97

TFW-AM9-97-002

Literature Review and Monitoring Recommendations: Trends in Disturbance and Recovery of Selected Salmonid Habitat Attributes Related to Forest Practices

by

Amy Morgan
Devin Smith

October 1997

Trends in Disturbance and Recovery of Selected Salmonid Habitat Attributes Related to Forest Practices:

A Literature Review and Monitoring Recommendations

Amy Morgan and Devin Smith
TFW Monitoring Program
Northwest Indian Fisheries Commission
October 1997

Table of Contents

I. INTRODUCTION **1**

II. DISTURBANCE AND RECOVERY FRAMEWORK **2**

STREAM HABITAT ATTRIBUTES 2
WATERSHED AND CHANNEL PROCESSES 3
STRESSORS 7
DISTURBANCE 7
RECOVERY 7
INCORPORATING DISTURBANCE/RECOVERY THEORIES INTO SALMONID HABITAT MONITORING . 8

III. FINE AND COARSE SEDIMENT **10**

INTRODUCTION 10
RELATION OF SEDIMENT TO HABITAT ATTRIBUTES 10
PROCESSES AFFECTING THE DELIVERY OF SEDIMENT AND ITS ROUTING IN THE CHANNEL 11
Delivery Processes *11*
Routing Processes *14*
Effect of Forest Practices on Sediment Delivery and Routing *15*
CASE STUDIES 16
Sediment Budgets *16*
Northern California Coast Ranges/Redwood Creek *18*
South Fork Salmon River *19*
MODELS 20
DISCUSSION AND CONCLUSIONS 21
RECOMMENDATIONS FOR HABITAT ASSESSMENT AND MONITORING 22

IV. LARGE WOODY DEBRIS (LWD) **24**

RELATION OF LWD TO HABITAT ATTRIBUTES 24
DELIVERY PROCESSES 25
ROUTING PROCESSES 26
CASE STUDIES 27
Delivery *29*
Persistence and Decay rates *30*
MODELS 30
NATURAL DISTURBANCE/RECOVERY REGIMES 33
MANAGEMENT INDUCED DISTURBANCE AND RECOVERY 34
MONITORING VARIABLES/CONCEPTS 35
RECOMMENDATIONS FOR HABITAT ASSESSMENT AND MONITORING 35

V. STREAM TEMPERATURE **37**

RELATION OF TEMPERATURE TO HABITAT ATTRIBUTES 37
PROCESSES AFFECTING THERMAL ENERGY DELIVERY TO STREAMS AND RESULTING WATER TEMPERATURE CHANGES 38
CASE STUDIES 39

MODELS .... i 40
MANAGEMENT INDUCED DISTURBANCE AND RECOVERY 41
MONITORING VARIABLES/CONCEPTS 42
RECOMMENDATIONS FOR HABITAT ASSESSMENT AND MONITORING 42

VI. PEAK DISCHARGE 44

RELATION OF PEAK FLOWS TO HABITAT ATTRIBUTES 44
PROCESSES AFFECTING DELIVERY AND ROUTING OF INCREASED PEAK FLOWS 44
CASE STUDIES 44
MANAGEMENT INDUCED DISTURBANCE AND RECOVERY 45
MONITORING VARIABLES/CONCEPTS 46
RECOMMENDATIONS FOR HABITAT ASSESSMENT AND MONITORING 46

REFERENCES 48

I. Introduction

Management of salmonid habitat on forest lands in the Pacific Northwest requires an understanding of the complex relationships between watershed conditions, stream channel processes, and fish habitat requirements. Management is especially challenging because channel and habitat conditions change over time in response to a wide range of natural disturbances, human activities, and normal environmental fluctuations. Consequently, monitoring trends in salmonid habitat and stream channel conditions; is an important aspect of habitat management. It allows managers to document habitat changes that affect fish populations over time and to track patterns of disturbance and recovery in response to natural events or human activities. This kind of monitoring can also be used to evaluate the effectiveness of habitat management programs.

Successful habitat monitoring requires knowledge of channel and habitat disturbance and recovery patterns, the factors that control them, and the time frames on which they operate. This literature review provides information to assist the design of programs to monitor habitat disturbance and recovery trends in streams affected by forest management. It is guided by the following questions:

1) What disturbances to salmonid stream habitat are associated with forestry practices?
2) How long does it take stream habitat to recover from these disturbances?
3) How has stream habitat recovery been monitored?
4) How can this information be incorporated in the design of trend monitoring programs?

In order to answer these questions, a process-based framework has been developed for interpreting patterns of disturbance and recovery in freshwater salmonid habitat that may result from forest practices. This frame work is presented below, and is used to examine disturbance and recovery trends for four specific groups of watershed inputs: 1) fine and coarse sediment; 2) large woody debris (LWD); 3) stream temperature or the input of thermal energy; and 4) peak flows. For each watershed input, relationships with habitat attributes, processes controlling delivery and routing, and specific forest practices that can have an impact are reviewed. Additionally, case studies and models of habitat disturbance and recovery are summarized, general conclusions about the rates of disturbance and recovery are discussed, and recommendations for designing trend monitoring studies are presented.

II. Disturbance and Recovery Framework

Habitat disturbance and recovery occurs through the interaction of channel and watershed processes operating over a range of temporal scales. In many cases, forest practices that take Place on a hill slope may result in habitat disturbances in stream channels that are far removed in time and space. Designing a program to monitor trends in habitat disturbance and recovery requires an understanding the connections between forest practices, watershed and channel processes, and habitat conditions. In order to develop a framework for interpreting these connections, a brief overview of stream habitat attributes and watershed processes is provided here, followed by a review of theoretical approaches to habitat disturbance and recovery.

Stream Habitat Attributes

Salmonids have an anadromous life-cycle, meaning they are born in freshwater streams, spend a portion of their adult life in the ocean, and return to the stream of their origin to spawn. The unique habitat requirements for each life history stage vary widely by species and stock, but some essential habitat attributes can be identified. Habitat attributes that are important during the freshwater life history stage can be divided into those needed for upstream migration, spawning and incubation, and rearing.

Desirable habitat for fish migrating upstream to spawn consists of holding pools out of the main flow that allow fish to expend less energy to maintain position. These pools, which are often formed by LWD, should be deep and have cool temperatures. Migrating fish also require cover from undercut banks, overhanging vegetation, or LWD to provide protection from predators. Upstream migration can be affected by lack of connectivity between holding pools, increased water temperatures, or migration blockages such as culverts or dams. Low stream flows can interfere with migration because of increased temperature and predation, limited access to spawning sites, and deficiency of dissolved oxygen (Wickett 1958; Murphy 1985).

Spawning fish excavate redds in submerged gravel bars, where eggs are deposited, fertilized, buried, and then left to incubate until they emerge as fry several months later. Spawning sites require particles of a suitable size for redd construction, cool water temperatures, and sufficient water depth and velocity (McNeil 1962). Productive incubation habitat consists of stable streambed gravel that has a steady flow of oxygenated water (McNeil 1966). Movement of the stream bed during the incubation period can lead to mortality caused by physical injury to the eggs or mechanical shock (Bjornn and Reiser 1991). Fine sediments can cause mortality by reducing the flow of oxygen-bearing water through the gravel and blocking interstitial spaces between gravel particles needed by emerging fry (Scrivener and Brownlee 1989; Platts et al. 1989).

After emerging from the gravel, juveniles of different species spend varying amounts of time in fresh water before migrating to the ocean. During this rearing stage, juveniles of some species require a sufficient number and volume of pools with adequate cover and cool temperatures, and a good supply of food and nutrients (Groot and Margolis 1991). Species, such as coho, that over-winter before migration also benefit from off-channel habitat that provides protection during high flows (Peterson and Reid 1984).

Watershed and Channel Processes

Stream habitat attributes are controlled by watershed and channel processes. Through the interaction of these processes, the impacts of forest practices that take place throughout a watershed can be delivered to the stream channel, and then routed downstream over time, ultimately resulting in habitat disturbances. Understanding the linkages between these processes is essential for successfully monitoring trends in habitat disturbance and recovery.

A watershed is the geographic area drained by a network of streams that lead to a single outlet. Within a watershed, streams are formed by the movement of surface water through well-defined channels. The watershed provides water, sediment, and wood to these channels through a variety of input processes, including runoff, mass wasting, erosion, and wind throw. The characteristics of riparian vegetation in a watershed also influence inputs of nutrients and solar radiation. The magnitude and frequency of watershed inputs to stream channels can be altered by forest practices. While water, nutrients, and thermal energy are generally supplied to channels continuously, the delivery of wood and sediment generally occurs episodically, in conjunction with large storm events.

Once in the channel, inputs supplied from the watershed are routed progressively downstream at a variety of temporal scales (Table 1), forming both channel and habitat features. Water moves through a channel rather quickly, while wood and sediment are moved episodically, usually in conjunction with peak flow events. Forest practices that alter the intensity or timing of peak flows or the quantity of inputs will alter routing processes, channel morphology, and habitat conditions. Routing is also influenced by local channel factors such as gradient, confinement, and the composition of the bed and banks. Through channel routing processes, disturbances to watershed inputs or processes that are delivered to the channel in one location are transferred downstream over time.

Table 2-1. Approximate ranges of recurrence of major disrupting events and the effects of these events on channel and habitat conditions in streams (from Swanston [1991]).

