutting and slash burning normally result in a temporary increase in nitrate concentration, but at levels well below water quality standards, and that concentration levels return to normal following vegetation recovery. Other types of timber harvest, including patch-cut, showed very limited effects on nitrate levels in streams. Total nitrogen loss from the forest ecosystem is also very minor, although whole-tree harvest in short rotations was not evaluated.

A similar conclusion was developed regarding nitrogen input from fertilizer application, although only two studies were found that documented stream quality following aerial application. Nitrate concentrations do not approach water-quality standards, and initial direct application of fertilizers to surface water, the primary transport mechanism into streams, can be limited by maintaining a buffer strip along flowing streams. Current Washington forest practice regulations require a 25-foot buffer strip along Type 4 and 5 Waters. Secondary peaks of nitrate, following fall rains, were found in all studies, although peak concentrations remained well below standards.

The literature reviewed regarding stream entry, fate, and toxicity of pesticides was limited to a few early-1970s studies. Direct application and drift onto surface waters appears to be the primary mode of entry, as evidenced by detectable concentrations shortly after application. Long-term entry of pesticide residues via surface or subsurface runoff has not been found, probably because overland runoff is not common in western Washington and Oregon, where all the studies were performed. Application techniques and chemical types have changed during the past decade, probably resulting in better control of direct application and drift to surface water. Current Washington forest practice regulations on aerially applied forest chemicals other than fertilizer require a 50-foot buffer strip along Type 4 and 5 Waters. Careful monitoring of weather and stream location is necessary to make effective use of the buffer strip.

REGIONAL CHARACTERISTICS OF TYPE 4 AND 5 WATERS AND THE EFFECTS OF TIMBER HARVEST PRACTICES ON TYPE 4 AND 5 WATERS: RESULTS OF THE QUESTIONNAIRE AND WORKSHOP

An important aspect of developing a research strategy to improve management of Type 4 and 5 Waters is to assess the problems or perceived problems that land managers involved in TFW have encountered in addressing issues related to headwater streams. The questionnaire used to elicit answers from these individuals consisted of five parts (Appendix A). Responses are summarized in this section. Because of the number of open-ended questions asked in the questionnaire, PTI believes that the best understanding of the range of responses can only come from an independent review of the questionnaire itself. Therefore, it is the intent of PTI to turn over all questionnaires at the end of the contract to the SHAM Committee.

The first part of the questionnaire addressed the respondents themselves: who they are professionally, what geographic area they are working in, and how much on-the ground experience they have. A summary of respondent characteristics is given in Table 5. Note that most respondents come from either industry (38 percent) or state, federal and local agencies (40 percent), with the rest split between tribal (13 percent), environmental (8 percent) representatives and unidentified (3 percent). People were asked to respond by "ecoregion," simplified from the DNR map (Figure 1), even though meetings and mailing lists were coordinated through the political DNR regions. Based on ecoregion, the Puget lowlands, northwest Cascades, and Southeast Cascades were the best represented; the remaining 39 percent came from all other regions. Only a few responses from the northwest coast, southwestern hills, and Blue Mountains were received. Fifty-five percent of the respondents were professional foresters, 14 percent were fisheries biologists, with physical scientists, engineers, and general environmentalists constituting the remainder. The professional composition of groups at regional meetings, which was similar, explains some of the difficulties in interpretation of questionnaire results. Foresters and fisheries biologists both operate peripherally to a sophisticated understanding of the geomorphic processes involved in moving sediment through very small channels, although they are appreciative of management impacts on these channels. While they could recall having observed a particular process or set of processes, they were uncomfortable in assessing a magnitude or frequency. When asked for the basis on which they made their judgment, "casual observation" was most often given in response.

TABLE 5. QUESTIONNAIRE RESPONDENT CHARACTERISTICS

			Constituency				Occupation					Years Experience (Modal)	
Ecoregion	DNR Region	No. of Responses[a]	Agency	Industry	Tribal	Environmental	Forestry	Fisheries	Soils/ Geology	Hydrology/ Engineer	Other	Sediment Dynamics	Forestry Practices
N.W. Coast	Olympic	5	2	2	0	0	2	1	1	0	0	11-20	11-20
Southwest	Central/SW	7	2	3	0	2	3	0	0	0	4	6-10, >20	6-10, >20
Puget Lowland	Olympic/ Central/SPS/NW	13	1	8	4	0	7	3	1	1	1	6-10	11-20
N.W. Cascades	NW/SPS	16	6	6	2	2	8	3	3	0	2	11-20	>20
S.W. Cascades	SPS/Central/ SW	10	3	5	0	1	7	0	0	0	2	11-20	11-20
N.E. Cascades	NE/SE	8	4	3	0	1	5	1	0	1	1	11-20	11-20
S.E. Cascades	SE	11	7	3	1	0	8	1	1	1	0	11-20	11-20
N.E. Highlands	NE	15	7	3	4	1	7	3	1	2	2	11-20	6-10
Blue Mountains	SE	3	3	0	0	0	1	0	0	2	0	11-20	11-20
TOTAL		88	35	33	11	7	48	12	7	7	12	–	–

[a] Not all respondents completed Part I of questionnaire, Respondent Characteristics; this accounts for discrepancies between total questionnaires tabulated and constituency and occupational subtotals in each region. Tabulation includes questionnaires received through 31 May 1989.

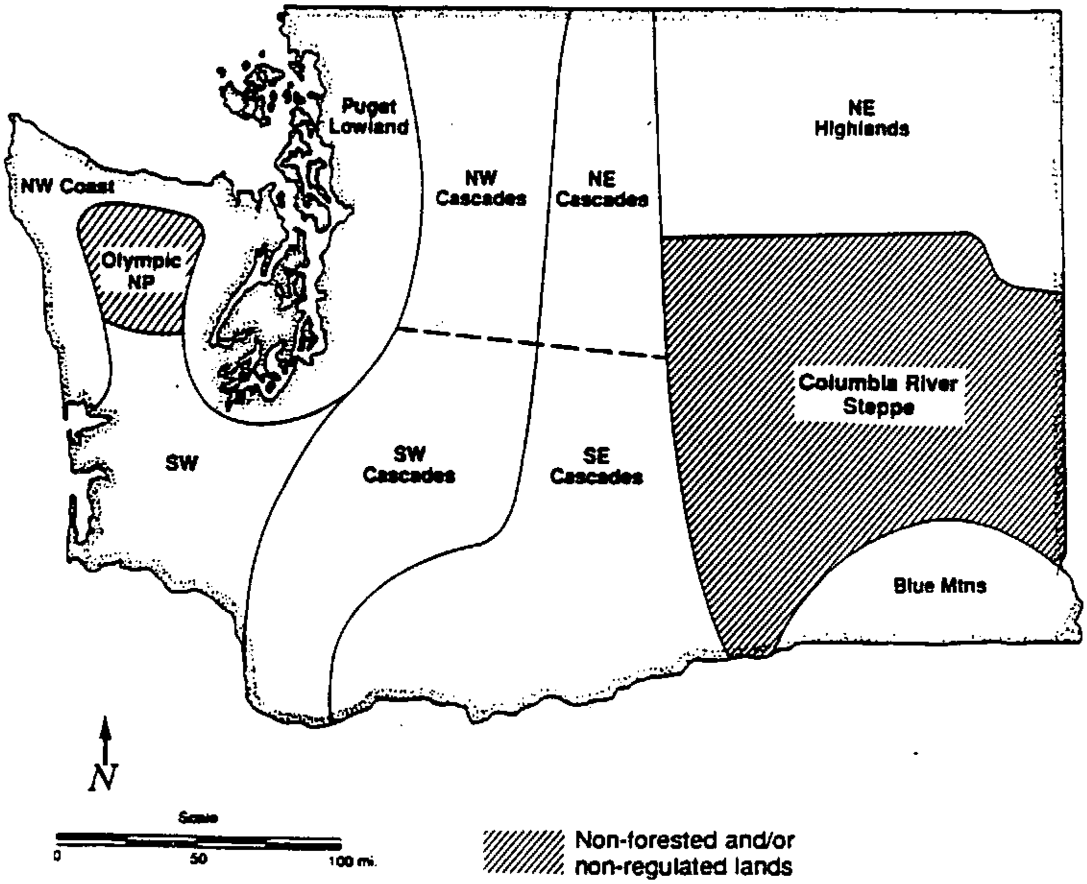


Figure 1. Simplified forest ecoregions

PHYSICAL, SILVICULTURAL, AND MANAGEMENT CHARACTERISTICS OF THE ECOREGIONS

Based upon the responses to this section, most of the TFW participants distinguished between hilly (Puget lowlands, southwest, and to a lesser extent the northeast highlands) and very mountainous regions (all four Cascade regions). They also defined a clear break between the east and west sides of the Cascades. Dominant responses in each ecoregion are tabulated in Table 6. However, it should be noted that respondents felt uncomfortable about being the first-level integrators of a great deal of descriptive geographic data. The DNR geographic information system (GIS), currently in development, appears to be a necessary tool for managers. The GIS should allow them to get descriptive information on the distribution of Type 4 and 5 Waters in the landscape, to quantify the properties of discrete channel segments (gradient, dominant rock type, etc.), or to determine the frequency of specific sediment delivery process relative to physical environmental features.

Topography alone defined the first axis of distinction, with the hilly areas having moderate to moderately steep slopes and stream channels, while the Cascades and Blue Mountains had dominantly steep hillslopes and channels. Climatic variables, and hence vegetation and forest management), distinguished the east-west axis. These climatic variables are also defined in Figures 2 through 4. Forests are generally restricted to areas which average more than 30 cm of rain annually (Figure 2), with July maximum temperatures less than 30°C (Figure 4). Snowmelt runoff is significant where the January minimum temperature is less than -5°C (Figure 3). Geology played little or no role in defining major environmental gradients, as each ecoregion is geologically distinct. Volcanic and sedimentary rocks dominate all ecoregions except the northeast highlands and the North Cascades, which have high concentrations of crystalline granitic and metamorphic rock (Figure 5). The effects of glaciation were obvious only in the oversteepened slopes of the western Cascades. East-side forests are characterized by the presence of ponderosa pine along with Douglas-fir; the west side is dominated by a hemlock/ Douglas-fir assemblage, although spruce appear on the western coast of the Olympic Peninsula, and hardwoods are a major component of Puget Lowland forests (Figure 6).

PERCEPTIONS OF SEDIMENT DYNAMICS IN TYPE 4 AND 5 WATERS

The questions under this heading were designed to explore sediment dynamics on the most *undisturbed* lands in each ecoregion. Unfortunately, this was relatively difficult for most respondents to do. A large number of responses ranked the important processes and then related them to timber harvest activities while answering questions concerning the frequency and magnitude of these processes, even after written and verbal instructions to the contrary. This points out the need for the baseline inventory component of the ambient monitoring workplan, as well as the

TABLE 6. REGIONAL PHYSICAL, FOREST, AND MANAGEMENT CHARACTERISTICS AS REPORTED BY QUESTIONNAIRE RESPONDENTS[a]

		Runoff Characteristics		Topography			Geology and Soils				Timber Harvest Practices				
													Roads		
Ecoregion	Number of Responses	Rainfall	Flood Frequency and Duration	Hillslopes	Type 5 Stream	Type 4 Streams	Geology	Glaciation	Soils	Dominant Tree Species	Harvest	Yarding	Age	Construction	Maintenance
N.W. Coast	2	moderate intensity winter rain	moderate frequency and duration	steep to moderately steep	steep to moderately steep	moderately steep	sedimentary, unconsolidated	local continental and alpine	moderate to thick, mixed soils	hemlock, Douglas-fir, cedar, spruce	clearcut	high lead	mostly post-1974	newer on ridge and valley	abandoned after logging
Southwest	3	moderate to high intensity winter rain	moderate to frequent frequency, moderate duration	moderate to steep	steep	moderate to moderately steep	sedimentary	none	thin, mixed soils	hemlock and Douglas-fir	clearcut	high lead, tractor	all years	through out watershed	poor
Puget Lowland	11	moderate, some high intensity winter rain	moderate frequency, moderate to short duration	moderate, straight	moderately steep	moderate	unconsolidated, sedimentary	continental	moderate to thick, sandy to silty	hemlock, Douglas-fir, mixed hardwoods	clearcut	high lead, skidder	all years	throughout watershed, many landings	variable
N.W. Cascades	16	rain on snow and high to moderate intensity rain	frequent to moderate, moderate to short duration	steep to oversteep	very steep	steep	metamorphic, unconsolidated	continental and alpine	moderate to thick, mixed soils	hemlock, Douglas-fir, true fir	clearcut	high lead, shovel and skidder	all years	throughout watershed, many landings	depends on owner
S.W. Cascades	7	high to moderate intensity winter rain, glacial melt in spring	frequent to moderately frequent, short duration.	steep to oversteep	steep	moderately steep	volcanic, unconsolidated	local alpine and continental	varying depth mostly sandy	hemlock, Douglas-fir, true fir	clearcut	high lead, some skidder and shovel	all years, post-1974 at high elevations	throughout watershed, many landings	poor after logging
N.E. Cascades	3	spring snowmelt	moderate to infrequent, moderate to short duration	steep to moderate	steep	steep	highly variable	alpine	thin and thick, sandy to silty	Douglas-fir and pine, ponderosa pine	mostly selective	tractor	mostly pre-1974	throughout watershed	well maintained (recreation)
S.E. Cascades	11	spring snowmelt, some rain-on-snow and intense rainfall low elevations	moderate frequency and duration	all slopes/classes represented	all slopes/classes represented	moderately steep	basaltic, volcanic sedimentary and unconsolidated	local alpine and continental	moderate to thin, variable type	Douglas-fir, pines, ponderosa pine	clearcut at higher elevations, others lower	tractor lower, cable in higher elevations	mostly pre-1974	--	variable
N.E. Highlands	8	snowmelt, some rain-on-snow, summer showers	moderate frequency, moderately long duration	moderate to steep	moderate to moderately steep	moderately steep to moderate	sedimentary, unconsolidated, granitic, metamorphic	continental	variable, sandy	mixed true fir, pine, Douglas-fir, ponderosa pine	shelter, partial	tractor, skidder	mostly pre-1974	throughout watershed, many landings	poor after logging
Blue Mountains	2	high intensity, summer and winter	moderate frequency, moderate duration	steep and straight	very steep	moderately steep	volcanic	none	moderate to thin, silty	Douglas-fir, true fir, ponderosa pine	partial	tractor	all years	throughout watershed, few landings	poor after logging

[a] Refer to questionnaire (Appendix A) for quantitative ranges associated with individual categories.