Event	**Range of Recurrence (years)**	**Inputs** Affected	**Channel Changes**	Habitat Effects
Daily to weekly precipitation and discharge	0.01 - 0.1	rater, sediment, LWD --	Channel width and depth; movement and deposition of fine woody debris; fine sediment transport and deposition	Minor siltation of spawning gravels; minor variation in spawning and rearing habitat; increased temperature during summer low flows

Event	**Range of Recurrence (years)**	Inputs **Affected**	**Channel Changes**	**Habitat Effects**
Seasonal precipitation and discharge; moderate storms; freezing and ice formation	0.1 - 1.0	water, sediment	Increased flow to bankfull width; moderate channel erosion; high base flow erosion; increased mobility of in-channel sediment and debris; local damming and flooding; sediment transport by anchor ice; gouging of channel bed; reduced winter flows	Changes in pool:riffle ratio; siltation of spawning gravels; increased channel area; increased access to spawning sites; flooding of side-channel areas; amelioration of temperatures at high flows; decreased temperatures during freezing; dewatering of gravels during freezing; gravel disturbance by gouging and anchor ice
Major storms; foods; rain-on-snow events	**1.0- 10.0**	water, sediment, LWD	Increased movement of sediment and woody debris to channels; flood flows; local channel scour; movement and redistribution of coarse sediments; flushing of fine sediments; movement and redistribution of LWD, increased LWD recruitment from bank erosion	Changes in pool:riffle ratio; shifting of spawning gravels; increased LWD jams; siltation of spawning gravels; disturbance of side channel rearing areas; increased rearing and over wintering habitat; local blockage offish access; filling and scouring of pools and riffles; formation of new rearing and over wintering habitat

Event	**Range of Recurrence (years)**	Inputs **Affected**	**Channel Changes**	**Habitat Effects**
Debris avalanches and debris torrents	5.0-100	sediment, LWD	Large, short-term increases in sediment and LWD contributions to channels; flood flows; local channel scour; movement and redistribution of coarse sediments; flushing of fine sediments; movement and redistribution of LWD; damming and obstruction of channels; accelerated channel bank erosion and undercutting; alteration of channel shape by flow obstruction; flooding	Changes in pool:riffle ratio; shifting of spawning gravels; siltation of spawning gravels; disturbance of side-channel rearing areas; blockage of fish access; filling and scouring of pools and riffles; formation of new rearing and over wintering habitat
Activities of beavers	5.0-100	LWD	Channel damming; obstruction and redirection of channel flow; flooding of banks and ,fide channel; ponding of streamflow; siltation of gravels behind dams	Improved rearing and over wintering habitat; increased water volumes during low flows; slack-water and back-water refuge areas during floods; refuge from reduced habitat quality in adjoining areas; limitation on fish migration; elevated water temperatures; local reductions in dissolved oxygen
Major disturbances to vegetation - Wind throw, limb loss from ice storms or snow weight	10-100	LWD, sediment	Increased sediment delivery to channels; decreased litterfall; increased LWD in channel; loss of riparian cover	Increased sedimentation of spawning and rearing habitat; increased summer temperatures; decreased winter temperatures; increased rearing and over wintering habitat; decreased fine organic debris

Event	Range of Recurrence (years)	Inputs Affected	Channel Changes	Habitat Effects
Wildfire		LWD, sediment	Increased sediment delivery to channel; increased LWD in channels; loss of riparian vegetation cover; decreased litterfall; increased channel flows; increased nutrient levels in streams	Increased sedimentation of spawning and rearing habitat; increased summer temperatures; decreased winter temperatures; increased rearing and overwintering habitat; decreased availability of fine woody debris; increased availability of food organisms
Insects and Disease		LWD, sediment	Increased sediment delivery to channels; loss of riparian vegetation cover; increased LWD in channels; decreased litterfall	Increased sedimentation of spawning and rearing habitat; increased summer temperatures; decreased winter temperatures; increased rearing and overwintering habitat
Slumps and earthflows	100-1000	LWD, sediment	Low-level, long-term contributions of sediment and LWD to stream channels; partial blockage of channel; local baselevel constriction below point of entry; shifts in channel configuration	Siltation of spawning gravels; scour of channel below point of entry; accumulation of gravels behind obstructions; partial blockage of fish passage; local flooding and disturbance of side-channel rearing areas
Climatic change	1000-100,000	water	Major changes in channel direction; major changes in channel grade and configuration; valley broadening or downcutting; alteration of flow regime	Changes in type and distribution of spawning gravels; changes in frequency and timing of disturbing events; shifts in species composition and diversity

Clearly, monitoring trends in disturbance and recovery of stream habitat is made challenging by the complex relationship between forest practices, watershed and channel processes, and stream habitat attributes. An examination of existing definitions and theoretical approaches to disturbance and recovery provides some insight for confronting this challenge and developing a monitoring framework.

Stressors

A stressor is a specific effect that causes a stress upon a population by impacting required habitat attributes. Stressors interact with one another and also differ in frequency, intensity, and duration. Common stressors resulting from timber harvest are siltation of spawning gravels, in-filling of pools, increased water temperatures, channel instability or loss of pools due to decrease in volume of LWD, and higher peak flows. Monitoring at the stressor level involves establishing the cause-and-effect linkage between the activity, the stressor and the population.

Disturbance

Disturbance is defined as the situation when stressor(s) result in a change in the state of the habitat that ultimately reduces the abundance of the salmonid population below its historical range. For example, as shown in Figure 1, a disturbance could be road building, which has an indirect effect on salmonid habitat manifested through a change in sediment input process, or stream channelization, which has a direct effect on habitat. One of the changes associated with road building could be an increased input of fine sediment to the stream channel. The increased fine sediment levels could then alter the fish habitat, reducing the abundance of the fish population

A press disturbance is one which causes a sustained alteration of certain species densities, and this alteration is maintained until the other species adjust. Pulse disturbances cause a relatively instantaneous alteration of the densities of certain selected species, after which the system recovers to its previously defined state (Bender et al. t984). Most forestry activities act as press rather than pulse disturbances. When monitoring the effect of a disturbance, the cause-and-effect pathway should be carefully traced from the effect on the population, through the effect on the habitat attributes back to the cause.

Recovery

Many different definitions of recovery have been developed. Recovery of fish populations has been judged by return of population densities to pre-disturbance levels, first appearance of individuals after disturbance, recovery of average size (Niemi et al. 1990), and return to prior relative abundances (Grossman et al. 1990). The definition used in this literature review is of a trend towards a state of dynamic equilibrium with natural processes that provides habitat conditions capable of sustaining natural fish populations. Recovery of function is emphasized over population numbers.

Recovery rates of stream assemblages were found to be strongly affected by (1) persistence of the effects of disturbance, (2) species' differential abilities to survive disturbance (Kelly and Harwell 1990, Yount and Niemi 1990), (3) presence of refugia (Sedell et al. 1990), and (4) hydrologic conditions (Cairns 1990, Yount and Niemi 1990). Fisher (1990) applied plant successional theory to recovery processes in stream, environments, and found that most disturbances to stream systems resulted in secondary rather than primary succession. He also found that the disturbance effects were patchy in nature such that a patch at a certain successional stage might be centimeters away from a patch at a very different stage and that these recovery phases tended to move from the edges of the channel toward the center. This concept of recovery in patches is an important concept for salmonid habitat. Although the stream channel morphology can imply a linear and connected system of habitat attributes, disturbance and recovery can happen in patches. This characteristic needs to be recognized and factored into monitoring plan design.

Other aspects of recovery that need to be incorporated into monitoring plan design are recovery end points or the expected time to recovery. Recovery end points must be clearly defined during the planning stage of monitoring activities. For example, if the objective of monitoring was to test the effectiveness of the road maintenance plan in reducing surface erosion and fine sediment delivery to segments 15 - 17 on Salmon Creek, then the recovery end point could be set at the stressor level of a certain percentage of fine sediment in the streambed gravels. The longest recovery times are associated with press stressors leading to long-term alterations in physical habitat; the recovery process involves an adjustment to a new steady state determined by a change in carrying capacity (Niemi et al. 1990).

Defining recovery as an end point or range in fish habitat parameters considered desirable or necessary for maintenance of fish populations is somewhat problematic. It is difficult to relate changes in population abundance to specific forest practices due to the multitude of confounding factors (such as ocean conditions) and high natural variability. In order to monitor trends in disturbance and recovery, it is more effective to examine changes in specific habitat parameters that have been linked to population abundance and can be modified by forest practices. This process-based approach involves looking at impacts one input at a time to establish meaningful cause-and-effect relationships.

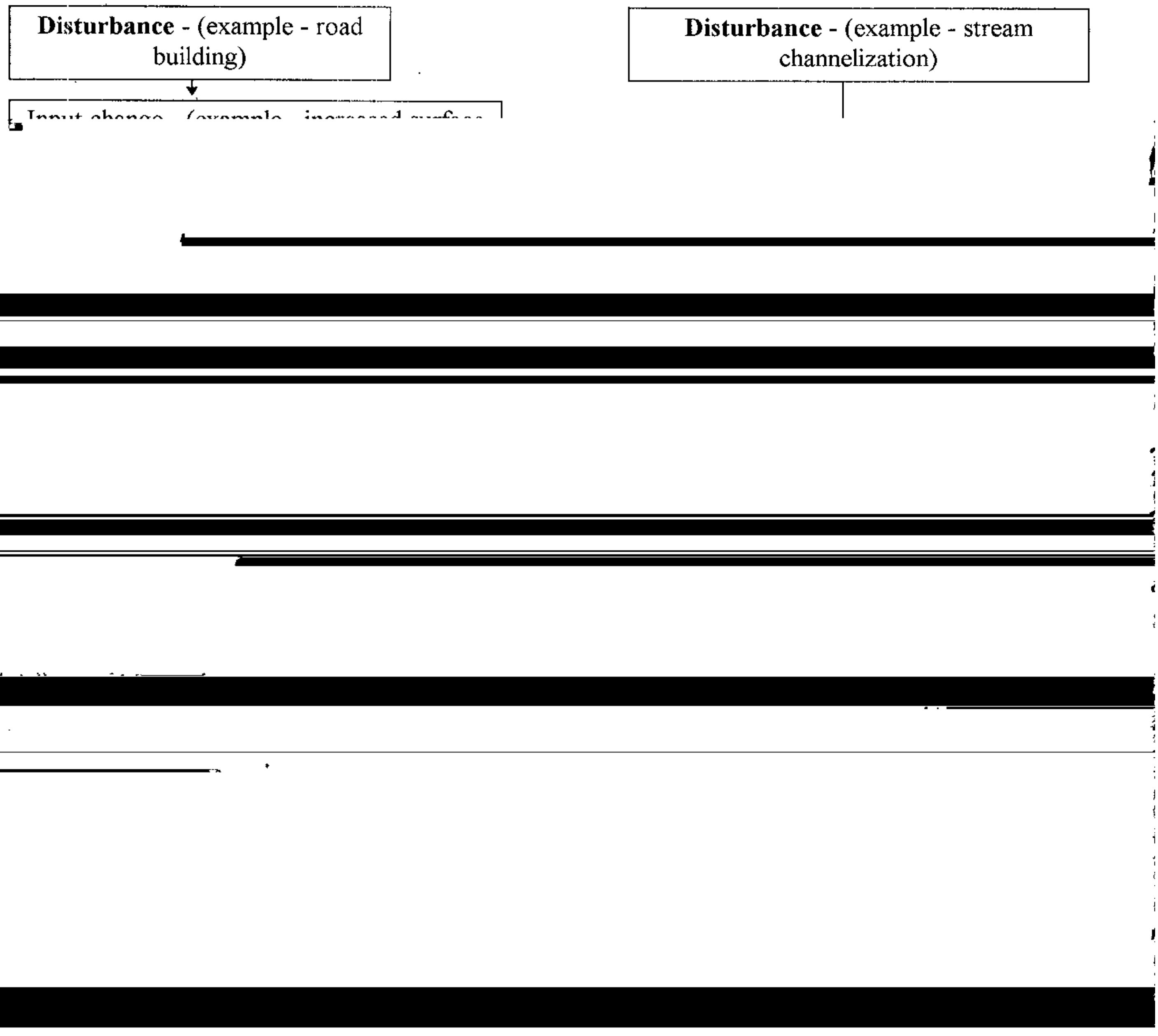
Incorporating Theories of Disturbance and Recovery into Salmonid Habitat Monitoring