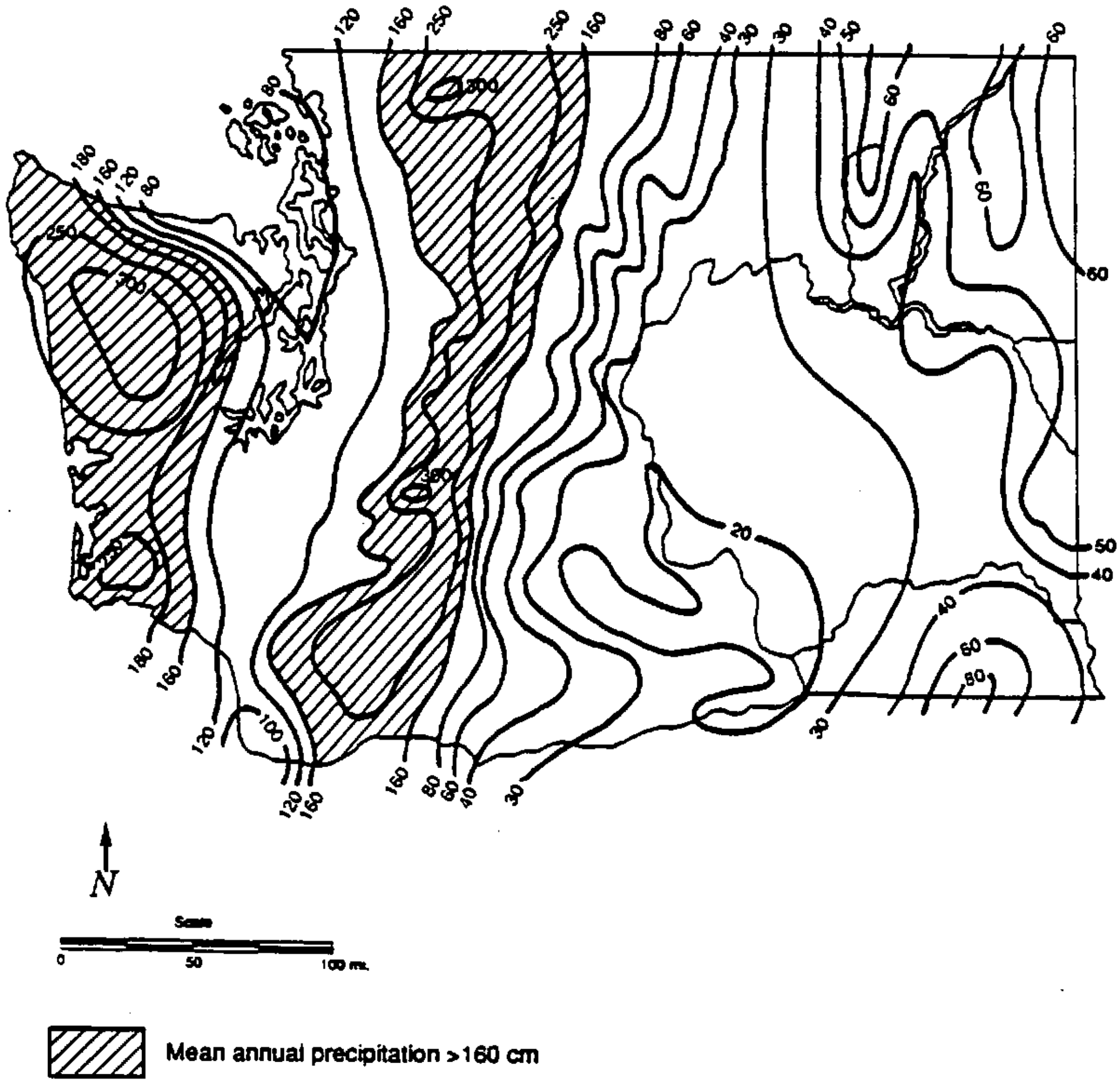


Figure 2. Mean annual precipitation, cm (U.S. Weather Bureau 1960)

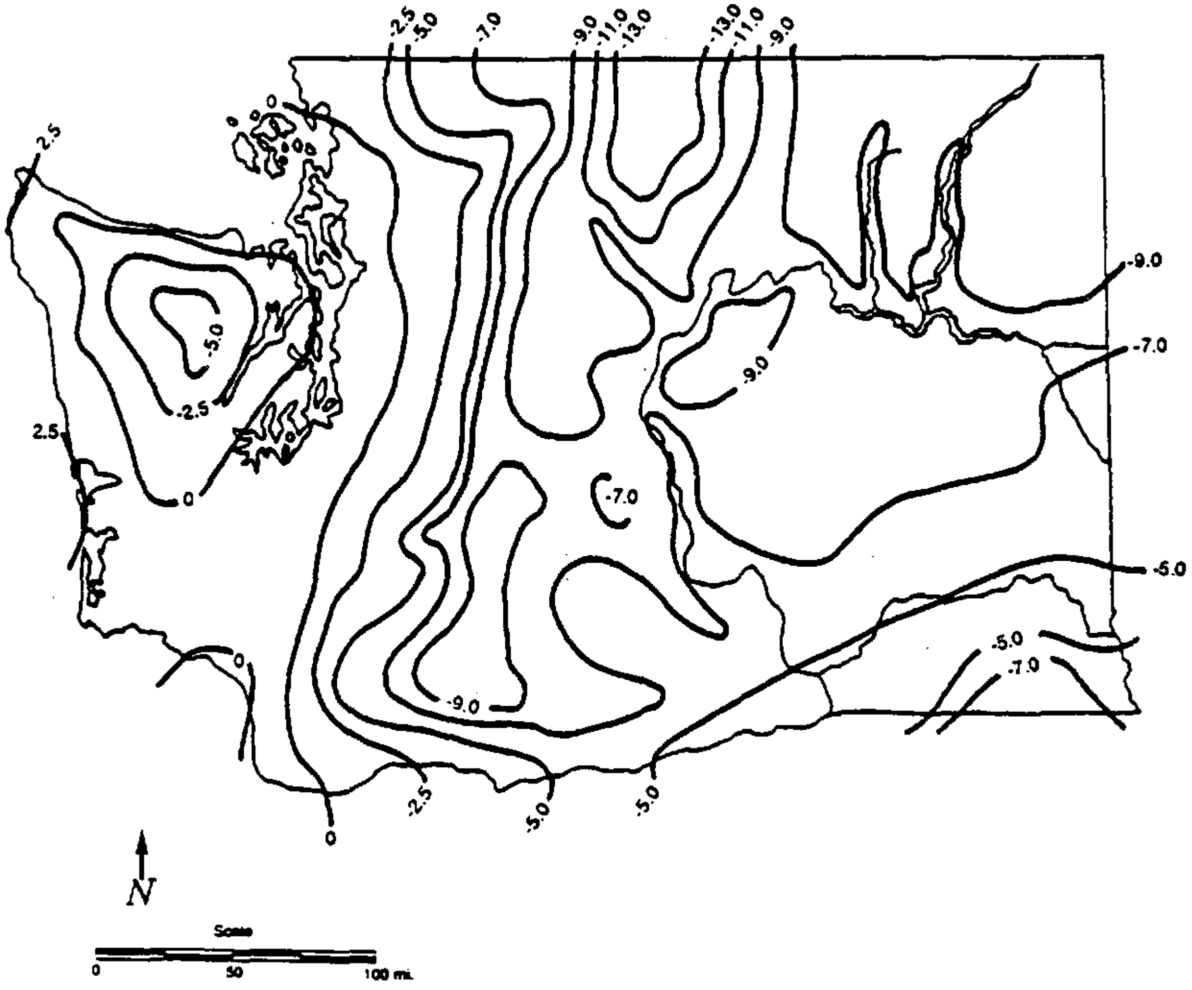


Figure 3. January mean minimum temperature,°C (U.S. Weather Bureau 1960)

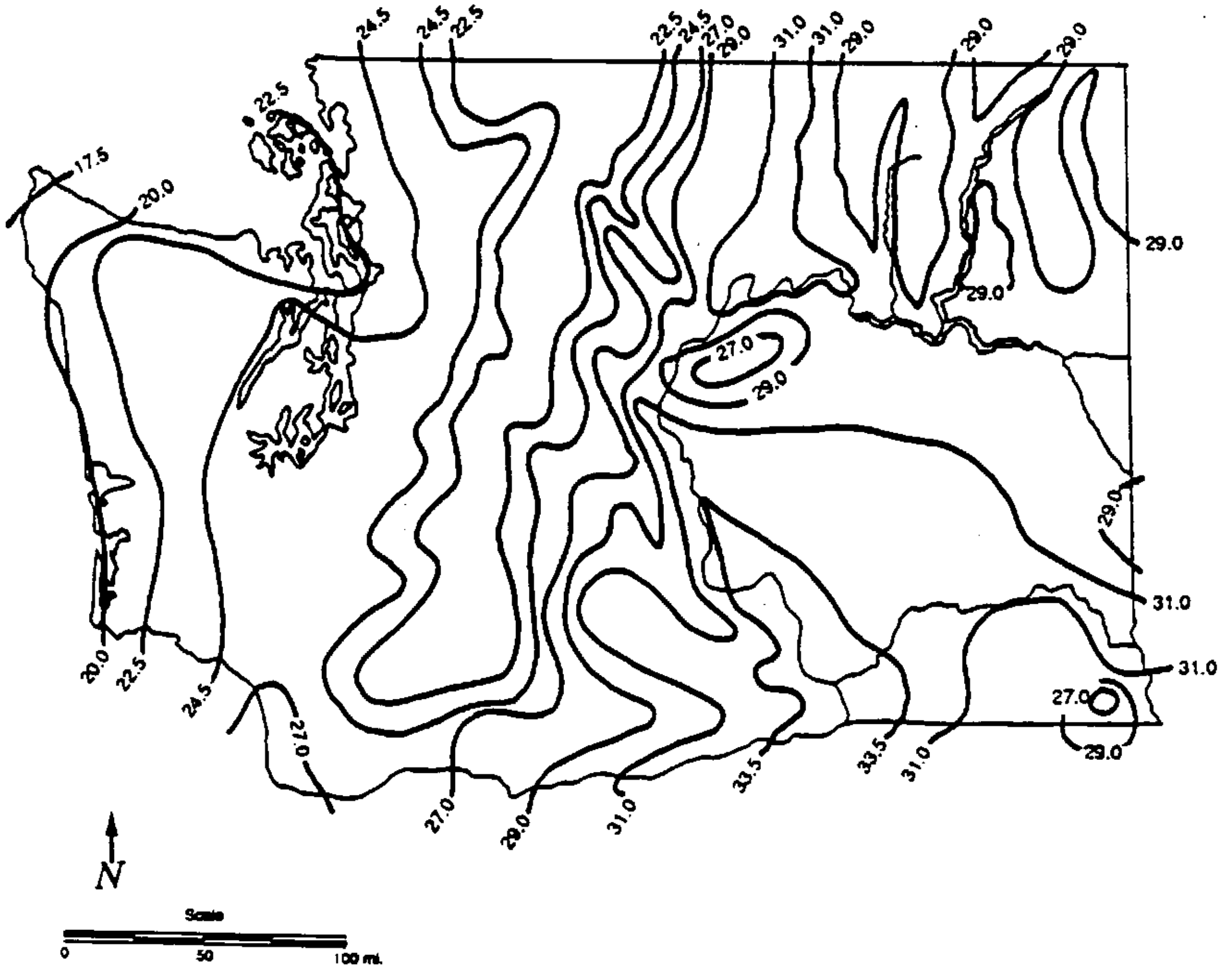


Figure 4. July mean maximum temperature,°C(U.S. Weather Bureau 1960)