Although much of the literature on disturbance and recovery has focused on population abundance, that approach is problematic when the population of concern includes anadromous salmonids and the only ready access to studying them is when they are in the freshwater phase of their life history. This issue is addressed by identifying habitat attributes that have been clearly linked with population abundance and then tracing a cause-and-effEct pathway from these habitat attributes to the related watershed inputs and finally to the forest practices that can alter these inputs. Figure 1 illustrates this process-based framework for monitoring disturbance and recovery as it occurs between forest practices and salmonid populations.

This literature review focuses on the recovery rates of the habitat attributes that are important to salmonids, such as the number of pools, volume of in-channel LWD, water temperature, and the composition of streambed gravels. Because of the wide range of habitat effects forest practices can have, these attributes are examined through a discussion of watershed inputs that can be altered by forest practices. These watershed inputs will be discussed in four major groups: fine and coarse sediment, large woody debris, solar radiation (stream temperature), and peak flows.

Breaking down forest practices by watershed input processes, allows emphasis to be placed on specific forest practices and resulting habitat effects. Among other factors to be taken into consideration when creating a monitoring plan, this helps to identify the time scales that each of the input processes operates on, indicating how often to monitor for each specific process. Potential monitoring parameters, possible confounding factors and specific recommendations for monitoring trends in the disturbance and recovery of habitat attributes are provided for each type of watershed input in the chapters that follow.

Figure 2-1. Flow chart showing relationship between disturbance and fish population



IlL Fine and Coarse Sediment

Introduction

Sediment delivered to a stream channel by erosional processes is transported by the activity of moving water toward the outlet of the stream. In a stable channel, there is a dynamic equilibrium between the amount of sediment supplied and the amount transported through the system. Forest practices can disrupt this balance by increasing the supply of sediment, causing physical changes in stream channel characteristics and disturbances to significant habitat attributes. Accordingly, monitoring trends in habitat disturbance and recovery from the effects of forest practices requires an understanding of sediment delivery and routing processes in stream channels, and the time scales over which they operate.

The type of habitat impacts that result from sediment inputs and the processes that dominate routing in the channel are dependent on the size class of individual sediment particles. While coarse sediment panicles form the habitat features used by salmonids, there has been substantial research focused on fine sediment (variously defined as < 0.85 mm, < 3.35 mm, and < 9 mm) because of its unique effects on habitat attributes (e.g. Cederholm et at. 1981; Cederholm and Reid 1987; Scrivener and Brownlee 1989). In this literature review, all size classes have been treated together, with important differences noted where appropriate.

In this chapter, the impacts of sediment inputs on stream channels and habitat attributes are reviewed, specific sediment delivery and routing processes are described, and the impacts of forest practices are examined. With this background, several case studies are discussed and recommendations for monitoring trends in habitat disturbance and recovery are presented.

Relation of sediment to habitat attributes

inputs of fine and coarse sediment to stream channels affect salmonid spawning and rearing habitat in a variety of ways. Fine sediments that infiltrate spawning substrate can cause mortality by reducing the flow of oxygen to embryos and physically preventing fry from emerging to the surface (Koski 1975; Tagart 1976; Scrivener and Brownlee 1989). High sediment inputs of mixed size classes can cause channel aggradation and widening, decrease average bed particle size, and increase sediment transport rates (Madej 1982; 1992). This can destabilize spawning gravels and cause egg mortality from mechanical shock and crushing (Bjornn and Reiser 1991). The bed of an aggraded channel may also have a high infiltration capacity that could lead to de-watering of spawning redds and provide a barrier to upstream migration of adult spawners by reducing surface flows (Cederholm and Reid 1987). Finally, sediment inputs of any size class can reduce the frequency and volume of pools in a channel, which are essential components of habitat for adult migration and for juvenile rearing in some species (Tripp and Poulin 1986; Megahan, et. al. 1992). This reduction in pools may also alter the species composition to benefit fish that prefer riffle habitats, such as steelhead trout (Sullivan et. al. 1987).

Processes affecting the delivery of sediment and its routing in the channel

An understanding of how sediment is supplied to stream channels and then routed downstream over time is essential for designing a monitoring program. Awareness of the spatial and temporal variability of these processes can improve the selection of monitoring sites and sampling intervals that are appropriate for capturing trends in habitat disturbance and recovery. Also, examining the processes at work can help establish cause-and-effect relationships with the activities that resulted in disturbance and aid in the interpretation of habitat monitoring results. This section describes the processes that deliver sediment to stream channels, those that route sediment inputs through the stream network, and the forest practices that can impact these processes.

Delivery Processes

Site-specific factors controlling sediment delivery include climate, geology, hydrology, slope angle, vegetation cover, and land use. in the humid, mountainous terrain of the Pacific Northwest, delivery of sediment to low-order stream channels draining steep slopes occurs primarily through mass movements of hill slope material (mass wasting). Mass wasting events can be divided into two general categories: shallow failures, which include landslides and debris flows, and deep-seated failures, which include slumps and earth flows. Smaller scale processes, such as soil creep, tree throw, and animal burrowing, also deliver sediment to channels, and surface erosion.may contribute significant quantities of fine sediment in disturbed areas (Swanson et al. 1987a). In high-order channels that do not drain steep slopes, sediment is supplied mostly from bank erosion and upstream contributions (Naiman et al. 1992). The characteristics of each of these processes are briefly described below.

Shallow failures are rapid mass movements that are triggered by subsurface pore water pressure during large storm events and generally have a thickness of less than two meters (Swanson et al. 1987a). Landslides (also known as debris avalanches) are shallow failures that stop on the hillslope or immediately upon entering the channel. These types of failures are most likely to occur on steep slopes where the toe is undercut by stream erosion or in bedrock hollows, which are unchannelized extensions of the stream network extending toward the ridge divide. Hollows (also known as swales or zero-order basins) are formed by converging topography that collects colluvium deposits over very long time intervals and concentrates subsurface water flow, eventually leading to failure (Reneau and Dietrich 1987).

Debris flows are shallow failures that travel considerable distances after entering steep, confined channels. While moving through first- and second-order channels, debris flows often entrain additional material, remove riparian vegetation, scour the channel bed, and leave large deposits of sediment and debris when they finally come to a stop. In the Oregon Coast Range, Benda (1985) found that debris flows generally stop when reaching a tributary junction that has an angle greater than 70°, or when the channel gradient is reduced to between 2° (3.5%) and 9° (15.8%).

Debris flows may travel even further downstream as debris floods when entering large channels (drainage area >28 km^2) at flood stage. Also, deposits from landslides or debris flows may temporarily dam the channel, leading to high intensity dam-break floods that can travel in channels with gradients below 1° (1.7%). These flood e, vents have a direct impact on a greater percentage of the stream network and more area of salmonid habitat than debris flows alone (Johnson 1991).

Deep-seated landslides are relatively slow mass movements that have a failure surface generally located well below the soil-rock boundary. They are not triggered by individual storms, but rather by the accumulation of water throughout the wet season (Sidle et al. 1985). Slumps are discrete rotational failures, while earth flows are continuously deforming translational failures. Earth flows are generally much larger than slumps and may remain active for thousands of years, with alternating periods of dormancy and activity. Sediment is typically delivered to stream channels from deep-seated failures by stream erosion at the toe of the slide (Swanson et al. 1987a).

Sediment can also enter the stream channel through smaller-scale erosion processes, such as surface erosion and bank erosion. Surface erosion delivers fine material to stream channels from areas cleared of vegetation by logging activity or natural processes. Animal activity, tree throw, dry ravel, and the steady creep of soil downslope under the influence of gravity can also contribute sediment to stream channels (Swanson et. al. 1987a). Bank erosion occurs when moving water brings material into the channel directly from the banks of the stream, generally during dam-break floods or peak flow events of moderate to high magnitude. This material may be entrained directly or enter as small landslides triggered by undercutting. Bank erosion may occur more often in channels that already have a large sediment load, because sediment deposits can direct flow toward the banks (Roberts and Church 1986).

For monitoring purposes, it would be useful to know where in a watershed various sediment supply processes are most likely to occur. It is difficult to make generalizations because there is a wide range of variables involved, but slope gradient is often a limiting factor for mass erosion processes. Sidle et al. (1985) compiled ranges of minimum slope gradients required for various processes from numerous studies (Table 3.1). Despite the wide range of minimum gradients, it is clear that slumps, earth flows and soil creep cart operate on much gentler slopes than landslides or debris flows.

Table 3.1. Lower limit of slope gradient for soil mass movements (adapted from Sidle et al. [1985]).