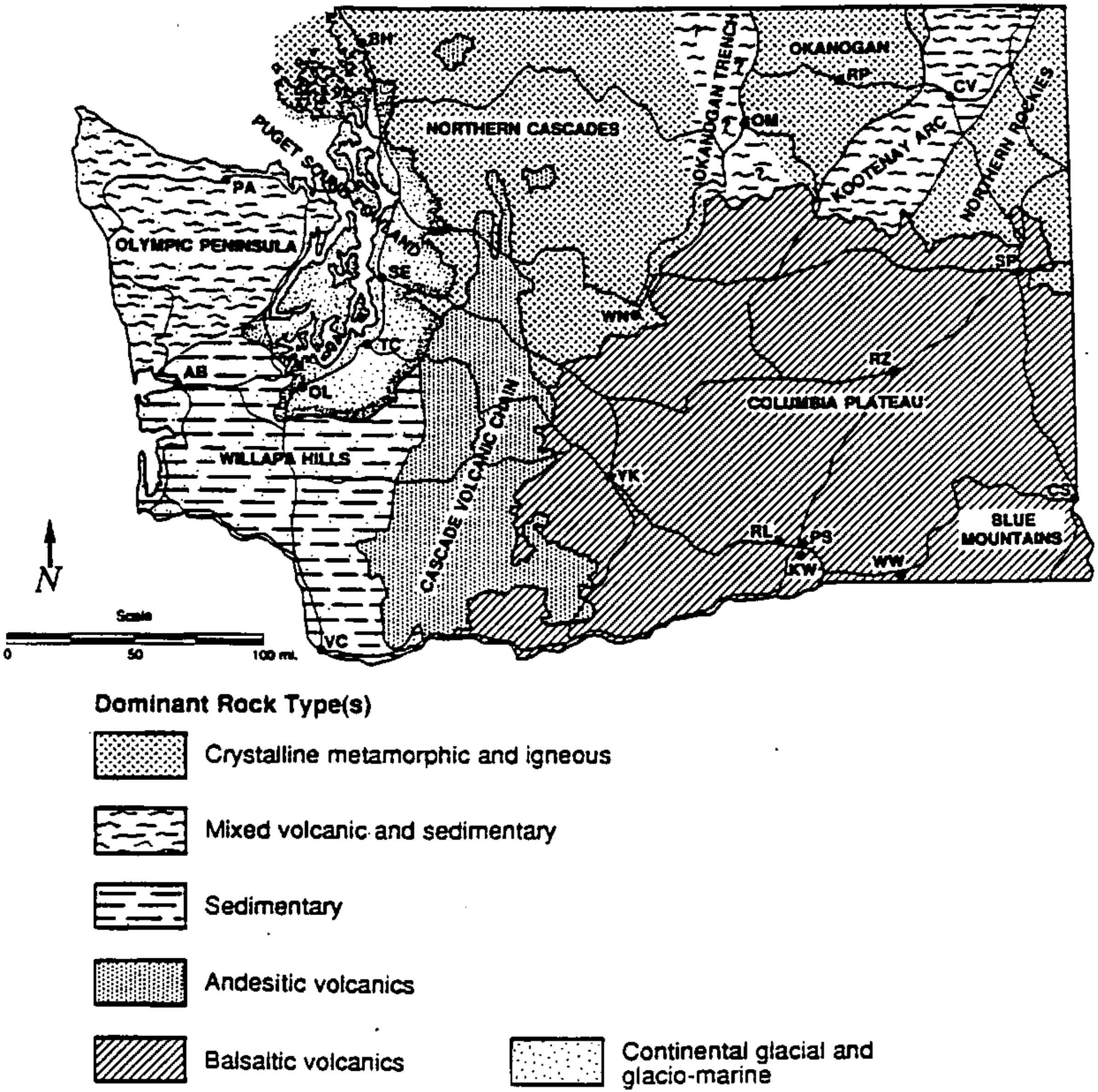


Figure 5. Generalized geologic provinces (Modified after Alt and Hyndman 1984)

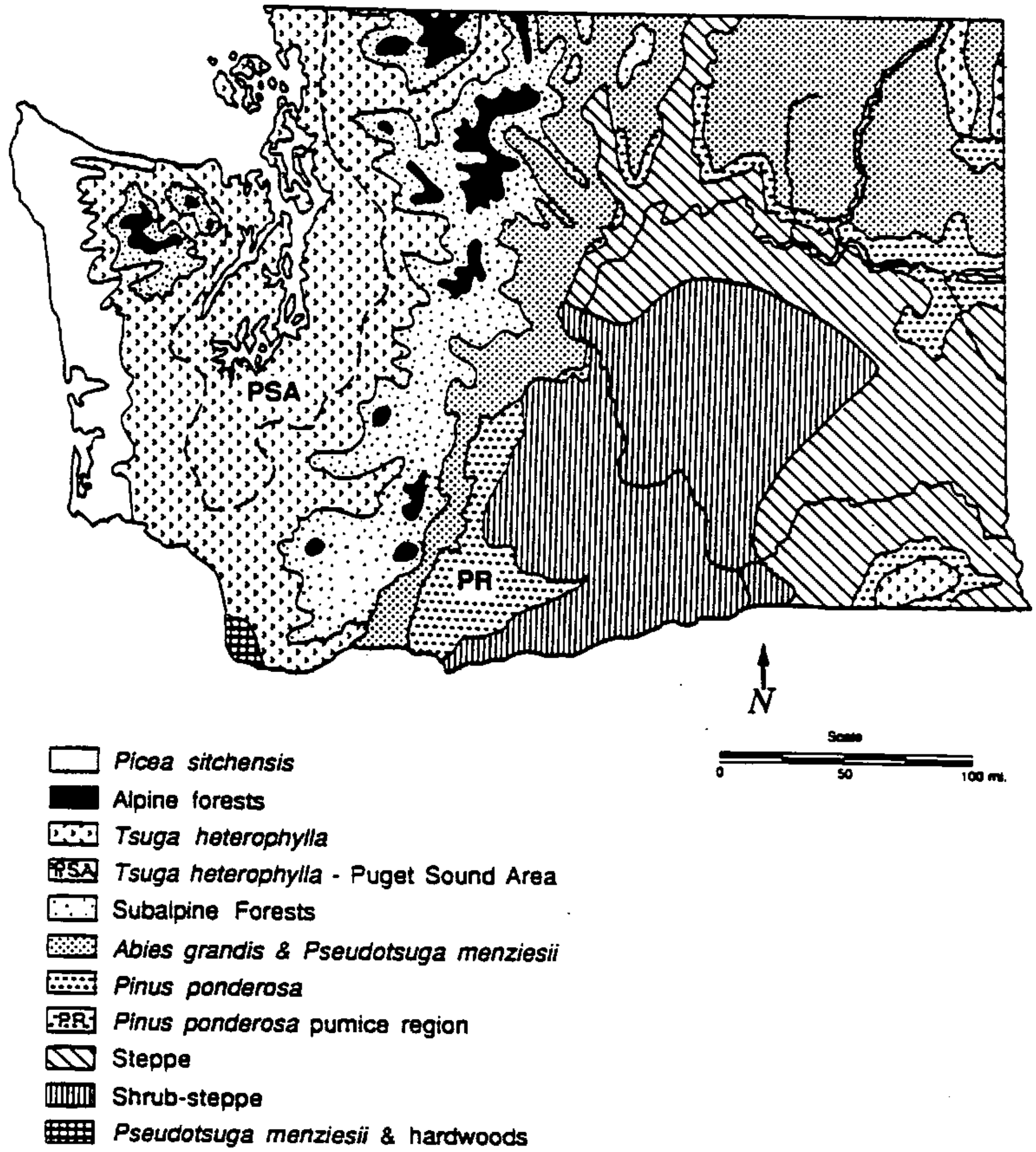


Figure 6. Generalized vegetation map (Franklin and Dymess 1973)

importance of better training of land managers to observe the details of erosion and sedimentation. In addition, responses in this section were commonly sketchy due to lack of time or familiarity with the technical aspects of sediment dynamics.

Debris flows and debris avalanching were consistently ranked as important in the western Cascades, the northwest coast, and on a smaller or less frequent scale, the eastern Cascades, Blue Mountains and southwestern Washington. Ravel, bank erosion, and translational slides/debris avalanches were important delivery mechanisms in the other ecoregions. Sediment storage in headwater channels was strongly associated with obstructions, not always LOD. Only a very few respondents attempted to comment on frequency, magnitude, or causal connections between watershed characteristics and the processes. Channel recovery was generally thought to be rapid, with most action occurring in the first two or three years after disturbance. Efficiency of transport was thought to be high in the north Cascades, variable in the south Cascades, and low in the Puget lowlands and northeast highlands. Mentioned by respondents were the following causal factors:

- Northwest Cascades: plenty of LOD, shallow soils, and very high hillslope/small channel gradients
- Southwest Cascades: high rainfall, shallow(?), fine-grained soils, and very high hillslope/small channel gradients
- Northeast highlands and northeastern Cascades: low precipitation, mostly as snow, and coarse soils
- Puget lowlands: large amount of LOD, along with climate, geology, and topography
- Southeast Cascades: sediment flushing during snowmelt at higher elevations, with LOD important.

PERCEPTIONS REGARDING THE EFFECTS OF TIMBER HARVEST ACTIVITIES ON TYPE 4 AND 5 WATERS

This section of the questionnaire was used to extract perceptions of TFW participants on effects of timber harvest. Due to the uneven quality of the responses, no attempt was made to categorize them by profession or constituency. Nor can lack of a response to a particular issue always be interpreted to mean that a particular management effect is absent from an ecoregion, although it is probably not as significant as those stated below. Workshop participants reviewed questionnaire results from the southwest, northwestern, and southeastern Cascades, and northeastern highlands ecosystems, and their additional responses are included as well.

Water Quality

The only sediment-related water quality issue raised was a short-term increase in turbidity, with a mean maximum estimated recovery period of two years "after logging". Turbidity increase was noted in all ecoregions, although about half of the respondents said there was no significant water quality impact from timber harvest, or did not answer the question. (Temperature effects were not the focus of this question, but were noted by one or two respondents from each of the Puget lowlands, southwestern Washington, the northwest and southeast Cascades, the northeast highlands and Blue Mountains; water quality degradation by aerial application of forest chemicals was noted by one respondent from the northwest Cascades only.)

In the northwest coast ecoregion, road construction and road use were cited as turbidity sources, with a few weeks duration; in some minds, the rise in turbidity followed a major storm, and in others, active logging. In southwestern Washington and the Puget lowlands, road use in wet periods and cross-channel yarding were cited as contributing factors to turbidity increases; wet-weather road use and channel clearing were given by respondents from the northwest Cascades, and culvert placement during road construction and cross-channel yarding were cited in the southwest Cascades.

In the northeast Cascades, significant timber harvest efforts usually occur when Type 4 and 5 Waters are dry or the ground frozen, limiting impacts observed by respondents. In the southeast Cascades, turbidity increases were associated with roads and their maintenance (e.g., snowplows scraping road surface as well). In the northeast highlands, turbidity impacts differed between operators, while in the Blue Mountains, turbidity peaks were greatest when snow melted rapidly from road surfaces on south-facing slopes.

Sediment Production

Patterns of additional sediment production from timber harvest activities were markedly different between the east and west sides of the Cascades. All respondents concentrated on roads, but those from west slope regions noted that they posed sediment problems regardless of maintenance effort. Increased debris avalanching associated with roads was noted from all west side and Cascade ecoregions, with increased debris flows observed in the western and (locally only) in the northeastern Cascades, particularly associated with road construction and landings. (One respondent commented that obviously unstable areas were uncommon in the northeastern Cascades; no mention of wildfire effects were noted.) Failures of landings and road crossings (from plugged culverts) have been observed in the western Cascades. Respondents also associated debris avalanching with channel widening in the southwest and Puget lowlands ecoregions, and with debris removal in the Puget lowlands. Timber harvest-related local channel widening was noted in the northeast highlands with no specific causative practices given.

Roads were recognized as a source of sediment from surface runoff in all ecoregions, with this input decreasing with time after timber harvest and heavy road use end. Skid (or fire) trails were listed as sediment sources in the northwest coast, Puget lowlands, southwest hills, and southeast Cascade ecoregions, particularly in the southeast Cascades where skidding occurs parallel to the channel. Cross-channel yarding without full suspension, or heavy equipment in channels for other purposes, was cited as a source of sediment in all ecoregions except the northwest coast and northeast Cascades. Finally, poor road layout and maintenance were given as the major sedimentation causes in the Blue Mountains, particularly in areas of ash-rich soil.

Increased sedimentation was considered to be a short-term effect (recovery in <5 years), particularly in eastern Washington, as long as forest practices rules are adhered to. In the northeast Cascades, logging when the ground is either dry or frozen limits coarse sediment production also. Little change in in-channel sediment storage was noted by respondents, unless channels were cleared of LOD (northwest Cascades, Puget lowlands, southwest and northeast highlands ecoregions).

Large Organic Debris

Logging-induced changes in the distribution of large organic debris was an issue in all ecoregions, but most important west of the Cascades. Input was stated to increase from harvest in western Washington ecoregions and the southeast Cascades; increases in small pieces were also mentioned in the northwest coast and the Puget lowlands, from blowdown in riparian management zones (RMZ) in the south Cascades, and from roads throughout the west and southwest Cascades. In the western Cascades, channel clearance for debris flow hazard reduction was controversial, with most respondents noting some detrimental effect (bank erosion, loss of channel storage, etc.) while others sensing only minimal impacts. Those respondents in the northeast highlands expect some loss eventually in LOD recruitment, but persons interviewed felt that it was not significant given the initially low load; recruitment was also an issue in the northern Cascades and Blue Mountains. A respondent from southwest Washington noted that today's timber harvest practices have less impact than previous ones did; harvest was also considered to have little present impact on LOD in the northeast Cascades and highlands. The east side, however, was concerned with a lack of baseline LOD loading and distribution data.