Sediment Delivery Process	**Lower Limit of Slope Gradient**	
Landslides and Debris Flows	25°	35°
Earthflows	4°	20°
Slumps	7°	18°
Soil Creep	1.3°	25°

In many cases, a useful first step for monitoring habitat disturbance and recovery would be to determine what the dominant sediment delivery processes are for a particular watershed or region of interest. Benda (1990) did this for Knowles Creek basin, a 52 km^2 basin draining marine sandstones in Oregon Coast Range (Table 3.2) Hillslopes have gradients of 35° to 45° in this basin, and the average annual precipitation is 1600 mm, most of which falls as rain in the winter.

Sediment delivery processes are dominated by landslides and soil creep in low-order channels, with debris flows gaining dominance as stream order increases. Other examples of regional sediment delivery quantification will be provided in the case studies section.

Table 3.2. Proportions of sediment delivered to first- through fifth-order channels in Knowles Creek basin from various processes (Adapted from Benda [1990]).

Sediment Delivery Process	First-Order Channels	Second-Order Channels	Third- through Fifth-Order Channels
Landslides	52 %	32 %	10 %
Debris Flows	0 %	38 %	68 %
Soil creep	48 %	10 %	6 %
Stream transport	0 %	20 %	16 %

For monitoring purposes, it is also useful to know over what time scales sediment delivery processes operate. Table 3.3 provides a generalized description of time scales. In addition to site-specific factors, the rates at which delivery processes occur are strongly controlled by the frequency and intensity of storm events, especially for landslides and debris flows. Site conditions or forest practices may make a particular watershed more vulnerable to mass wasting, but an intense storm is often necessary to actually trigger failures (Beschta 1978; Grant 1986). High variability in climatic processes makes it especially difficult to distinguish the effects of forest practices from natural disturbances and to define expected rates of sediment input.

Table 3.3. Generalized time scales for sediment delivery processes

Sediment Delivery Process	**Time Scale of Occurrence**	**Minimum Triggering Event**
Landslides, Debris Flows	Catastrophic, Episodic	intense storm
Slumps, Earth flows	Chronic, Episodic	accumulation of water throughout the storm season
Soil Creep	Chronic	influence of gravity
Surface Erosion	Chronic, Episodic:	moderate storm
Bank Erosion	Episodic, Catastrophic	moderate peak flow event

In addition to temporal variability of sediment delivery, Benda (1995) used field data from the Oregon Coast Range and a simulation model to demonstrate high spatial variability. Landslides occurring from the failure of individual bedrock hollows have recurrence intervals on the order of 6,000 years (Benda and Dunne 1987) and contribute an extreme quantity of sediment to low-order channels. As drainage area increases, sediment inputs occur more often because there are more potential failure sites, but sediment supply is moderated because the quantity of each input is smaller relative to the capacity of the channel. Benda (1995) suggests that frequency distributions may be useful for characterizing sediment yields due to the high temporal and spatial variability of sediment delivery processes, and warns that estimating long-term averages from short data sets is likely to result in large errors

Routing Processes

Once in the channel, both fine and coarse sediment are transported through the stream system in conjunction with peak flow events. Most of the work of transporting sediment is performed by the channel-forming discharge, which in many channels is the peak flow that occurs every one to two years on average (Wolman and Miller 1960). Therefore, the frequency of discharge events that exceed the channel-forming discharge has an important influence on the rate of sediment transport. In addition to flow regime, routing is also controlled by the quantity and size class of sediment in the channel, the ability of the channel to transport sediment, and the availability and distribution of storage sites.

Sediment is transported through a stream channel as either suspended load or bed load. The suspended load includes smaller particles that are entrained by the main flow of a stream and are carried a considerable distance suspended in moving water. The bed load consists of larger particles that remain supported by the bed as they roll, slide or saltate under the pressure of moving water and gravity. Over a critical discharge, the grain sizes that can be transported by suspended load increase with discharge (with an approximate upper limit of about 1 mm), and the grain sizes and transport distances of bed load increase with discharge and gradient (Leopold et al. 1964). Suspended sediments are generally transported much faster than bed load, leaving the coarse component behind. Fine sediment may infiltrate the coarse layer of particles through a variety of processes and be protected there for longer periods of time (Scrivener and Brownlee 1989). In periods between sediment inputs, channels may become armored with coarse sediment as smaller size classes are transported downstream during peak discharge events. Additionally, individual grains decrease in size over time as a result of abrasion during transport and weathering while in storage, making them more susceptible to transport processes (Madej 1992).

Sediment inputs are generally transported rapidly through high gradient channels and are deposited in lower gradient channels downstream, where they are transported more slowly. Perkins (1989) found that between 20% to 80% of sediment deposits were eroded within seven years from four stream channels with gradients from 1.4% to 7.0%. Pitlick (1993) documented recovery of a small mountain stream from sediment input within five years of a catastrophic flood. In contrast, studies of large sediment inputs to low gradient channels from logging and floods have documented much slower transport rates. Madej (1982) estimated a recovery time of 20 to 40 years for a 1.0% gradient reach of Big Beef Creek and Madej and Ozaki (1996) used 20 years of data to estimate a recovery time of 40 to 45 years for a 0.3% gradient reach of Redwood Creek. These studies suggest an order of magnitude of recovery after disturbance from sediment inputs to be 1 to I0 years for high gradient (>1%) channels and 10 to 50 years for low gradient channels.

The presence of sediment storage sites can slow down the rate of transport. Sediment may be stored as large bars in low gradient channels when sediment supply is greater than transport capacity. The presence of large roughness elements, such as bedrock outcrops, boulders or large woody debris, can slow down the rate of transport by providing storage sites and dissipating stream energy through turbulence. Floodplains located adjacent to unconfined channels provide storage sites for sediment and flood waters outside the active channel (Sullivan et. al. 1987).

Montgomery and Buffington (1993) have developed a channel classification system that uses gradient and confinement categories to delineate channels into reaches that are dominated by either supply, transport, or response processes High gradient channels tend to be supply-limited, which means transport capacity exceeds sediment supply. As a result, these channels provide efficient transportation for sediment supplied from hillslopes to lower gradient response reaches downstream. Response reaches are transport-limited, which means sediment supply exceeds transport capacity, and they are likely to respond with morphologic adjustment to increases in sediment. Specific response reaches are identified for a variety of important habitat attributes that would be expected to change in response to sediment supplied to higher gradient reaches upstream. Using a system such as this one to determine where the most likely response reaches are for specific habitat attributes of Concern could be useful for locating monitoring sites.

Effect of Forest Practices on Sediment Delivery and Routing

There are a variety of forest practices that can increase the delivery of sediment to stream channels. Forest sites that have exposed soil, such as clear cuts, landings, skid trails, landslide scars, burnt areas, and roads, can deliver substantial quantities of fine sediments to streams from surface erosion until they are revegetated (Swanson et al. 1987a). Areas that do not become quickly revegetated, such as landslide scars and roads, can provide chronic sources of fine sediment to stream channels. Cederholm et al. (1981) documented the importance of roads in generating fine sediments in the Clearwater River in Washington. When over 2.5% of basin area was roaded, the percentage of’ fine sediments found in spawning gravels significantly exceeded natural levels.

Timber harvest and logging roads can also increase the occurrence of mass wasting events. Clearing vegetation decreases slope stability from loss of root strength, which can result in landslides. Clear cuts are most vulnerable to mass wasting after the roots have decayed, but before new vegetation has been established In a review of numerous studies, Sidle et al. (1985) found that this sensitive period was from approximately 4 to 12 years after harvest. Pentec Environmental (1991), in a review of 14 landslide inventories conducted in the Pacific Northwest between 1970 and 1990, found that between 200 and 3,300 percent (average of 900 percent) more landslides occurred in clear cuts than in mature forests.

Logging roads decrease slope stability by undercutting and steepening the slope, increasing weight from fill material, and altering drainage patterns for both surface and subsurface flow (Furniss, et al. 1991). In a review of landslide inventories, Pentec Environmental (1991) documented that landslides associated with logging roads occurred from 1,000 to 38,000 percent (average of 11,100 percent) more than landslides in forests that did not contain roads. While some problems can be reduced through improved placement, construction, and maintenance, logging roads can clearly provide a substantial increase in both fine and coarse sediment supply to nearby streams.

Case Studies

Sediment delivery and transport processes are influenced by a wide range of variables, which confounds the effort to generalize about rates of disturbance and recovery. In this section, case studies are presented that document disturbance or recovery in specific watersheds and illustrate concepts that can be used in the design of trend monitoring studies First, several sediment budgets are presented that chronicle regional differences in dominant sediment delivery processes and the short-term impact of forest practices on delivery rates. Then, case studies from Redwood Creek and South Fork Salmon Creek are reviewed as examples of disturbance and recovery from coarse sediment and fine sediment, respectively.

Sediment Budgets

A sediment budget is a quantitative description of the rates of sediment production and transport in a drainage basin that can be used to establish the relative contribution of different delivery mechanisms and to estimate trends in the volume and rate of sediment movement over time. Construction of a sediment budget requires the identification of individual erosion processes and storage sites throughout the basin, and quantification of the transport processes that link them together (Dietrich et al. 1982). This conceptual model allows a researcher to estimate trends in watershed condition that may occur over larger time scales than could be investigated with a single research project. Sediment budgets can also be used to identify important processes or sites that should be monitored to track changes in watershed or channel condition. Table 3.4 provides a summary of four sediment budgets that have been constructed for small watersheds in the Pacific Northwest. These sediment budgets provide information on conditions both before and after logging.

Table 3.4 Sediment budgets for small watersheds in the Pacific Northwest (adapted from MacDonald and Ritland [1989])

	Queen Charlotte Islands, British Columbia		Clearwater River, Olympic Peninsula, WA		Watershed (WS) 10, Cascade Range, OR		Idaho Batholith, Central Idaho	
Forest Type	Sitka spruce, western red cedar		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 (km^2)	1.4		10		0.1		1.26 (average)	
Road Density after Logging (km/km^2)	0.3		2.5		0		?	
Hillslope Sediment Delivered to Streams (t/km^2/yr):	Old Growth	After Logging	Old Growth	After Logging	Old Growth	After Logging	Old Growth	After Logging
Mass Wasting	34-53	926-1480	38	136-235	60	126	no data	17
Soil creep/treethrow	34-88	42-102	29/9	29/9	11/1	11/1	no data	—
Slope wash/ravel	4-15	12-18	0	16	5	17	no data	7-22 (total,
Gullying (slide scars)	4-8	54-217	0	0	0	0	no data	all 4 rows)
Other (bioturbation, etc.)	0	0	4	4	0	0	no data	—
Road surface, backcut	0	6	0	65-74	0	0	no data	49
Total	76-164	1040-1823	80	259-367	77	155	> 7-22	73-88
Fluvial Erosion (t/km^2/yr):								
Stream banks	19-99	223-463	46	29	6	31	< 3- 10	< 3-10
Debris flows	0	0	0	26	0	494	0	0
Grand Total (t/km^2/yr):	**95-263**	**1263-2286**	**126**	**314-422**	**83**	**680**	**10-32**	**76-98**
References:	Roberts and Church (1986)		Reid (1981)		Swanson et. al. (1982) and Swanson et. al. (1987)		Megahan (1982) and Megahan et al. (1986)	
Methods used:	synthetic, based on regional rates, aerial photography 1936-1967, and field measurements		synthetic, based on regional rates, geologic and dendrochronologic interpretation, and field measurements 1977-1979		synthetic, based on measurements of process in Oregon Cascade Range, 1957-1982		based on field measurements 1973-1978, 1980	

Northern California Coast Ranges/Redwood (;reek

In the northern California Coast Ranges, a combination of easily erodible Franciscan rocks, recent tectonic uplift, and high annual precipitation (1250 mm to 2500 mm) results in some of the highest natural erosion rates in North America (Madej and Kelsey 1982). Timber harvest and associated road building increased dramatically in this area starting in the 1950s. Lisle (1982) documented widespread channel aggradation, channel widening, and destruction of riparian vegetation throughout the Coast Ranges as a result of logging activity and major floods in 1953, 1955, 1964, 1972, and 1975, with the flood of 1964 singled out as particularly significant. Habitat effects included loss of riparian vegetation bordering the channel, resulting in increased temperatures and loss of nutrients and cover, reduction in the number and volume of pools, and de-watering of channel substrate during low flows.

The post-disturbance sequence of flows was identified as an important factor in recovery (Lisle 1982). Moderately high flows are necessary for transporting sediment out of the system, but large storm events may deposit additional sediment and prevent the re-growth of bank-stabilizing vegetation. As an example, three episodes of aggradation were evident in the Smith River starting in the 1950s, and the channel never fully recovered in between. Most fourth-order and smaller streams had degraded to stable levels by 1980, but larger, mainstem channels, such as Redwood Creek, stored greater volumes of sediment and were expected to remain aggraded for a decade or longer. In most channels, width did not decrease with channel degradation, primarily because bank vegetation was not quickly re-established. Also, while there was some increase in the number and volume of pools, full recovery was not expected until channels become narrower and deeper, and LWD carried out by flood flows is replenished.

Redwood Creek drains a 720 km^2 watershed in the California Coast Ranges that experienced dramatic disturbances from the logging and floods described above. Due to reductions in fish abundance and damage to redwood groves in Redwood National Park, 194 km^2 of land in the Redwood Creek basin were added to the park in 1978, and an extensive rehabilitation and monitoring program was initiated (Sonnevil and Weaver, 1982). Rehabilitation efforts included removal of road fill from stream crossings, revegetation of disturbed sites, and improving road drainage. The monitoring program has allowed for long-term studies on the recovery of stream habitat and channel conditions after major disturbance to Redwood Creek

Madej (1996) documented the recovery of stream habitat in Redwood Creek and Redwood National Park. While the study was intended to evaluate the watershed rehabilitation programs initiated in 1978, it was difficult to distinguish effects of the rehabilitation from natural recovery, because there was no storm with greater than a five year recurrence interval since 1975. Nonetheless, recovery was evident in riparian conditions, pool frequency arid spacing, and mean stream bed elevation. The riparian corridor recovered substantially along reaches that were narrow enough to have a closed canopy before disturbance. In the upper 11.2 km of Redwood Creek, for example, the length of closed canopy changed from 67% in 1954 to 0% in 1966, less than 1% in 1978, and 40% in 1992. The recovered canopy was composed of alders, however, while the canopy before disturbance was composed of conifers. This indicates that disturbance to large woody debris abundance may continue for decades, but data have not been collected for this parameter. The frequency of pools increased to nearly pre-disturbance levels between 1977 and 1995. Mean pool depths also increased in that time period, but did not fully recover to pre-disturbance levels.

The mean stream bed elevation in Redwood (;reek recovered rapidly in small tributaries and upstream reaches, and is recovering more slowly in mainstem reaches as an aggradational wave of sediment moves downstream from the initial sediment input (Madej and Ozaki 1996). Recovery times ranged from eight years at km 26 to more than 15 years at km 21.3. Downstream of km 16.6, the average bed elevation was still 0.6 m higher in 1995 than in 1974. Based on these transport times, it may take an additional 20 to 25 years for the sediment to completely move through the lower reach, suggesting a total recovery time on the order of 40 to 45 years. Despite these reductions in average stream bed elevation, the channel width has not decreased significantly since it widened during the initial floods.

South Fork Salmon Rivet'

The South Fork (SF) Salmon River in central Idaho provides a well-documented case study of salmonid habitat disturbance and recovery resulting from large inputs of fine sediment. The SF Salmon PAver drains an area of 3,290 km^2 located almost entirely within the Idaho batholith. Elevations within the basin range from 640 m to 2,740 m, and the region is characterized by steep slopes covered with shallow, coarse-textured granitic soils. Approximately 65% of the annual precipitation, which ranges from 760 mm to 1520 mm, falls as snow during the winter (Platts et al. 1989).

Extensive road construction and timber harvest in the SF Salmon River watershed resulted in a 350% increase in sediment supply during storm events from 1950 through 1966. The primary sediment sources were surface erosion and mass failures associated with logging roads (Arnold and Lundeen 1968). Between 1958 and 1964, surface erosion delivered large quantities of fine sediment to low-order streams. Storms in 1964 and 1965 transported.most of this sediment downstream to salmon spawning areas in the low-gradient (< 2%) main river, and triggered many new landslides. Salmon populations decreased as spawning gravels were clogged with fine sediment, holding and rearing pools were filled with sand, and average particle size on the channel bed decreased as fine material covered the predominately gravel streambed (Megahan et al. 1980).

A moratorium was placed on logging operations in 1965, and an extensive rehabilitation program was initiated, which included road closure, revegetation and cross ditching of disturbed sites, removal of culverts and bridges, and removal of road fills. Ptatts et al.

(1989) monitored levels of surface and subsurface fine sediment (< 4.75 ram) in salmon spawning and rearing areas in the SF Salmon River from 1965 to 1985 and found a significant overall reduction in fine sediment during that time period. A summary of specific results is provided in Table 3.5. For the first eight year period, there was a rapid decrease in surface fine sediments and moderate decrease in subsurface fines, and for the second eight year period, there was a moderate decrease in both surface and subsurface fines. The Slower rate of decrease in subsurface fines was explained by the protection of an armor layer. As fines infiltrate between larger particles found on the bed, they are only transported during flows strong enough to scour the larger particles, while fine sediments located on the surface of the bed can be transported at lower flows.

For the final four years of monitoring, there was a small increase in surface and subsurface fine sediments. Possible explanations include a sediment input from a large mud slide, continued supply of sediment from logging roads, and reduced transport power as the channel bed regained its complexity. Although the SF Salmon River exhibited substantial recovery from the major disturbances in the 19605, fine sediment delivery may not have been reduced to pre-logging levels by the restoration effort, and more time may be needed for full recovery.

Table 3.5. Trends in fine sediments at various sampling sites in SF Salmon River (adapted from Platts et al. [1989])

Time Period	Rearing_ Surface	Spawning Surface	Spawning Subsurface
1966-1974	78% reduction	38% reduction	16.1% reduction
1974-1981	No Data	18% reduction	15.8% reduction
1981- 1985	No Data	variable increases	10.9% increase
Whole period of record (1966-1985)		31% reduction	21% reduction

Models

By integrating many data sets that link responses to measurable variables, models attempt to estimate future conditions or trends based on measurements of the relevant variables. Because of the wide range of variables that influence sediment delivery and transport processes, this is a challenging task. There were no models discovered in the literature search that attempted to predict habitat conditions that would result from sediment inputs. Kelsey et al. (1987), however, developed a stochastic model for sediment transport that can be used to predict changes in storage as sediment is transported through a stream reach and estimate long-term flushing times; for four types of sediment storage reservoirs (Table 3.6).

Table 3.6. Four types of reservoirs used in the Kelsey et al. (1987) model.

Reservoir Type	Approximate Flow Recurrence Interval Required to Mobilize Sediment	Example
active	1-5 years	active main channel
semi-active	5-20 years	adjacent to but slightly higher than main channel
inactive	20-100 years	vegetated flood berms or terraces 3-5 m above channel
stable	>> 10© years	floodplain deposits high above and far away from main channel covered by mature forest

The data that must be collected or estimated to run the model are the volume of sediment in each of the four defined storage reservoirs, bedload transport information, including quantity of inputs to the stream reach, and sediment residence times in each reservoir. By focusing specifically on the active channel, it would be possible to use the model to predict residence time of sediment inputs that would be expected to have direct effects on habitat attributes. The model was tested with data from Redwood Creek, and accurately predicted 18 years of peak channel destabilization and 30 years of increased sediment volume in the main Redwood Creek channel after logging-related disturbances following a major storm in 1964.

Discussion and Conclusions

Based on the literature reviewed, some generalizations can be made about the sediment disturbance and recovery regime in forested watersheds of the Pacific Northwest. Landslides and debris flows dominate sediment delivery processes in steep, mountainous regions. Forestry activities in these regions; can destabilize slopes, resulting in catastrophic failures during large storm events that deliver large quantities of coarse and fine sediment to low-order stream channels. Smaller storms may deliver fine sediment from surface erosion and. recruit coarse sediment from bank erosion on a more regular time interval. High gradient channels typically transport sediment downstream during moderate to large peak flow events to lower gradient channels downstream in 1-10 years. Habitat disturbance will occur in lower gradient channels in response to inputs from upstream, and will recover on the order of 10-100 years. Fine sediment may be flushed out on the shorter end of this time frame, but recovery will not occur unless chronic delivery sources are reduced. Habitat disturbances resulting from coarser sediment clasts, such as channel widening, aggradation, reduction in pool frequency and volume, subsurface flows, and destabilized spawning gravels will recover at various rates over the course of the time frame, influenced by the frequency and intensity of peak flow events. Channel widening may take the longest to recover from because riparian vegetation regrows slowly.