Water Quantity and Routing

The most consistent set of observations was on the topic of changes in water discharge associated with logging. Some form of water quantity increase was noted in all ecoregions, although the increase was not thought to be significant in the Puget lowlands, north and southwest Cascades, and northeast highlands. However, only one respondent had corroborating discharge measurements, and these may not have adequate climatic control. When defended, observations were based on specific locations which "seemed to stay wetter longer following logging." Flashier peak flows, more snow accumulating in clearcuts in the northwest Cascades, southwestern Washington, the southeast Cascades and the Blue Mountains were observed. Increases in flow were also listed as causing additional culvert plugs in the northwest Cascades. Summer baseflow changed following timber harvest in two ecoregions: it increased in the Blue Mountains and decreased in the southeast Cascades. When duration of the alteration was given, these changes were considered short-term (<2 years post-harvest), except for one respondent from the southwest Cascades who felt that they lasted 5-10 years post-harvest. Robert Beschta (31 May 1989, written communication) doubts that all of these effects are as significant as generally perceived.

Effectiveness of Forest Practices Rules

Nearly all respondents agreed that the 1974 Forest Practices Act (and associated 1976 regulations) went a long way in minimizing the effects of timber harvest, particularly road-related impacts, in the Puget lowlands, southwestern Washington, and the northeast Cascades. Unfortunately, as Beschta noted (31 May 1989, written communication), data are not available to substantiate this perception. One respondent noted significant differences in practice between operators in the southwest Cascades. TFW was seen as a way to improve communication and promote greater care in harvest and road construction and maintenance on the part of timber operators, but at a cost; an example of this is the practice of voluntary RMZ on Type 4 Waters in northeastern Washington. It was generally agreed that conditioning allowed increased protection of Type 4 Waters but little change in the protection of Type 5 Waters. Respondents were pleased so far with conditioning as practiced in the northeast Cascades and highlands but felt overly constrained in the western Cascades.

Respondents did want to see some changes in regulations or current practice. Improved road construction in the southeast Cascades was an example of the latter. Reducing channel bank disturbance was a goal for many respondents across the state, whether from RMZ, more stringent regulation of cross-channel yarding, or increased effort to minimize channel crossings with roads. Better control of road drainage (including greater culvert size) was suggested for the northwest Cascades and Puget lowlands. Several respondents from the northwest Cascades felt that channel cleaning (of LOD) in that ecoregion was of dubious value. More frequent use of RMZ on Type 4 Waters were sought by respondents in the Puget lowlands, western Cascades and northeast highlands. Better enforcement of existing regulations was also cited as a concern in the northwest coast, southwest Cascades, and northeast highlands, while education of small operators was noted in the Southeast Cascades. Several respondents from the western and northeastern Cascades called for increased protection of "sensitive areas", while others from the northeast and southwest Cascades wanted fewer fish and wildlife-based restrictions on Type 4 Waters.

CONCLUSIONS: DIRECTION OF FUTURE EFFORTS

The ultimate purpose of this document has been to determine what information field managers need to employ site-specific management prescriptions on Type 4 and 5 Waters. The review of existing information served to scope out gaps in understanding small watershed sediment dynamics. Questionnaire respondents were asked about perceived management and information needs. Based upon the results from these two tasks, the SHAM Channel Morphology Group made its determination of priorities for the development of management tools and needs for future research.

Questionnaire Response: Management Tools and Information Needs

The last section of the questionnaire queried the respondents on their needs in terms of improved management tools and directions for further research. A commonly used tool is the local DNR soil survey. These were uniformly regarded as ineffective and too broad to be site-specific, or as useful only as a "red flag" for unstable areas. Respondents were roughly evenly divided between these two responses to the query. Other management needs listed, in decreasing order of frequency of response, were:

- A better stream typing system (in terms of relating the legal definition to process information) and typing maps, which do not reliably (and to everyone's satisfaction) fix boundaries between Type 3 and 4 Waters or, less significantly, between Type 4 and 5 Waters

- More accurate maps, including site specific geographic (including geologic, climatic/meteorologic, etc.) data of the sort a geographic information system (GIS) could provide

- Baseline data on sediment yields

- Tools for risk/hazard analysis including the hazard zonation map currently being developed

- Field survey forms to allow non-geomorphologists to make basic survey observations, and which would become part of the forest practices permit application, allowing review by those not permitted onsite, and evaluation of long-term management impacts or channel changes

- More frequent aerial photo coverage (southwest Cascades only)

- Site specific impact assessment tools.

Some of these impact assessment tools do exist but are not currently in use (Brunengo, M., 18 May 1989, written communication). Responses to the questionnaire did not indicate whether existing tools were not deemed appropriate for the tasks, or were not available to the appropriate people. The present ambient monitoring workplan is addressing at least some of these needs. Finally, broader education on terrain-forming processes was requested in several ecoregions (northwest, southwest, eastern Cascades and northeast highlands).

Under the topic of research direction, most of the questionnaire respondents desired basic information, whether data or guidelines, that concentrated on how specific processes respond to management. Included in the list were:

- Relationships between slope failure mechanisms, basin characteristics, and management practices

- Data on sediment, water quality, headwall soil and soil moisture characteristics, and root strength

- Usefulness of temporary channel crossings

- Effects of small LOD

- Grazing impacts (particularly on the east side)
- Roles of headwaters on downstream channels
- Collation and evaluation of existing unpublished data
- Determining when and at what level sediment becomes a problem.

Recommendations of the SHAM Committee

The SHAM Committee's Channel Morphology Group recognizes that managers need tools by which they can screen forest practices applications to concentrate their efforts on sensitive areas (or site applications). The group also must understand these areas sufficiently to determine potential hazards and associated risks. This should all be done in the context of basin-wide planning. These tasks require systematic assessment methods or tools such as those listed above, the acquisition of baseline resource information pertinent to Washington, and research directed at specific issues on which relevant information is scarce.

As seen by Dr. Kathleen Sullivan, Ms. Judy Turpin, and the committee, the level of effort required in each of these areas will be variable (Sullivan, K., 19 June 1989, personal communication). In some instances, existing management tools may need only to be adapted for use within TFW and verified for baseline conditions in Washington prior to widespread transfer to managers. If sufficient conceptual information and knowledge are available, the required management tool or design guidelines must be developed, and then put through the verification and technology transfer process. The greatest effort is required in those areas where information gaps exist. These gaps can exist for two reasons: first, because insufficient resource information is available in specific regions within the state to determine the applicability of existing conceptual models developed elsewhere. Generally, such resource information must be broadly distributed in time and/or space. Observations of a specific process or feature over a wide area allow the influences of watershed variables (e.g., relief, geology, drainage density) to be detected, while observations that are broad in time at a restricted location allow the examination of effects of persistent climatic change or inherent response lags to be documented. Second, on a few topics, true knowledge gaps are present. For instance, conceptual models of specific processes relative to headwater streams or other landscape elements are not fully developed and require significant basic research. The SHAM committee's Channel Morphology Group and PTI Environmental Services concur that the following topics constitute information gaps relative to headwater channels, which TFW must address over the next several years:

- Acquisition of baseline resource data (and compilation of existing unpublished data) on the relative frequency of sediment input processes, stratified by basin characteristics, climate, and management treatments (this need is echoed by Swanson and Grant (1982) in the Oregon Cascades)

- Filling of knowledge, data, or application gaps related to mass wasting, specifically: landslide initiation mechanisms; impacts on headwater channels; channel recovery processes; regional variations in spatial and temporal frequency; and impacts of management on failure rates

- Addressing knowledge, data, and application gaps related to channel processes: morphologic descriptions from channels across the state, in both high and low gradient systems and disturbed and undisturbed areas; hydraulics in spill roughness-dominated channels; sediment transport mechanisms and rates in headwater channels; initiation of dam-break torrents; sediment storage capacity and buffering relative to LOD and bedrock control; response of channels to road construction (particularly crossings); and processes governing the maintenance of important biological characteristics

- Filling resource information and application gaps relative to woody debris management, particularly in managed forests: baseline data from across the state on LOD loading, decay, and recruitment; export rates and mechanisms from Type 4 and 5 Waters; stability characteristics and the problems of floatable debris; the role of debris in channel recovery after debris flows and dam-break torrents; and appropriateness (and implementation) of existing channel clearance guidelines

- Addressing knowledge, data, and application gaps in small watershed hydrology, specifically: the hydrograph in headwater channels relative to debris stability, sediment transport and storage, and bank stability; management effects on runoff regime of headwater channels, particularly relative to flows required for significant total geomorphic work or critical activity periods for salmonids downstream; influence of rain-on-snow events under managed conditions on peak flows; and management strategies for ephemeral or intermittent streams.

- Addressing other region-specific issues, such as grazing impact in eastern Washington.

This is an ambitious research and implementation agenda, to be accomplished over many years of work within the TFW program. It will be important for these topics to be further refined into discrete, researchable questions by the committee, and adequately funded, in order that the results can be placed in the appropriate management hands. It is anticipated that management techniques will evolve as these new pieces of information and assessment tools become available.

REFERENCES

Adams, P.W., and W.R. Stack. 1989. Streamwater quality after logging in southwest Oregon. Project Completion Report. Prepared for the U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. Oregon State University, Forest Engineering Department, Corvallis, OR.

Alt, D.D., and D.W. Hyndman. 1984. Roadside geology of Washington. Mountain Press Publishing Co., Missoula, MT. p. xii.

Anderson, B., and D.F. Potts. 1987. Suspended sediment and turbidity following road construction and logging in western Montana. Water Res. Bull. 23:681-690.

Baker, C.O. 1979. The impacts of logjam removal on fish populations and stream habitat in western Oregon. Masters Thesis. Oregon State University, Corvallis, OR. 86 pp.

Bathurst, J.C. 1987. Critical conditions for bed material movement in steep, boulder bed streams. pp. 309-318. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Benda, L.E. 1988. Debris flows in the Tyee sandstone formation of the Oregon Coast Range. Masters Thesis. University of Washington, Seattle, WA.

Benda, L.E. 26 May 1989. Written Communication (comments on Progress Report, Sediment Dynamics in Type 4 and 5 Waters, produced by PTI Environmental Services). University of Washington, Department of Geological Sciences, Seattle, WA.

Benda, L.E., and T. Dunne. 1987. Sediment routing by debris flow. pp. 213-223. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Benda, L.E., and T. Dunne. (In preparation.) Unsteady sediment routing in mountain stream channels. University of Washington, Seattle, WA.

Benda, L.E., T.W. Cundy, and T. Dunne. (In preparation.) Predicting the deposition of debris flows for hazard recognition. Submitted to Can. Geotechnical J.

Berris, S.N., and R.D. Harr. 1987. Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the western Cascades of Oregon. Water Res. Research 23(1):135-142.

Beschta, R.L. 1978. Long-term patterns of sediment production following road construction and logging in the Oregon coast range. Water Res. Research 14:1011-1016.

Beschta, R.L. 1979. Debris removal and its effects on sedimentation in an Oregon Coast Range stream. Northwest Science 53:71-77.

Beschta, R.L. 1983. The effects of large organic debris upon channel morphology: a flume study. pp. 8-63 to 8-78. In: Proceedings of the D.B. Simons Symposium on Erosion and Sedimentation. Li and Associates, Ft. Collins, CO.

Beschta, R.L., and W.S. Platts. 1986. Morphological features of small streams: significance and function. Water Res. Bull. 22:369-379.

Beschta, R.L. 31 May 1989. Written Communication (letter to Ms. Anne MacDonald, PTI Environmental Services, Bellevue, WA). Oregon State University, Department of Forest Engineering, Corvallis, OR.

Bilby, R.E. 1984. Removal of woody debris may affect stream channel stability. J. Forestry 82:609-613.

Bilby, R.E., and G.E. Likens. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61:1107-1113.

Bisson, P.A., R.E. Bilby, M.D. Bryant, C.A. Dolloff, G.B. Grette, R.A. House, M.L. Murphy, K.V. Koski, and J.R. Sedell. 1987. Large woody debris in forested streams in the Pacific northwest: past, present, and future. pp. 143-190. In: Proceedings of the Symposium on Streamside Management--Forestry and Fisheries Interactions. Contribution No. 57. E.O. Salo, and T.W. Cundy (eds). University of Washington, Institute of Forest Resources, Seattle, WA.

Bowman, D. 1977. Stepped-bed morphology in arid gravelly channels. Geol. Soc. Am. Bull. 88:291-298.

Brown, G.W. 1979. Forestry and water quality. Oregon State University, School of Forestry, Corvallis, OR. 74 pp.

Brown, G.W., A.R. Gahler, and R.B. Marston. 1973. Nutrient losses after clear-cut logging and slash burning in the Oregon Coast Range. Water Res. Research 9:1450-1453.

Brunengo, M. 18 May 1989. Written Communication (comments on Progress Report, Sediment Dynamics in Type 4 and 5 Waters, produced by PTI Environmental Services). Washington Department of Natural Resources.

Bryant, M.D. 1980. Evolution of large, organic debris after timber harvest: Maybeso Creek, 1949-1978. USDA Forest Service General Technical Report PNW-101. U.S. Department of Agriculture, Washington, DC. 30 pp.

Campbell, A.J., and R.C. Sidle. 1984. Prediction of peak flows on small watersheds in Oregon for use in culvert design. Water Res. Bull. 20:9-14.

Cheng, J.D. 1989. Streamflow changes after clear-cut logging of a pine beetle-infested watershed in southern British Columbia, Canada. Water Res. Research 25:449-456.

Cummins, K.W., G.W. Marshall, J.R. Sedell, C.E. Cushing, and R.C. Peterson. 1984. Stream ecosystem theory. Proceedings of the International Association of Theoretical and Applied Limnology 22:1818-1827.

DeGraff, J.V. 1979. Initiation of shallow mass movement by vegetative-type conversion. Geology 7:426-433.

Dietrich, W.E., T. Dunne, N.F. Humphrey, and L.M. Reid. 1982. Construction of sediment budgets for drainage basins. pp. 5-23. In: Sediment Budgets and Routing in Forested Drainage Basins. USDA Forest Service General Technical Report PNW-141. F.J. Swanson, R.J. Janda, T. Dunne, and D.N Swanston (eds). USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 165 pp.

Dietrich, W.E., S.L. Reneau, and C.J. Wilson. 1987. Overview: "zero-order basins" and problems of drainage density, sediment transport and hillslope morphology. pp. 27-37. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Duncan, S.H., R.E. Bilby, J.W. Ward, and J.T. Heffner. 1987. Transport of road-surface sediment through ephemeral stream channels. Water Res. Bull. 23:113-119.

Everest, F.H., R.L. Beschta, J.C. Scrivener, K.V. Koski, J.R. Sedell, and C.J. Cederholm. 1987. Fine sediment and salmonid production: a paradox. pp. 98-142. In: Proceedings of the Symposium on Streamside Management--Forestry and Fisheries Interactions. Contribution No. 57. E.O. Salo, and T.W. Cundy (eds). University of Washington, Institute of Forest Resources, Seattle, WA.

Franklin, J.F., and C.T. Dyrness. 1973. Natural vegetation of Oregon and Washington. USDA Forest Service General Technical Report PNW-8. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 417 pp.

Fredriksen, R.L. 1970. Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds. USDA Forest Service Research Paper PNW-104. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 15 pp.

Fredriksen, R.L., D.G. Moore, and L.A. Norris. 1975. The impact of timber harvest, fertilization, and herbicide treatment on streamwater quality in western Oregon and Washington. pp. 283-313. In: Proceedings of the Fourth North American Forest Soils Conference, Forest Soils and Forest Land Management. B. Bernier, and C.H. Winget (eds). International Scholarly Books Services, Inc., Portland, OR.

Froehlich, H.A. 1973. Natural and man-caused slash in headwater streams. Pacific Logging Congress Logger's Handbook, Volume 33. 8 pp.

Furbish, D.J., and R.M. Rice. 1981. Predicting logging-related landslides in northwest California. EOS, Transactions of the American Geophysical Union 62(45):856 [abs].

Grant, G. 1988. The RAPID technique: a new method for evaluating downstream effects of forest practices on riparian zones. USDA Forest Service General Technical Report PNW-GTR-220. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. 36 pp.

Gray, D.H., and W.F. Megahan. 1980. Forest vegetation removal and slope stability in the Idaho batholith. USDA Research Paper INT-271. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT. 23 pp.

Gregory, K.J., A.M. Gurnell, and C.T. Hill. 1985. The permanence of debris dams related to river channel processes. Hydrol. Sci. J. 30:371-381.

Hack, J.T., and J.C. Goodlett. 1960. Geomorphology and forest ecology of a mountain region for the central Appalachians. U.S. Geological Survey Professional Paper 347. U.S. Geological Survey, Washington, DC.

Hagans, D.K., and W.E. Weaver. 1987. Magnitude, cause and basin response to fluvial erosion, Redwood Creek basin, northern California. pp. 419-428. In: Proceedings of the Corvallis Symposium, Erosion, and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Harr, R.D. 1976. Forest practices and streamflow in western Oregon. USDA Forest Service Technical Report PNW-49. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Harr, R.D. 1986. Effects of clearcutting on rain-on-snow runoff in western Oregon: a new look at old studies. Water Res. Research 22:1095-1100.

Harr, R.D. 1987. Myths and misconceptions about forest hydrologic systems and cumulative effects. pp. 137-141. In: Proceedings of the California Watershed Management Conference, 18-20 November 1986. Wildland Resources Center Publication Report No. 11. University of California, Berkeley, CA.

Harr, R.D. 5 May 1989. Written Communication (letter to Ms. Anne MacDonald, PTI Environmental Services, Bellevue, WA). USDA Forest Service, Pacific Northwest Research Station, Seattle, WA.

Harr, R.D., R.L. Fredrikson, and J. Rothacher. 1979. Changes in streamflow following timber harvest in southwestern Oregon. USDA Forest Service Research Paper PNW-249. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Harr, R.D., A. Levno, and R. Mersereau. 1982. Streamflow changes after logging 130-year-old Douglas fir in two small watersheds. Water Res. Research 18:367-644.

Hart, G.E., N.V. DeByle, and R.W. Hennes. 1981. Slash treatment after clearcutting lodgepole pine affects nutrients in soil water. J. Forestry 79:446-451.

Heede, B.H. 1972. Influences of a forest on the hydraulic geometry of two mountain streams. Water Res. Bull. 8:523-30.

Heede, B.H. 1981. Dynamics of selected mountain streams in the western United States of America. Zeitschrift für Geomorhpologie N.F. 25:17-32.

Helvey, J.D. 1980. Effects of a north central Washington wildfire on runoff and sediment production. Water Res. Bull. 16:627-634.

Helvey, J.D., A.R. Tiedemann, and T.D. Anderson. 1975. Plant nutrient losses by soil erosion and mass movement after wildfire. J. of Soil and Water Conserv. 40:168-173.

Hicks, B.A., and G.W. Lienkaemper. 1983. Movement of two active earthflows in the Middle Santiam Basin, western Cascades, Oregon. Association of Engineering Geologists 26th Annual Meeting Abstracts and Program. p. 74 [abs].

Hogan, D.L. 1987. The influence of large organic debris on channel recovery in the Queen Charlotte Islands, British Columbia, Canada. pp. 343-353. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Johnson, M.G., and R.L. Beschta. 1980. Logging, infiltration capacity, and surface erodibility in western Oregon. J. Forestry 78:334-337.

Kaufmann, P.R. 1987. Slackwater habitat in torrent-impacted streams. pp. 407-408. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Keller, E.A., and F.J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361-380.

Keller, E.A., and T. Tally. 1979. Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. pp. 361-380. In: Adjustments of the Fluvial System. D.D. Rhodes, and G.P. Williams (eds). Kendall Hunt Publishing, Dubuque, IA.

Keller, E.A., A. MacDonald, and T. Tally. 1982. Streams in the coastal redwood environment: the role of large organic debris. pp. 161-176. In: Proceedings of Watershed Rehabilitation in Redwood National Park and Other Pacific Coastal Areas. R.N. Coats (ed). Center for Natural Resource Studies of JMI, Inc., and the U.S. National Park Service. JMI, Inc., Berkeley, CA.

Keller, E.A., A. MacDonald, T. Tally, and N.J. Merritt. (In press). Effects of large organic debris on channel morphology and sediment storage in selected tributaries of Redwood Creek. K.M. Nolan, D.C. Marron, and H.M. Kelsey (eds). Submitted to U.S. Geological Survey Professional Paper 1454.

Koster, E.H. 1978. Transverse ribs: their characteristics, origin and paleohydraulic significance. In: Fluvial Sedimentology. Memoir No. 5. A.D. Maill (ed). Canadian Society of Petroleum Geologists, Calgary, Canada.

King, J.G., and L.C. Tennyson. 1984. Alteration of streamflow characteristics following road construction in north central Idaho. Water Res. Research 20:1159-1163.

Krag, R.K., E.A. Saunder, and G.U. Wellburn. 1986. A forest engineering analysis of landslides in logged areas of the Queen Charlotte Islands, British Columbia. Report 43. Forest Engineering Research Institute of Canada Land Management, Vancouver, British Columbia, Canada. 138 pp.

Lehre, A.K. 1987. Rates of soil creep on colluvium-mantled hillslopes in north-central California. pp. 91-100. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Lestelle, L. 1978. Effects of forest debris removal on a resident cutthroat trout population in a small headwater stream. Masters Thesis. University of Washington, Seattle, WA. 86 pp.

Lienkaemper, G.W., and F.J. Swanson. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. Can. J. For. Res. 17:150-156.

Lisle, T.E. 1986. Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California. Geol. Soc. Amer. Bull. 97:999-1011.

Lisle, T.E. 1987. Overview: channel morphology and sediment transport in steepland channels. pp. 287-297. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds.). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

MacDonald, A. (Unpublished). Data from Casper Creek (1979), Grider Creek (1981), and Lost Man Creek (1979-1982) watersheds, northwestern California.

MacDonald, A., and E.A. Keller. 1987. Stream channel response to the removal of large woody debris, Larry Damm Creek, northwestern California. pp. 405-406. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Madej, M.A. 1987. Residence times of channel-stored sediments in Redwood Creek, northwestern California. pp. 429-438. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Marron, D.C. 1985. Colluvium in bedrock hollows on steep slopes, Redwood Creek drainage basin, northwestern California. pp. 59-68. In: Soils and Geomorphology. Catena Supplement No. 6. P.D. Jungerius (ed). Catena Verlag, West Germany.

Marston, R.A. 1982. The geomorphic significance of log steps in forest streams. Ann. Am. Assoc. of Geographers 72:99-108.

McCashion, J.D., and R.M. Rice. 1983. Erosion on logging roads in northwestern California: how much is avoidable? J. Forestry 81:23-26.

Megahan, W.F. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho batholith. pp. 114-121. In: Sediment Budgets and Routing in Forested Drainage Basins. USDA Forest Service General Technical Report PNW-141. F.J. Swanson, R.J. Janda, T.Dunne, and D.N. Swanston (eds). U.S. Department of Agriculture, Washington, DC. 165 pp.

Megahan, W.F. 1983. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. Water Res. Research 19:811-819.

Megahan, W.F., and R.A. Nowlin. 1976. Sediment storage in channels draining small forested watersheds in the mountains of central Idaho. pp. 4-115 to 4-126. In: Proceedings of the Third Federal Interagency Sedimentation Conference, Denver, CO. U.S. Government Printing Office, Washington, DC.

Megahan, W.F., K.A. Seyedbagheri, and P.C. Dodson. 1983. Long-term erosion on granitic roadcuts based on exposed tree roots. Earth Processes and Landforms 8:19-28.

Megahan, W.F., K.A. Seyedbagheri, T.L. Mosko, and G.L. Ketcheson. 1986. Construction phase sediment budget for forest roads on granitic slopes in Idaho. pp. 31-39. In: Proceedings of the Albuquerque Symposium, Drainage Basin Sediment Delivery, 4-8 August 1986. IAHS Publication No. 159. R.F. Hadley (ed). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Milhous, R.T. 1987. Discussion of bedload discharge equations for steep mountain rivers. pp. 479-480. In: Sediment transport in gravel-bed rivers. J.C. Bathurst, C.R. Thorne, and R.D. Hey (eds). John Wiley and Sons, New York, NY.

Mosley, M.P. 1981. The influence of organic debris on channel morphology and bedload transport in a New Zealand forest stream. Earth Surface Processes and Landforms 6:571-579.

Nolan, K.M., and R.J. Janda. 1981. Use of short-term water and suspended-sediment discharge observations to assess impacts of logging on stream-sediment discharge in the Redwood Creek basin, northwestern California, U.S.A. pp. 415-437. In: Erosion and Sediment Transport in Pacific Rim Steeplands. IAHS-AISH Publication No. 132. T.R.H. Davies, and A.J. Pearce (eds). The Royal Society of New Zealand, New Zealand Hydrological Society, IAHS, and the National Water and Soil Conservation Authority of New Zealand.

Pearce, A.J., M.K. Stewart, and M.G. Sklash. 1986. Storm runoff generation in humid headwater catchments. 1. Where does the water come from? Water Res. Research 22:1263-1272.

Perkins, S.J. (In press). Landslide deposits in low-order streams--their erosion rates and effects on channel morphology. In: Proceedings, American Water Resource Conference On Headwaters Hydrology, Missoula, MT.

Piehl, B.T., M.R. Pyles, and R.L. Beschta. 1988. Flow capacity of culverts on Oregon Coast Range forest roads. Water Res. Bull. 24:631-637.

Pierson, T.C., and J.E. Costa. 1987. A rheologic classification of subaerial sediment-water flows. Geological Society of America. Reviews in Engineering Geology 7:1-12.

Pitlick, J. 1982. Organic debris in tributary stream channels of the Redwood Creek basin. pp. 177-190. In: Proceedings of the Watershed Rehabilitation in Redwood National Park and Other Pacific Coastal Areas. R.N. Coats (ed). Center for Natural Resource Studies of JMI, Inc., and the U.S. National Park Service. JMI, Inc., Berkeley, CA.