Recommendations for Habitat Assessment and Monitoring

This review of literature related to habitat disturbance and recovery from sediment inputs has provided information that can be useful in the design of trend monitoring studies. Sediment delivery and transport processes are very complex and respond to a multitude of site-specific variables. Monitoring studies need to reflect this complexity by documenting changes in parameters over time and throughout a watershed. A description of some parameters that would be useful to monitor is provided in Table 3.7, followed by general recommendations for monitoring trends in habitat disturbance and recovery from sediment inputs.

Table 3.7. Some parameters that could be measured for monitoring trends in habitat disturbance and recovery from sediment inputs

Parameter	Information Gained	Method	Ideal Frequency
Sediment delivery processes and rates	Sources and magnitude of disturbance; changes in rates of inputs	Sediment budget	Once, with updates during/after major storm events
Stream bed elevation	Index of disturbance; location and rate of sediment transport	Channel cross-section surveys	Annually, after storm season
Sediment transport rates in channel	Spawning gravel stability; Estimate of recovery rate	Suspended sediment and bed load samplers or sediment budget	Continuously, throughout storm season
Particle size of surface substrate	Index of disturbance and recovery rate	Pebble counts	Annually, after storm season
Volume of large woody debris in channel	Potential sediment storage sites	Large woody debris surveys	One baseline study, then at multi-year intervals
Percent fines in spawning riffles	Spawning habitat quality	McNeil sampler and laboratory sieves	Annually, after storm season
Frequency and volume of pools	Spawning migration and rearing habitat quality and quantity	Habitat surveys; Longitudinal profiles	Annually, after storm season
Channel width and canopy opening	Index of disturbance and recovery rate	aerial photo interpretation or densiometer surveys	One baseline study, then at multi-year intervals

1) It is essential to consider an entire watershed when designing a monitoring plan. Habitat disturbances are often far removed in time and space from the forest practices that

cause them. Identifying likely sediment source areas, transport reaches, and downstream habitat response reaches is helpful for effectively targeting monitoring sites.

2) Monitoring all major processes involved in the delivery and routing of sediment is necessary for establishing causal linkages between forest practices or restoration activities, sediment delivery and routing, and habitat disturbance and recovery that may be spread out in space and time. Linking changes in habitat condition to specific upland activities can also help distinguish disturbances from natural variation.

3) Climate needs to be considered when interpreting monitoring results. Climatic fluctuations' cause wide temporal and spatial variability in sediment delivery and routing processes, so monitoring data need to be compared with records of storm events and stream flow to distinguish habitat disturbance and recovery from natural variation. The absence of a major storm event over a period of years can provide the illusion that complete watershed recovery has occurred, while a series of extreme events can cause significant disturbances that take many years to recover from.

4) Regular monitoring is essential for documenting trends in habitat disturbance and recovery over time. Pre-disturbance monitoring data can be useful in interpreting these trends and determining the magnitude of disturbance. In its absence, regular monitoring may be the only way to document the timing and magnitude of disturbance and/or recovery. Regular monitoring can also help generate estimates for how long recovery will take.

5) It would be valuable to monitor over the. long time frame that recovery processes operate on. In many cases, [his suggests monitoring for 10 to 50 years or more. With this kind of long-term monitoring, it may not be possible to measure all parameters at the frequency suggested in the table 3.7. Longer time-intervals between surveys may be appropriate for some parameters.

6) Comprehensive sediment budgets can be useful for interpreting sediment delivery and routing processes throughout a watershed and can be useful in the design of a monitoring program. Sediment budgets, in conjunction with monitoring data, can also help fill in gaps and identify trends over the short time frame of most monitoring studies.

IV. Large Woody Debris (LWD)

Large woody debris originates as trees that fall or break and are recruited into the stream channel by one or a combination of processes (Table 4.2). Once in the channel LWD acts as large roughness elements that vary the water speed and direction, reducing average velocity and locally elevating the water surface (Gippel 1995). The sediment transport ability of the stream is thereby lowered and local areas of scour and deposition are created.

In this chapter, the relationship between large woody debris and salmonid habitat, and the delivery and routing processes of the LWD to and through the channel are described first. Next, case studies that have examined the disturbance or recovery of in-channel LWD levels and predictive models for any one or combination of these conditions are presented. Finally, what is known about disturbance and recovery of in-channel LWD levels and how to use that information when planning monitoring activities are discussed.

When looking at the disturbance and recovery of LWD inputs in the context offish habitat, the two main forestry activities of concern are stream clean-outs and harvest of potential LWD from the riparian area. Each of these activities can lead to reduced volumes of functional, in-.channel LWD and a consequent reduction in quality and quantity of salmonid habitat. When examining the disturbance and recovery trends associated with these activities, two main areas are usually targeted for monitoring: delivery or recruitment of LWD to the stream channel, and routing or persistence of LWD within the channel system.

Relation of LWD to habitat attributes

Large woody debris serves several purposes for salmonid habitat. Often a single piece of wood or root wad offers benefits to multiple life stages and species. Habitat complexity and diversity are created by in-channel LWD through pool formation, sediment storage and sorting, channel stabilization, flow dissipation, nutrient production, and cover. Complexity is the distribution and abundance of habitat types (Bisson et al. 1982) and their connectivity throughout the salmon’s range (Lichatowich et al. 1995). Diversity refers to the variety of habitat types in an ecosystem.

Formation of pools is a primary function of LWD. Between 70 and 86% of pools on two test streams in western Washington were associated with debris and 70% of pools with a volume greater than 1.0m^3 were associated with LWD in a coastal Oregon stream (Andrus et al. 1988; Bilby 1984). Pool volume did not differ significantly between old-growth and buffered streams, but was significantly less in the clear cut areas, implying that reduced recruitment of larger pieces of LWD reduces pool volume (Bilby and Ward 1991).

Spawning habitat, as noted previously, consists of areas with suitably sized substrate particles with good permeability, sufficient water depth and velocity, and a stable streambed. LWD can act as a scour agent, causing a scour pool to form around the piece(s). Tail outs of these pools offer sorted and cleaned gravels with flows permeating through them. Flow patterns around complex LWD can also lead to deposition of gravel in patches, creating spawning habitat.

Delivery Processes

Table 4.1 lists the processes that can deliver LWD to the stream channel, along with the natural and human-derived factors that affect these processes. The rates at which these input processes deliver LWD to the channel are also given on a dominant and subdominant event basis. Catastrophic events are relatively rare (10 - 100+ years recurrence interval) but can add large volumes over short periods of time, episodic events occur more frequently (1 - 10 years recurrence interval), and chronic events have a recurrence interval of less than one year, but deliver relatively small volumes of LWD to the channel (based on Bisson et al. 1987).

Table 4.1. Processes that deliver LWD to the channel

Delivery Process	Natural Factors Affecting Process	Human Factors Affecting Process	Dominant and Subdominant

Delivery Process	**Natural Factors** Affecting **Process**	**Human Factors Affecting Process**	**Dominant and Subdominant Rates of Process**
beaver	riparian stand composition, channel morphology, gradient	tree removal, tree age reduction, pest control	Dominant = Chronic
toppling due to instability of rooting environment	riparian stand composition, riparian type, soil depth and moisture	tree removal, tree age reduction, reduced evapotranspiration	Dominant = Chronic
lightning	riparian stand composition, climate	tree removal, tree age reduction	Dominant = Chronic
insect/disease	climate, stand composition	tree removal, fire suppression, pest control	Dominant = Chronic, Subdominant = Episodic

To summarize the information contained in Table 4.1, wood has many different potential avenues of delivery to the channel. These delivery processes are affected by the topography and climate of the specific site, and the proximity of the tree to the channel. In the context of disturbance and recovery, proximity is an important concern because the probability of a tree landing in the’ channel decreases with distance from the channel (McDade et al. 1970). Many of the delivery processes are unpredictable, though regular over long periods of time. Recovery from decreased volumes of in-channel wood can only occur with the availability of large trees located a deliverable distance from the channel.

Routing Processes

Delivery alone, though, does not assure increased quality or quantity of salmonid habitat. The function provided depends on size and persistence. The routing of wood, whether a piece is stable and maintains position for long periods of time (thus increasing channel stability) or whether it move.,; fairly quickly through the system (possibly causing damage to existent salmonid habitat) is also important in the context of disturbance and recovery.

To capture the change in number and volume of in-channel LWD, the length of time that a piece of LWD persists once it has entered the channel is needed. Wood can be removed by flushing (pieces being floated), decay, breakage and debris flows. The flushing process, whether it is caused by high flows or debris flows, is affected by tree size, wood piece shape, the type of wood or tree species, the channel morphology and gradient, climate, flow regime, and piece orientation. Decay and breakage are affected by tree size or bole diameter, wood type, and climate.’

Persistence and routing are influenced by piece size, shape and species. Pieces need to be big enough to form pools and remain in the,, channel. Downstream movement of debris has been shown to be strongly related to the length of individual pieces; most pieces that moved were shorter than bankfull width distance (Lienkaemper and Swanson 198'7). Coniferous pieces tend to be larger and pieces with larger bole diameters have been shown to decay slower than smaller, more easily broken pieces (Murphy and Koski 1989). Rootwads and trees oriented perpendicular to the channel are more likely to become functional and remain in place, and smaller pieces can be anchored by essential key pieces (Robison and Beschta 1990).

Case Studies

Case studies provide information on how researchers have approached specific questions, designed studies, handled problematic issues, and collected data. For the purpose of crafting a monitoring plan, important aspects of a case study are: what question did the research answer, how was the study designed, what assumptions were made, what are the caveats, what was the sampling plan and why, what parameters were measured, how was the data analyzed, what were the' specific site characteristics, and what were the results?