Pitlick, J. 1988. The response of coarse-bed rivers to large floods in California and Colorado. Ph.D. Dissertation. Colorado State University, Department of Earth Sciences, Fort Collins, CO. 137 pp.

Pyles, M.R., K. Mills, and G. Saunders. 1987. Mechanics and stability of the Lookout Creek earth flow. Bulletin of the Association of Engineering Geologists 24:267-280.

Reid, L.M. 1981. Sediment production from gravel-surfaced forest roads, Clearwater Basin, Washington. Masters Thesis. University of Washington, Seattle, WA. 247 pp.

Reid, L.M., and T. Dunne. 1984. Sediment production from forest road surfaces. Water Res. Research 20:1753-1761.

Reneau, S.L., W.E. Dietrich, M. Rubin, D.J. Donahue, and A.J.T. Jull. 1989. Analysis of hillslope erosion rates using dated colluvial deposits. J. Geol. 97:45-63.

Rice, R.M. 1981. Common and uncommon sense about erosional process in mountain lands. EOS, Transactions of the American Geophysical Union 62:855 [abs].

Roberts, R.G., and M. Church. 1986. The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia. Can. J. of Forest Res. 16:1092-1106.

Rothacher, J. 1970. Increases in water yield following clear-cut logging in the Pacific northwest. Water Res. Research 6:653-658.

Schulz, M.G. 1980. The quantification of soil mass movements and their relationship to bedrock geology in the Bull Run watershed, Multnomah and Clackamas counties, Oregon. Masters Thesis. Oregon State University, Corvallis, OR. 170 pp.

Scrivener, J.C. 1982. Logging impacts on the concentration patterns of dissolved ions in Carnation Creek, British Columbia. pp. 64-80. In: Proceedings of the Carnation Creek Workshop, a 10 Year Review. G. Hartman (ed). Malaspina College, Nanaimo, British Columbia, Canada.

Sidle, R.C. 1987. A dynamic model of slope stability in zero-order basins. pp. 101-110. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Sidle, R.C. 1988. Bed load transport regime of a small forest stream. Water Res. Research 24:207-218.

Sidle, R.C., and D.N. Swanston. 1986. Groundwater dynamics in unstable zero-order basins of coastal Alaska. EOS, Transactions of the American Geophysical Union 67:956 [abs].

Speaker, R., K. Moore, and S.V. Gregory. 1984. Analysis of the process of retention of organic matter in stream ecosystems. In: Proceedings of the International Association of Theoretical and Applied Limnology. 22:1835-1841.

Steinbrenner, E.C., and S.P. Gessel. 1955. The effect of tractor logging on physical properties of some forest soils in southwestern Washington. In: Proceedings of the Soil Science Society. 20:372-376.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. Am. Geophys. Union Trans. 38:913-920.

Sullivan, K. 1985. Long-term patterns of water quality in a managed watershed in Oregon: 1. suspended sediment. Water Res. Bull. 21:977-987.

Sullivan, K. 20 May 1989. Written Communication (letter to Ms. Anne MacDonald, PTI Environmental Services, Bellevue, WA). Weyerhaeuser Company, Tacoma, WA.

Sullivan, K., T.E. Lisle, C.A. Dolloff, G.E. Grant, and L.M. Reid. 1987a. Stream channels: the link between forests and fishes. pp. 39-97. In: Proceedings of the Symposium on Streamside Management--Forestry and Fisheries Interactions. Contribution No. 57. E.O. Salo, and T.W. Cundy (eds). University of Washington, Institute of Forest Resources, Seattle, WA.

Sullivan, K., S.H. Duncan, P.A. Bisson, J.T. Heffener, J.W. Ward, R.E. Bilby, and J.L. Nielson. 1987b. A summary report of the Deschutes River basin: sediment, flow, temperature and fish habitat. Weyerhaeuser Company, Technology Center, Tacoma, WA. 129 pp.

Swanson, F.J. 1981. Characteristics of forested mountain streams. EOS, Transactions of the American Geophysical Union 62:856 [abs].

Swanson, F.J., and G. Grant. 1982. Rates of soil erosion by surface and mass erosion process in the Willamette National Forest. Prepared for the Willamette National Forest. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Swanson, F.J., and G.W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific northwest streams. USDA Forest Service Technical Report PNW-69. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 12 pp.

Swanson, F.J., and G.W. Lienkaemper. 1985. Geologic zoning of slope movements in western Oregon, U.S.A. pp. 41-45. In: Proceedings of the IVth International Conference and Field Workshop on Landslides, Tokyo, Japan.

Swanson, F.J., and C.J. Roach. 1985. Frequency of debris avalanches from hollows in clearcuts, Siuslaw River basin, Oregon. EOS, Transactions of the American Geophysical Union 66:900 [abs].

Swanson, F.J., and C.J. Roach. 1987. Mapleton leave area study. Administrative Report. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Swanson, F.J., G.W. Lienkaemper, and J.R. Sedell. 1976. History, physical effects and management implications of large organic debris in western Oregon streams. USDA Forest Service General Technical Report PNW-56. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 15 pp.

Swanson, F.J., M.M. Swanson, and C. Woods. 1981. Analysis of debris-avalanche erosion in steep forest lands: and example from Mapleton, Oregon, USA. pp. 67-75. In: Erosion and Sediment Transport in Pacific Rim Steeplands. IAHS-AISH Publication No. 132. T.R.H. Davies, and A.J. Pearce (eds). The Royal Society of New Zealand, New Zealand Hydrological Society, IAHS, and the National Water and Soil Conservation Authority of New Zealand.

Swanson, F.J., R.L. Fredriksen, and F.M. McCorison. 1982. Material transfer in a western Oregon forested watershed. pp. 233-266 In: Analysis of Coniferous Forest Ecosystems in the Western United States. US/IBP Synthesis Series 14. R.L. Edmonds (ed). Hutchinson Ross, Stroudsburg, PA.

Swanson, F.J., M.S. Bryant, G.W. Lienkaemper, and J.R. Sedell. 1984. Organic debris in small streams, Prince of Wales Island, southeast Alaska. USDA Forest Service General Technical Report PNW-166. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Swanson, F.J., G.E. Grant, and G.W. Lienkaemper. 1987a. Field trip guide to the H.J. Andrews Experimental Forest. Presented at the International Symposium on Erosion and Sedimentation in the Pacific Rim. Oregon State University, Corvallis, OR. 46 pp.

Swanson, F.J., L.E. Benda, S.H. Duncan, G.E. Grant, W.F. Megahan, L.M. Reid, and R.R. Ziemer. 1987b. Mass failures and other processes of sediment production in Pacific northwest forest landscapes. pp. 9-38. In: Proceedings of the Symposium on Streamside Management--Forestry and Fisheries Interactions. Contribution No. 57. E.O. Salo, and T.W. Cundy (eds). University of Washington, Institute of Forest Resources, Seattle, WA.

Swanston, D., G.W. Lienkaemper, R.C. Mersereau, and A.B. Levno. 1988. Timber harvest and progressive deformation of slopes in southwestern Oregon. Bull. Asso. Eng. Geo. 25:371-381.

Tally, T. 1980. The effects of geology and large organic debris on stream channel morphology and processes for streams flowing through old-growth redwood forests in northwestern California. Ph.D. Dissertation. University of California at Santa Barbara, Santa Barbara, CA. 273 pp.

Tally, T., A. MacDonald, and E.A. Keller. 1980. The effects of large organic debris on sediment routing in redwood forest streams. Geological Society of America Abstracts with Programs 12:155 [abs].

Toews, D.A., and M.K. Moore. 1982. The effect of streamside logging on large organic debris in Carnation Creek. Publication R 28-81071. Province of British Columbia, Ministry of Forests, Victoria, British Columbia, Canada. 29 pp.

Troendle, C.A., and R.M. King. 1985. The effect of timber harvest on the Fool Creek watershed, 30 years later. Water Res. Research 21:1915-1922.

U.S. EPA. 1975. Logging roads and protection of water quality. Prepared in cooperation with Arnold, Arnold, and Associates, Seattle, WA and Dames & Moore, Seattle, WA. U.S. Environmental Protection Agency Region 10, Water Division, Seattle, WA.

U.S. EPA. 1976. Forest harvest, residue treatment, reforestation and protection of water quality. Prepared by James M. Montgomery, Consulting Engineers, Inc., Boise, ID. U.S. Environmental Protection Agency Region 10, Seattle, WA. 273 pp.

U.S. EPA. 1977. Silvicultural chemicals and protection of water quality. Prepared by Oregon State University, School of Forestry, Corvallis, OR. EPA 910/9-77-036. U.S. Environmental Protection Agency Region 10, Seattle, WA. 232 pp.

U.S. EPA. 1986. Quality criteria for water 1986. U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Washington, DC.

Washington State Forest Practices Board. 1988. Washington Forest Practices Rules and Regulations. Title 222 WAC, RCW 76.09, and Forest Practices Board Manual. Washington State Forest Practices Board, Olympia, WA.

Weaver, W., A. Choquette, D. Hagans, and J. Schlosser. 1981. Causes and rates of accelerated sediment production and yield, Copper Creek, northern California. EOS, Transactions of the American Geophysical Union 62:857 [abs].

Whittaker, J.G. 1987. Modelling bed-load transport in steep mountain streams. pp. 319-332. In: Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987. IAHS Publication No. 165. R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson (eds). IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England.

Whittaker, J.G., and M.N.R. Jaeggi. 1982. Origin of step-pool systems in mountain streams. J. Hydraulics Div. Amer. Soc. Civil Engineers. 108(HY6):758-773.

Wolfe, M.D., and J.W. Williams. 1986. Rates of landsliding as impacted by timber management activities in northwestern California. Bull. Asso. Eng. Geo. 23:53-60.

Wolman, M.G., and R. Gerson. 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes 3:189-208.

Ziemer, R.R. 1981. Storm flow response to road building and partial cutting in small streams of northern California. Water Res. Research 17:907-917.

APPENDIX A

QUESTIONNAIRE

SEDIMENT DYNAMICS IN TYPE 4 AND 5 WATERS

QUESTIONNAIRE - SEDIMENT DYNAMICS IN TYPE 4 AND 5 WATERS

PTI Environmental Services, of Bellevue, has been requested by the Sediment, Hydrology, and Mass Wasting Steering Committee of Cooperative Monitoring, evaluation, and research (CMER), to assess the state of knowledge of sediment dynamics of Type 4 and 5 Waters. This questionnaire is a tool in this effort. Our purpose is to query persons associated with the Timber, Fish, and Wildlife (TFW) Project throughout the State of Washington on 1) their assessment of patterns and magnitudes of sediment routing characteristic of their specific region, and 2) the recognized effects of timber harvest practices on sediment routing. Please respond to this questionnaire in your role as TFW participant.

PART I: RESPONDENT CHARACTERISTICS

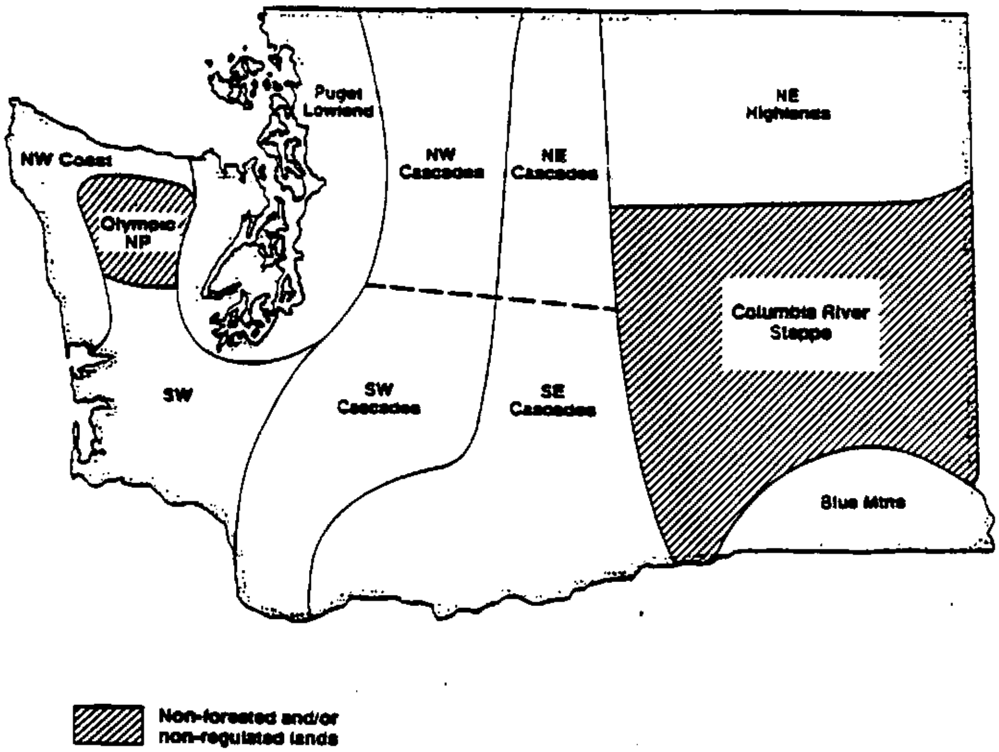
In order to better understand your responses to this questionnaire, please provide the following information on your background as it applies to your role in TFW. Multiple responses are requested where appropriate.