A summary of case studies is presented in Table 4.2. When possible, caveats and confounding variables are reported in the interest of establishing comparable areas for extrapolation of the rates of' LWD deliver5, or persistence. It is important to note that applying the extracted information to design of a monitoring study without referring to the original published work is not advised.

TabLe 4.2. Rates of LWD related processes from case studies and research for disturbance or recovery.

Researcher	**Location**	**Basin / Stream**	**Stream Order**	**Gradient**	**Parameter(s)**	**Triggering Activity**
Bilby and Ward] 991	South Western Wash. (Cascade Range foothills, Willapa Hills)	69 different reaches	2nd to 5th	not given	channel width, LWD frequency, LWD volume index, % of LWD pieces by species, riparian vegetation age, pool frequency, pool type, pool area	timber harvest

Researcher	**Location**	**Basin Stream**	**Stream Order**	**Gradient**	**Parameter(s)**	**Triggering Activity**
Lamberti et al. 1991	Cascade Mtns., OR	Quartz Creek	3rd	avg 5%	2 yr. after cutthroat trout pop. Returned to prior levels due to immigration & enhanced recruitment	rain-on-snow event
Minore and Weatherly 1993	Coastal Mtns. , OR	22 different streams	various	~.-40%	Conifer basal area inc. with elevation, gradient, time since disturbance &distance from stream; dec. with stream width	Removal of conifers from riparian area/ disturbance
Swanson et al. 1984	Tongass National Forest Prince of Wales Island, Southeast Alaska	7 different streams		7%	volume of fine and potential and effective coarse debris in different successional stage areas post clearcut	harvest related debris loading, stream cleaning and natural processes
Lienkaemper and Swanson 1987	H.J. Andrews Experimental Forest, Willamette National Forest, Oregon	Wtrshd 9 Wtrshd 2 Mack Cr U Lkout L Lkout	1 2 3 3 5	;7% ~6 [3 ; 	initial no. of pieces; no. of pieces moved; no. of pieces added; no. of added pieces that moved	windthrow possibly coupled with stem or root decay; bankcutting or instability of bankside rooting medium
Grette 1985	Olympic Peninsula, WA	28 different streams		).5 - L0%	no. of pieces, volume, years since logging, instream and overstream cover, decay class of pieces	timber harvest

Researcher	Location	Basin/ Stream	Stream Order	Gradient	Parameter(s)	Triggering Activity
Murphy and Koski 1989	Southeast Alaska	7 different streams in undisturbed old growth watersheds	2.d _3"d ’ (3) 4th - 5th (4)	**1-3% 0.4-1%**	no. of pieces, piece volume, decay class, channel type	non-human factors

Defivecv

Several researchers have focused their attentions on delivery or recruitment of LWD. Studies have been done for the following purposes:

1. to estimate the rate at which new pieces of LWD enter the channel (Lienkaemper and Swanson 1987, Murphy and Koski 1989),
2. to compare quantities (piece counts and/or piece volumes) of in-channel (or "effective") LWD in stream reaches with differing streamside management regimes (Ralph et al. 1994, Bilby and Ward 1991, Grette 1985, Bryant 1985, Swanson et al. 1984),
3. to correlate salmonid densities with in-channel LWD and differing streamside management regimes (Fausch and Northcote 1992), and
4. to characterize the LWD present in a stream (Robison and Beschta 1990, Bilby and Ward 1989).

Measuring delivery has been done by monitoring the volume of individual pieces of LWD that met minimum size criteria in a stream reach over time, tagging individual pieces, or determining the source site and distance from the channel. Measuring delivery is usually done: 1) comparing the effects of riparian management regimes; 2) estimating the rate of recovery of. in-channel LWD levels after a disturbance such as stream cleaning; or 3) determining the source location of the LWD.

In the case studies reviewe, d here, the number of pieces of in-channel LWD did not significantly differ between second-growth and old-growth reaches, but the volumes did. The largest difference in recruitment or delivery rates was found between clearcut reaches with no riparian buffer areas and old-growth reaches (Grette 1985, Ralph et al. 1994, Bilby and Ward 1991). The iaput from second-growth did not deliver a sufficient volume of LWD to offset the losses (from natural processes) of old-growth LWD (Grette 1985). The majority of source trees from old-growth coniferous forests were located within 30 meters of the channel (Murphy and Koski 1989, VanSickle and Gregory 1990). Downstream movement correlated with piece length, pieces shorter than the bankfull width distance were more likely to move downstream (Lienkaemper and Swanson 1987). Use of buffer strips maintain,; or increases (due to increased susceptibility to windthrow) LWD levels (Murphy et al 1986). Stream cleaning after adjacent timber harvest was found to create extended disturbance to salmonid habitat due to the removal of both riparian trees and in-channel lwd (House mid Boehne 1987; Dolloff 1986; Bryant 1983).

Persistence and Decay rates

Large woody debris is removed from a stream reach by flushing flows or by decay, abrasion and breakage. Grette (1985) developed a seven class system to measure decay and estimated the loss rate to be approximately 0.5% per year per 100 meter of lineal stream channel for large old-growth conifer pieces. Murphy and Koski (1989) found the weighted mean age of LWD in all the stream channels was 54 years, but it differed among channel types and was inversely proportional to bole diameter. Small pieces were 33-48 years old and larger pieces were 77-125 years old. Depletion rates varied by channel type, and varied inversely with LWD diameter. Quantities of larger volume pieces have been found to vary with harvest regime, reduced in more heavily or more recently harvested areas (Ralph et al. 1994, Bilby and Ward 1991, Grette 1985, Bryant 1985, Swanson et al. 1984).

Murphy and Koski (1989) estimated that 90 years after clear cut logging without stream side buffers, large LWD would be reduced by 70% and recovery to pre-logging levels would take more than 250 years. Second growth LWD was found to accumulate very slowly and not contribute significantly until about 50 - 60 years after logging (Grette 1985).

In summary, decay rates of LWD pieces were found to be slower for larger conifer pieces and faster for smaller deciduous pieces and the in-channel LWD composition shifted from mostly conifer to a higher percentage of deciduous pieces after timber harvest on the adjacent watershed.

Models

When the relationship between variables is shown to be consistent over several data sets, a model of the relationship(s) can be developed and be used for predictive purposes. Several models have been developed to predict different aspects of the LWD cycle. Table 4.3 presents several models in their most basic form. When creating a monitoring plan, the output of one or more of these models could assist in defining the scope of the monitoring activities.

Table 4.3. Models used for LWD recruitment, in-channel loading and pool formation.

Researcher	Objective	Input Variables	Output Variables	Assumptions	Caveats
VanSickle and Gregory, 1990	To predict LWD recruitment	trees/area, tree size distribution, distance from channel, species	of pieces, total volume of LWD input to stream	static riparian stand	downslope or downstream movement of LWD not addressed, breakage of tree boles leads to overestimation of predicted volumes
McDade et al., 1990	To provide a general representation of the relation between source distance and tree height.	Distance from source to streambank, tree height, angle formed by intersection of two tree length radii extending from the tree to the stream bank	distribution of debris origins as a function of :tee height	uniform tree height, random direction of tree fall, and uniform stocking density	Most riparian areas do not have uniform tree height, stocking density or random tree fall

Researcher	**Objective**	**Input Variables**	**Output Variables**	**Assumptions**	**Caveats**
Robison and Beschta, 1990	To determine the conditional probability of a tree's adding LWD to a stream	distance of tree from stream, effective tree height, diameter at breast height, tree species	Probability of a tree adding LWD to a stream	trees will have equal chance of falling in any direction, tree will fall whole and not break	evaluates tree (by size) for the time of the evaluation - the probability will change over time with i growth, channel adjustments may move the channel further from the tree, riparian trees on slopes do not display random fall direction
Kennard et at., 1997	To evaluate different riparian prescriptions for LWD recruitment and pool formation	initial channel conditions (LWD, pools, width), stems/acre by diameter class, average tree height per size class	LWD pieces after depletion, key piece and jam designations	wood entry is as whole tree, tree is cylindrical, trees will fall independently	tree growth model created from one species, uses upland growth models, does not account for import of LWD from upstream or catastrophic events, doesn't count broken pieces

Researcher	Objective	Input Variables	Output Variables	Assumptions	Caveats
Murphy & Koski 1989 (update via personal commun.)	To evaluate riparian mgmt schemes by their effect on pool area and thus coho juveniles	channel width, # of pools, pool area-LWD formed and non-LWD, tree basal area, logging start and rotation, RMZ width, basal area target	basal area of riparian stand through time, pool area (from LWD caused pools), coho smolt yield	Buffer integrity, fully seeded system ltd by winter habitat, processes gradual and continual, LWD only role is pool former, trees in buffer are randomly distributed	storm events not considered, other roles of LWD in fish habitat not considered, tree age and distribution is important to LWD recruitment and often differs from assumed riparian conditions

Model output can be useful for the initial stages of designing a monitoring plan and interpreting monitoring results. Necessary information to be drawn from these models include the direction and scale of expected change in the parameter to be measured, and the variables that directly affect the process so that all can be accounted for in the study design.

Natural Disturbance/Recovery Regimes

Natural disturbances of in-channel LWD that move large amounts of LWD out of the channel are generally oftw0 types; peak flows and debris flows. Large flow events can completely change the channel of a stream by relocating wood, large amounts of sediment and even sometimes the channel it self. Large flows also increase recruitment of large woody debris from the riparian forest, the net effect being extremely variable and dependent on the characteristics of the peak flow event or cumulative effect of several events. For example, high flows that rise suddenly and drop equally quickly, often move some LWD to the channel margins, flush some out and recruit some resulting in small net changes in the total in-channel LWD volume. Extended periods of high flow, however, often result in a decrease in volumes of in-channel LWD.