A. Circle the Washington Department of Natural Resources (DNR) region(s) in which you are available for TFW:
NE NW SE SPS OLY CEN SW All
B. Circle the constituency that you represent:
Tribal Agency(s) Private Industry Environmental Group
C. Who is your employer? ____________________
D. What is your job title? ____________________
E. What is your professional area of expertise (if different from job title)?
____
F. The average number of days per year which you spend in watersheds upstream of Type 3 Waters is:
<1 1-5 6-10 11-30 31-50 >50
G. Your years of experience observing sediment dynamics in the forests of the Pacific Northwest are: <1 1-2 3-5 6-10 11-20 >20
H. Your years of experience observing forest practices in Washington State are:
<1 1-2 3-5 6-10 11-20 >20
I. Would you prefer that your identity be kept confidential? Yes No
(If so, only information from Parts II - V will be made available to the SHAM Committee.)
J. Comments:

PART II: IDENTIFY PERTINENT REGIONAL CHARACTERISTICS AFFECTING SEDIMENT DYNAMICS IN TYPE 4 AND 5 WATERS

For the area with which you are most familiar, (see ecoregions on the map below), please rank the dominant mode(s) of processes/characteristics that control sediment generation and transport in portions of watersheds drained exclusively by Type 4 and 5 Waters. Based on your experience, please check all responses that apply, because ecoregions are not homogeneous with respect to characteristics that influence sediment dynamics, several answers may apply to the region you know best. If multiple responses are apropos, then please give a rank of "1" to the most important process, "10" to the least important processes, and "0" to those processes which do not apply to your area. If you do not fully understand a question or statement, please use the comment section liberally. Do not feel that you have to answer all questions; only answer those questions that you feel comfortable. If you are very familiar with more than one region, please respond to the duplicate of Parts II through Parts IV of this questionnaire. (The duplicate section is identified with "Ecoregion #2" at the bottom right corner of the page).

Simplified Forest "Ecoregions"



This ecoregion map has been adapted from one constructed by the U.S. Environmental Protection Agency (EPA), and is based upon the differences in topography, geology and climate (and therefore vegetation) Washington State. These ecoregions are not the same as DNR regions. In general, boundaries between regions are not sharp; nonetheless, it is most likely that you as an individual will have most of your experience in only one or two of these ecoregions. For additional ease, consider the following region descriptions:

NW Coast:	Primarily north and west coast of the Olympic Peninsula, may have glacial influence
SW:	Portions of DNR SW and CEN regions west of the Cascade Foothills, distinguished from Puget Lowland by being unglaciated
Puget Lowland:	Affected by continental glaciation, from the Olympic foothills to the Cascade foothills
NW Cascades:	North of I-90 and west of the Cascade crest
SW Cascades:	South of I-90 and west of the Cascade crest
NE Cascades:	North of I-90 and east of the Cascade crest to the Okanogan-Methow/ Salmon Cr. divide
SE Cascades:	South of I-90 and east of the Cascade crest
NE Highlands:	East of the Okanogan-Methow/Salmon Cr. divide (approx. Conconully)

PART II. [ctd.]
A. Area Name, Location:________________________________

B. Runoff Generation Results From:
_______ High intensity, short duration rainfall events, high soil moisture (usually winter)
_______ High intensity, short duration rainfall events, low soil moisture (usually summer)
_______ Moderate intensity, longer duration rainfall events, high soil moisture (usually winter)
_______ Rainfall on snowpack events (mid-winter thaws)
_______ Spring snowmelt
_______ Other (please describe):

C. Bankfull*/Overbank Flooding Frequency, Duration and Magnitude in Type 4 and 5 Waters (choose one in each group): [*Bankfull is the ordinary high water mark, or the top of a prominent break in slope between the channel banks and other streamside or hillslope surfaces, and is usually accompanied by a change in vegetation (little or none to perennial) and the presence of organic topsoil.]
1. Frequency:
_______ Frequent (more than once per year)
_______ Moderate (once every one to three years)
_______ Infrequent (less than once per three years)
2. Duration:
_______ Short duration (less than a day for each main event)
_______ Moderate duration (one to two days in a row)
_______ Long duration (more than two days in a row)
3. Magnitude:
_______ Rarely overbank
_______ Often overbank but rarely to valley sides
_______ Often flooded across valley if valley is present
4. Bankfull width of Type 4 Waters:
_______ Less than 0.5 meters (1.6 ft)
_______ 0.5 - 1 meters (1.6 - 3.3 ft)
_______ 1 - 2 meters (3.3 - 6.5 ft)
_______ 2 - 4 meters (6.5 - 13 ft)
_______ Greater than 4 meters (13 ft)

D. Topography in Small Watersheds:
1. Hillslope topography in the portion of the watershed drained by Type 4 and 5 Waters:
_______ Oversteepened (> 30 ° or 60%)
_______ Steep, straight hillslopes throughout (16° - 30° or 30% - 60%)
_______ Steep hillslopes near channels ("inner gorge") with gentler divides (convex)
_______ Moderate, straight slopes throughout (6° - 16° or 10% - 30%)
_______ Moderate to gentle (< 16° or 30%), concave to convex from divide to channel
_______ Other (please describe):
2. Channel topography of Type 5 Waters:
_______ Very steep (> 11° or 20%)
_______ Steep (8° - 11° or 14% - 20%)
_______ Moderately steep (3.6° - 8° or 6% - 14%)
_______ Moderate (0.6° - 3.6° or 1% - 6%)
_______ Gentle (< 0.6° or 1%)
_______ Other (please describe):
3. Channel topography of Type 4 Waters:
_______ Very steep (> 11° or 20%)
_______ Steep (8° - 11° or 14% - 20%)
_______ Moderately steep (3.6° - 8° or 6% - 14%)
_______ Moderate (0.6° - 3.6° or 1% - 6%)
_______ Gentle (< 0.6° or 1%)
_______ Other (please describe):

Ecoregion #1: ________________

E. Regional Geology and Soils:

1. Geology:

________ Volcanic - chiefly basalt (black or green-black)
________ Volcanic - non-basalt (gray, pink, gray-green)
________ Metamorphic - fine grained
________ Metamorphic or igneous ultramafic (e.g., serpentine)
________ Metamorphic - coarse grained (looks like granitic rocks)
________ Granite or granite-like
________ Sedimentary (sandstones, siltstones)
________ Unconsolidated sediments (e.g., glacial till, lake sediments, outwash sands/gravels)
________ Unknown/other (please specify):

2. Glaciation:

________ Continental
________ Alpine or valley glaciers
________ Unglaciated
________ Unknown/ other (please specify):

3. Soils in watersheds drained by Type 4 and 5 Waters:

a. Thickness:

________ Thick (> 1 meter [3 ft] from surface to unweathered rock/sediments)
________ Moderate (0.5 to 1 meters from surface to unweathered rock/sediments)
________ Thin (< 0.5 meters from surface to unweathered rock/sediments)

b. Texture:

________ Sandy, loose, coarse grained
________ Silty
________ Clayey, cohesive, fine grained
________ Other (please describe):

F. Forest Type [zones after Franklin and Dyrness (1973), Natural Vegetation of Oregon and Washington, with climax specie(s) listed first, followed by major non-climax species):

________ Sitka spruce dominated (Douglas fir, western red cedar and western hemlock)
________ Western hemlock with Douglas fir and western red cedar
________ True firs (Pacific silver fir, noble fir, subalpine fir) with Douglas fir, western or mountain hemlock and Alaska cedar
________ Subalpine fir and Engelmann spruce
________ Western hemlock, Douglas fir, western white pine, and grand or white fir
________ Grand or white fir, incense-cedar, western larch, lodgepole pine, western white pine, ponderosa pine
________ Douglas fir, lodgepole pine, ponderosa pine, western larch, incense-cedar
________ Ponderosa pine
________ Mixed hardwood (alder, maple) and conifer
________ Other (please specify):

G. Timber Harvest Practices Previously and Currently in Use (mark old practices that no longer occur with a "a"):

1. Most recent past peak harvest years in current rotation: ____________________

2. Harvest method:

________ Clearcut
________ Selective cut
________ Partial cut (volume reduction)
________ Other (please specify):

3. Yarding practice:

________ Tractor, skidder
________ Shovel
________ High lead cable
________ Helicopter/ balloon
________ Other (please specify):

4. Road construction:
________ Pre-Forest Practices Act (1974; final regulations 1976)
________ 1974 Forest Practices Act to TFW (1988)
________ Post TFW
________ Dominantly on ridgelines
________ On ridgelines and in valleys
________ Throughout upper watershed (i.e., midslope with numerous channel/swale crossings)
________ Many landings
________ Few landings
________ Road length per unit area (miles per square mile)
________ Other construction practices (e.g., compaction, fill vs. cut percentage)

5. Road maintenance with respect to grading, runoff control, culvert maintenance:
________ Well maintained after logging
________ Poorly maintained/orphaned after logging
________ Abandoned after logging

6. Burning:
________ Prescribed
________ Accidental

7. Comments on timber harvest practices in your region of primary expertise:

PART III: IDENTIFY PERTINENT REGIONAL PATTERNS OF SEDIMENT DYNAMICS

In this section, please concentrate as much as possible on portions of stream channels that have not been disturbed by timber harvest and related activities. The goal of this section is to tie controlling physical, biological and management patterns in each region to observed sediment dynamics, based upon the observations of personnel in the field (you). Please rank the processes that you have observed in order of importance, with "1" being the most important, "10" being the least important, and "0" ranking for those that you have not observed in your region. "Important" is a combination of both magnitude and frequency of these processes. For example, processes that deliver only a small volume of sediment infrequently to Type 4 and 5 Waters are least important, while processes that frequently deliver a great deal of sediment to these channels are very important.

A. What percentage of your region is in an undisturbed or minimally disturbed state? __________

B. Sediment delivery process(es) to **Type 4 and 5 Waters:**

1. Process categories:
________ Debris torrent (dominantly within existing channel)
________ Debris flow/avalanche (generally not within a channel)
________ Translational landslide (shallow with failure surface parallel to land surface)
________ Rotational landslide (deep with an arcuate failure surfaces)
________ Long reaches of eroded stream banks due to channel widening
________ Long reaches of eroded stream banks/bed due to channel incision
________ Accelerated soil creep
________ Dry soil fall (ravel)
________ Other (please specify):

2. Please comment on the magnitude of the two most important processes:

Ecoregion #1: ________________

3. Please comment on the frequency of occurrence (in time and space) of the two most important processes:

C. Sediment storage processes/patterns within **Type 4 and 5 Waters:**

1. Sediment storage processes/patterns:

________ Sediment stored behind obstructions (e.g., log jams, boulder steps) with pools common upstream and downstream of obstruction

________ Sediment stored behind obstructions with upstream pools filled

________ Sediment stored in bars not related to obstructions

________ Sediment stored in deposits flanking the channel (e.g., terraces, floodplain)

________ Sediment stored below channel bed (e.g., few exposures of bedrock/unweathered sediments in channel bed)

2. Please comment on the magnitude of the three most important processes/patterns:

3. Please comment on the frequency of occurrence (in time and space) of the three most important processes/patterns:

4. Which, if any, of the processes above are particularly widespread in your region?

5. Which, if any, of the processes above do not seem to occur in your region?

D. To which physical and biological characteristics of your ecoregion do you attribute these patterns of sediment delivery and storage?

E. Based upon your observations, how efficiently do **Type 4 and 5 Waters** appear to transport sediment to Type 3 and larger waters? (Efficiency is a measure of the percent of sediment moved out per unit input per year.)

F. Based upon your observations, how quickly do **Type 4 and 5 Waters** recover from floods, landslides, and other extreme events? Please be as specific as possible. If you have not had a chance to observe at least one case of channel recovery, please move on to the next section.

Ecoregion #1: ________________

PART IV: IDENTIFY EFFECTS OF TIMBER HARVEST PRACTICES ON SEDIMENT DYNAMICS OF TYPE 4 AND 5 WATERS

The goal of this section of the questionnaire is to examine the effects of timber harvest practices on **Type 4 and 5 Waters**. Except where noted, please try to consider only those practices that are currently approved (rather than those commonplace prior to 1974).

A. Regarding water quality:

1. What, if any, effects have timber harvest practices had on water quality in **Type 4 and 5 Waters**?

2. On which data or observations do you base this conclusion? Please note any causal relationships between a particular practice and its effect on these channels.

3. How long do these changes seem to persist after logging?

B. Regarding sediment production:

1. What, if any, effects have timber harvest practices had on sediment delivery to **Type 4 and 5 Waters**? (For a list of processes, refer back to Part III-A.)

2. On which data or observations do you base this conclusion? Please note any causal relationships between a particular practice and its effect on these channels.

3. What, if any, effects have timber harvest practices had on sediment storage within channels of **Type 4 and 5 Waters**? (For a list of processes, refer back to Part III-B.)

4. On which data or observations do you base this conclusion? Please note any causal relationships between a particular practice and its effect on these channels.

5. How long do these changes seem to persist after logging?

C. Regarding large organic debris:

1. What, if any, effects have yarding, channel cleaning, or road construction practices had on patterns of large organic debris delivery or in-channel redistribution in **Type 4 and 5 Waters**?

2. On which data or observations do you base this conclusion? Please note any causal relationships between a particular practice and its effect on these channels.

Ecoregion #1: ____________________

3. How long do these changes seem to persist after logging?

D. Regarding water quantity and routing:

1. What, if any, effects have timber harvest practices had on the amount or timing of runoff events in **Type 4 and 5 Waters**?

2. On which data or observations do you base this conclusion? Please note any causal relationships between a particular practice and its effect on these channels.

3. How long do these changes seem to persist after logging?

E. Regarding changes in timber harvest practices in the last decade:

1. How effective are recent (post-Forest Practices Act) changes in timber harvest practices (including road building, yarding, slash and large organic debris management) in reducing sediment delivery from **Type 4 and 5 Waters** to **Type 1-3 Waters**?

2. How effective are current (post-TFW) practices at minimizing disturbance within **Type 4 and 5 Waters**?

3. Are there any present limitations on timber harvest practices affecting sediment dynamics in **Type 4 and 5 Waters** that are ineffective and should be dropped? If so, why?

4. Are there any present limitations on timber harvest practices affecting sediment dynamics in **Type 4 and 5 Waters** that are ineffective and should be strengthened? If so, why?

F. Additional comments on the link between timber harvest practices and sediment dynamics in **Type 4 and 5 Waters**:

Ecoregion #1: ____________________

PART V: TOOLS AND INFORMATION NEEDS IN MANAGEMENT OF TYPE 4 AND 5 WATERS

A. Management Tools:
   1. How useful are the DNR soil surveys in making slope stability and management recommendations for hillslopes adjacent to Type 4 and 5 Waters? Why?

   2. What additional management tools are necessary to better manage Type 4 and 5 Waters?

B. Direction of CMER research on Type 4 and 5 Waters:
   1. What information about these channels are you lacking which is necessary for management purposes?

   2. What study topics, particular to your region, should be pursued in the purpose of improving management of Type 4 and 5 Waters?

C. Additional comments:

THANK YOU FOR YOUR EFFORTS!

PART II. **Additional Ecoregion**

A. Area Name, Location:____

B. Runoff Generation Results From:

________ High intensity, short duration rainfall events, high soil moisture (usually winter)
________ High intensity, short duration rainfall events, low soil moisture (usually summer)
________ Moderate intensity, longer duration rainfall events, high soil moisture (usually winter)
________ Rainfall on snowpack events (mid-winter thaws)
________ Spring snowmelt
________ Other (please describe):

C. Bankfull*/Overbank Flooding Frequency, Duration and Magnitude in Type 4 and 5 Waters (choose one in each group): [*Bankfull is the ordinary high water mark, or the top of a prominent break in slope between the channel banks and other streamside or hillslope surfaces, and is usually accompanied by a change in vegetation (little or none to perennial) and the presence of organic topsoil.]

1. Frequency:

________ Frequent (more than once per year)
________ Moderate (once every one to three years)
________ Infrequent (less than once per three years)

2. Duration:

________ Short duration (less than a day for each main event)
________ Moderate duration (one to two days in a row)
________ Long duration (more than two days in a row)

3. Magnitude:

________ Rarely overbank
________ Often overbank but rarely to valley sides
________ Often flooded across valley if valley is present

4. Bankfull width of Type 4 Waters:

________ Less than 0.5 meters (1.6 ft)
________ 0.5 - 1 meters (1.6 - 3.3 ft)
________ 1 - 2 meters (3.3 - 6.5 ft)
________ 2 - 4 meters (6.5 - 13 ft)
________ Greater than 4 meters (13 ft)

D. Topography in Small Watersheds:

1. Hillslope topography in the portion of the watershed drained by Type 4 and 5 Waters:

________ Oversteepened (> 30 ° or 60%)
________ Steep, straight hillslopes throughout (16° - 30° or 30% - 60%)
________ Steep hillslopes near channels ("inner gorge") with gentler divides (convex)
________ Moderate, straight slopes throughout (6° - 16° or 10% - 30%)
________ Moderate to gentle (< 16° or 30%), concave to convex from divide to channel
________ Other (please describe):

2. Channel topography of Type 5 Waters:

________ Very steep (> 11° or 20%)
________ Steep (8° - 11° or 14% - 20%)
________ Moderately steep (3.6° - 8° or 6% - 14%)
________ Moderate (0.6° - 3.6° or 1% - 6%)
________ Gentle (< 0.6° or 1%)
________ Other (please describe):

3. Channel topography of Type 4 Waters:

________ Very steep (> 11° or 20%)
________ Steep (8° - 11° or 14% - 20%)
________ Moderately steep (3.6° - 8° or 6% - 14%)
________ Moderate (0.6° - 3.6° or 1% - 6%)
________ Gentle (< 0.6° or 1%)
________ Other (please describe):

Ecoregion #2: ____________________

E. Regional Geology and Soils:

1. Geology:

________ Volcanic - chiefly basalt (black or green-black)
________ Volcanic - non-basalt (gray, pink, gray-green)
________ Metamorphic - fine grained
________ Metamorphic or igneous ultramafic (e.g., serpentine)
________ Metamorphic - coarse grained (looks like granitic rocks)
________ Granite or granite-like
________ Sedimentary (sandstones, siltstones)
________ Unconsolidated sediments (e.g., glacial till, lake sediments, outwash sands/gravels)
________ Unknown/other (please specify):

2. Glaciation:

________ Continental
________ Alpine or valley glaciers
________ Unglaciated
________ Unknown/ other (please specify):

3. Soils in watersheds drained by **Type 4 and 5 Waters:**

a. Thickness:

________ Thick (> 1 meter [3 ft] from surface to unweathered rock/sediments)
________ Moderate (0.5 to 1 meters from surface to unweathered rock/sediments)
________ Thin (< 0.5 meters from surface to unweathered rock/sediments)

b. Texture:

________ Sandy, loose, coarse grained
________ Silty
________ Clayey, cohesive, fine grained
________ Other (please describe):

F. Forest Type [zones after Franklin and Dyrness (1973), Natural Vegetation of Oregon and Washington, with climax specie(s) listed first, followed by major non-climax species):

________ Sitka spruce dominated (Douglas fir, western red cedar and western hemlock)
________ Western hemlock with Douglas fir and western red cedar
________ True firs (Pacific silver fir, noble fir, subalpine fir) with Douglas fir, western or mountain hemlock and Alaska cedar
________ Subalpine fir and Engelmann spruce
________ Western hemlock, Douglas fir, western white pine, and grand or white fir
________ Grand or white fir, incense-cedar, western larch, lodgepole pine, western white pine, ponderosa pine
________ Douglas fir, lodgepole pine, ponderosa pine, western larch, incense-cedar
________ Ponderosa pine
________ Mixed hardwood (alder, maple) and conifer
________ Other (please specify):

G. Timber Harvest Practices Previously and Currently in Use (mark old practices that no longer occur with a "a"):

1. Most recent past peak harvest years in current rotation: ____________________

2. Harvest method:

________ Clearcut
________ Selective cut
________ Partial cut (volume reduction)
________ Other (please specify):

3. Yarding practice:

________ Tractor, skidder
________ Shovel
________ High lead cable
________ Helicopter/ balloon
________ Other (please specify):

Ecoregion #2: ____________________

4. Road construction:
________ Pre-Forest Practices Act (1974; final regulations 1976)
________ 1974 Forest Practices Act to TFW (1988)
________ Post TFW
________ Dominantly on ridgelines
________ On ridgelines and in valleys
________ Throughout upper watershed (i.e., midslope with numerous channel/swale crossings)
________ Many landings
________ Few landings
________ Road length per unit area (miles per square mile)
________ Other construction practices (e.g., compaction, fill vs. cut percentage)
5. Road maintenance with respect to grading, runoff control, culvert maintenance:
________ Well maintained after logging
________ Poorly maintained/orphaned after logging
________ Abandoned after logging
6. Burning:
________ Prescribed
________ Accidental
7. Comments on timber harvest practices in your region of primary expertise:

PART III: IDENTIFY PERTINENT REGIONAL PATTERNS OF SEDIMENT DYNAMICS FOR ADDITIONAL ECOREGION

In this section, please concentrate as much as possible on portions of stream channels that have not been disturbed by timber harvest and related activities. The goal of this section is to tie controlling physical, biological and management patterns in each region to observed sediment dynamics, based upon the observations of personnel in the field (you). Please rank the processes that you have observed in order of importance, with "1" being the most important, "10" being the least important, and "0" ranking for those that you have not observed in your region. "Important" is a combination of both magnitude and frequency of these processes. For example, processes that deliver only a small volume of sediment infrequently to **Type 4 and 5 Waters** are least important, while processes that frequently deliver a great deal of sediment to these channels are very important.

A. What percentage of your region is in an undisturbed or minimally disturbed state? ________

B. Sediment delivery process(es) to **Type 4 and 5 Waters:**
1. Process categories:
________ Debris torrent (dominantly within existing channel)
________ Debris flow/avalanche (generally not within a channel)
________ Translational landslide (shallow with failure surface parallel to land surface)
________ Rotational landslide (deep with an arcuate failure surfaces)
________ Long reaches of eroded stream banks due to channel widening
________ Long reaches of eroded stream banks/bed due to channel incision
________ Accelerated soil creep
________ Dry soil fall (ravel)
________ Other (please specify):
2. Please comment on the magnitude of the two most important processes:

Ecoregion #2: ________________

3. Please comment on the frequency of occurrence (in time and space) of the two most important processes:

C. Sediment storage processes/patterns within **Type 4 and 5 Waters:**

1. Sediment storage processes/patterns:

________ Sediment stored behind obstructions (e.g., log jams, boulder steps) with pools common upstream and downstream of obstruction
________ Sediment stored behind obstructions with upstream pools filled
________ Sediment stored in bars not related to obstructions
________ Sediment stored in deposits flanking the channel (e.g., terraces, floodplain)
________ Sediment stored below channel bed (e.g., few exposures of bedrock/unweathered sediments in channel bed)

2. Please comment on the magnitude of the three most important processes/patterns:

3. Please comment on the frequency of occurrence (in time and space) of the three most important processes/patterns:

4. Which, if any, of the processes above are particularly widespread in your region?

5. Which, if any, of the processes above do not seem to occur in your region?

D. To which physical and biological characteristics of your ecoregion do you attribute these patterns of sediment delivery and storage?

E. Based upon your observations, how efficiently do **Type 4 and 5 Waters** appear to transport sediment to Type 3 and larger waters? (Efficiency is a measure of the percent of sediment moved out per unit input per year.)

F. Based upon your observations, how quickly do **Type 4 and 5 Waters** recover from floods, landslides, and other extreme events? Please be as specific as possible. If you have not had a chance to observe at least one case of channel recovery, please move on to the next section.

PART IV: IDENTIFY EFFECTS OF TIMBER HARVEST PRACTICES ON SEDIMENT DYNAMICS OF TYPE 4 AND 5 WATERS FOR ADDITIONAL ECOREGION

The goal of this section of the questionnaire is to examine the effects of timber harvest practices on **Type 4 and 5 Waters.** Except where noted, please try to consider only those practices that are currently approved (rather than those commonplace prior to 1974).

A. Regarding water quality:
   1. What, if any, effects have timber harvest practices had on water quality in **Type 4 and 5 Waters?**
   2. On which data or observations do you base this conclusion? Please note any causal relationships between a particular practice and its effect on these channels.
   3. How long do these changes seem to persist after logging?

B. Regarding sediment production:
   1. What, if any, effects have timber harvest practices had on sediment delivery to **Type 4 and 5 Waters?** (For a list of processes, refer back to Part III-A.)
   2. On which data or observations do you base this conclusion? Please note any causal relationships between a particular practice and its effect on these channels.
   3. What, if any, effects have timber harvest practices had on sediment storage within channels of **Type 4 and 5 Waters?** (For a list of processes, refer back to Part III-B.)
   4. On which data or observations do you base this conclusion? Please note any causal relationships between a particular practice and its effect on these channels.
   5. How long do these changes seem to persist after logging?

C. Regarding large organic debris:
   1. What, if any, effects have yarding, channel cleaning, or road construction practices had on patterns of large organic debris delivery or in-channel redistribution in **Type 4 and 5 Waters?**

Ecoregion #2: ____________________

2. On which data or observations do you base this conclusion? Please note any causal relationships between a particular practice and its effect on these channels.

3. How long do these changes seem to persist after logging?

D. Regarding water quantity and routing:
   1. What, if any, effects have timber harvest practices had on the amount or timing of runoff events in **Type 4 and 5 Waters?**

   2. On which data or observations do you base this conclusion? Please note any causal relationships between a particular practice and its effect on these channels.

   3. How long do these changes seem to persist after logging?

E. Regarding changes in timber harvest practices in the last decade:
   1. How effective are recent (post-Forest Practices Act) changes in timber harvest practices (including road building, yarding, slash and large organic debris management) in reducing sediment delivery from **Type 4 and 5 Waters** to **Type 1-3 Waters?**

   2. How effective are current (post-TFW) practices at minimizing disturbance within **Type 4 and 5 Waters?**

   3. Are there any present limitations on timber harvest practices affecting sediment dynamics in **Type 4 and 5 Waters** that are ineffective and should be dropped? If so, why?

   4. Are there any present limitations on timber harvest practices affecting sediment dynamics in **Type 4 and 5 Waters** that are ineffective and should be strengthened? If so, why?

F. Additional comments on the link between timber harvest practices and sediment dynamics in **Type 4 and 5 Waters:**

Ecoregion #2: ____________________