The other type of natural disturbance is a debris flow. Debris torrents or flows occur when a landslide flows downslope and enters the stream channel, creating a slurry of soil, water, boulders and woody debris that travels down the stream channel, scouring out debris, sediment and riparian vegetation. These flows can exceed 10,000 cubic meters in volume and travel distances ranging from meters to kilometers, at speeds greater than 10 meters per second (Swanson et al. 1987). Debris flows usually stop where the channel widens, the gradient declines, or constrictions impede their movement, often terminating in a large accumulation of debris or a debris dam. Events such as these are considered catastrophic

(>50 year recurrence interval) and are unpredictable. Disturbance by debris flow often leaves a channel devoid of LWD ('either scoured out or buried) with a downstream reach dammed by the flow terminus. This dam often acts as a sediment trap, reducing the gradient of the upstream channel reach, enhancing retention of newly recruited LWD due to the reduced transport capacity of the channel. Recovery periods depend on dominant input mechanisms, proximity of recruitable wood, and ability of the channel to retain wood that enters from upstream.

Management induced Disturbance and Recovery

in-channel LWD levels can be reduced by human activities. Harvest of stream side trees slows recruitment of the larger trees likely to be retained as functional wood in the stream, and stream cleaning directly reduces the quantity of in-channel lwd. During a disturbance period, usually the period of active harvest,, in-channel LWD levels change although research does not show agreement in characterizing change during this period. Some researchers have interpreted it as a time of little change (Swanson and Lienkaemper 1978) and others as a period of significant change,. (Bilby and Ward 1991). Stream cleaning has been shown to destabilize channels, and simplify available salmonid habitat types (Bilby 1984, Bryant 1981, 1983, Dolloff 1986, House and Boehne 1987).

Recovery can be defined as reaching LWD loading levels that mirror the conditions in the stream when the adjacent forest was old-growth, or as achieving levels of functional LWD that provide habitat capable of sustaining productive salmonid populations.

Initially, after harvest of the riparian area, levels of abundance and volume of in-channel LWD decreased with time since harvest (Grette 1985; Murphy and Koski 1989; Bilby and Ward 1991). There is disagreement about how rapidly these changes occur with estimates ranging from < 5 years (Bilby and Ward 1991) to approximately 50 years (Swanson and Lienkaemper 1978). Estimates of declines of in-channel LWD after clear cut harvest, over time, ranged from <1% per year (Grette 1985) to the percentages listed in Table 13 from Bilby and Ward (1991). Regrown riparian stands begin to contribute functional LWD 40 years after harvest, but at an insufficient rate to offset decomposition (Grette 1985).
Recovery rates of in-channel LWD levels have been inferred from estimating the age of pieces in the channel and correlating with the adjacent stand history (Grette 1985) More long-term studies of recovery rates (measured by tracking input and output of each individual piece) need to be clone.
Recovery of LWD requires regrowth of stream side trees to sizes functional in the channel and recruitment of these trees into the channel. This is a long-term process (100-600 years) due to time required for trees to become established, grow and be recruited to the channel.

Table 4.4. Decrease in Total Volume of LWD per 100 meters of Channel (Bilby and Ward 1991).

Mean stream width	**Decrease in volume by years after harvest from old-growth levels**	
	5 years	50 years
5 meters	22%	35%
10 meters	47	71
15 meters	86	94

Monitoring Variables/Concepts

Monitoring can focus on delivery, the processes of persistence or routing, or on the salmonid habitat attributes individually or in combination as shown in Table 4.5.

Table 4.5. Potential Parameters for Monitoring Change Due to LWD Disturbance and Recovery.

Process being monitored	**Delivery**	**Persistence**	**Fish habitat**
Examples of Potential Parameters	• rmz species composition and size (ht & diam.) • species growth rates • dominant input mechanism or process • distance from stream • pieces delivered to channel • piece volume per channel area (e.g., cubic	• in-channel piece numbers, size, volume • piece channel location • piece type (species) • decay class • decay rates • orientation • piece volume per channel area (e.g., cubic meters/ square meters)	• piece volume per channel area (e.g., cubic meters/ square meters) • pools forced by LWD (% wetted surface area and volume) • cover • piece function

Recommendations for Habitat Assessment and Monitoring

When monitoring LWD levels for disturbance and recovery, measuring in-channel piece volume per stream surface area is recommended for the most accurate characterization. The stream should be divided into segments and then, depending on the monitoring objective, reaches selected by the appropriate criteria. The degree of change to be detected, catastrophic events, and changes to the riparian structure (harvest) determine the sampling frequency. Gathering more information is not necessarily better, if the data gathering or measurement method is subjective (e.g., decay classifications) or not easily replicated. Table 4.6 displays additional monitoring guidelines based on the possible monitoring scenario.

Table 4.6. How monitoring at different points in the disturbance and recovery cycle will affect certain components of a monitoring plan.

Possible monitoring scenarios	**Hypothesis**	Paraaameters	**Sampling Frequency**	**Sampling Location**
Pre-disturbance	This is the environment that the biota evolved to fit. Monitor natural LWD disturbance and recovery regime and natural loading /levels to capture the diversity and accurately · characterize the baseline condition.	Number of pieces Volume of pieces Location, orientation, stability of pieces Function of pieces Pool surface area Average stream width	Every 5 -10 years or after a catastrophic event·	Selected response reaches, depends on objective.
Disturbance	Changes to the baseline condition are occurring. Monitor to capture the differences from the baseline condition. Test for significance.	Number of pieces Volume of pieces Location and Stability of pieces Function of pieces Pool surface area Average stream width	Annually or more often depending on objective,	Return to baseline reaches if possible, if no baseline was done, selected response reaches.
Post Disturbance	Changes to baseline condition have occurred Monitor to show change. Test whether they are moving in the direction of the changes charted during · disturbance or' toward the original baseline condition (recovery).	Number of pieces Volume of pieces Location and Stability of pieces Function of pieces Pool surface area Average stream width	Annually until riparian area stabilizes, then every 5-10 years, depending on objective,	Return to baseline reaches if possible, if no baseline was done, selected response reaches.

V. Stream Temperature

Trees not only provide large woody debris to the channel, they also provide shade to the stream and a control on solar radiation input.

Relation of Temperature to Habitat Attributes

Water temperature is one of the regulating factors of aquatic life in forest streams. Because salmonids are cold-blooded, the water temperature determines their internal temperature, and thus their metabolic rate. Water temperature helps determine how much oxygen is available for the fish. The ability of a liquid to hold a gas is inversely proportional to its temperature. In a stream this means the higher the temperature, the less dissolved oxygen it can hold. Group behavior can also be affected by water temperature changes, e.g., smolt migration can be hastened (Holtby 1988) and spawning migration delayed due to increased temperatures (Groot and Margolis 1991).

Temperature tolerances, preferred ranges, and effects have been much studied for salmonids, albeit with a focus on laboratory conditions and aquaculture (see Beschta et al. 1987 for a good review and discussion relating water temperature to forestry issues). For the purposes of this literature review, the focus will be on water temperatures ranges identified as optimal for the different salmonid species, as well as the upper lethal limits (Table 5.1), the Water Quality Standards for Washington State and how to monitor changes due to disturbance and recovery processes.

Table 5.1. Optimal Temperature Ranges and Upper Lethal Limits for Salmonid Species (Bell 1990).

Species	**Optimal Temperature** _Range	**Upper Lethal Limit**
Chum	11.1 - 14.4°C	25.5 °C
Chinook	7.2 - 14.4	25.0
Coho	11.6 - 14.4	25.5
Pink	5.5- 14.4	25.5
Sockeye	11.1 .. 14.4	24.4

The following passage from Rashin and Graber (1992) gives a good explanation of the temperature requirements of the water quality standards set by the State of Washington.

> The water quality' standards for surface waters in the State of Washington establish the beneficial uses of waters and incorporate specific numeric and narrative criteria for parameters such as water temperature. These criteria are intended to define the level of protection necessary to full$_3$, support the beneficial uses. The water quality standards include two types of temperature criteria applicable to forest streams: 1) an absolute maximum temperature not to be exceeded, and 2) a maximum allowable incremental increase in temperature that may be caused by nonpoint source activities (i.e. forest practices). The standards provide for different classifications of surface waters depending on water quality potential and beneficial uses to be protected. Streams subject to the RMZ [riparian management zone] provisions of the Forest Practices

Rules am either Class A or AA. (The actual classilication is based on the provisions found in CH 173-201-070 and 080 WAC, and is generally determined by whether the waterbody is within the drainage basin 0fa lake or stream which has been specifically designated Class AA.) Both Class A and AA streams are designated for the protection.of all aquatic life uses, including salmonid spawning, rearing, and migration.

Water quality criteria for temperature that apply to streams affected by forest management activities are described below. For Class AA streams, the maximum allowable temperature is 16,3 °C, except where exceeded by natural conditions. Incremental temperature increases caused by any nonpoint source activity (such as timber harvesting) may not exceed 2.8°C. For Class A Streams, the maximum allowable temperature is 18.3 °C, except where exceeded by natural conditions. Where natural conditions exceed the maximum for either stream type, increases due to human activities are limited to 0.3 °C. (In other words, the allowable incremental increase ranges from 0.3 to 2.8 °C depending on natural background conditions.)

Washington Forest Practices regulations also stipulate temperature requirements to protect fish habitat and other beneficial uses; the average maximum stream temperature should not exceed 15.6 °C for more than 7 consecutive days (Sullivan et al. 1990).

Processes Affecting Thermal Energy Delivery to Streams and Resulting Water Temperature Changes

The heating of water in small streams in forested catchments from direct or indirect effects of solar radiation has been discussed in great detail in Sullivan et al. (1990), Beschta et al. (1987), and Brown (1985). For this literature review and the purpose of examining monitoring strategies addressing changes in water temperature due to forest practices, we refer readers to these detailed examinations; of the actual physics of stream heating, while limiting this discussion to listing the processes and factors that are important in monitoring this input (Table 5.2).

Table 5.2. Processes that Affect. Water Temperature

Delivery **Process**	Natural **Factors Affecting Process**	**Management Practices Affecting Process**	**Dominant and Subdominant Rates of Process**
Solar radiation	stream size, width, depth, orientation, cloudiness, surrounding topography, type and density of vegetation adjacent to stream, humidity	removal or alteration of stream side vegetation, increase sediment input resulting in increased width to depth ratio	Chronic

Delivery **Process**	Natural **Factors Affecting Process**	**Management Practices Affecting Process**	**Dominant and Subdominant Rates of Process**
Groundwater input; quantity and temperature	climate, surrounding topography, air temperature, vegetation type and density;,_	removal or alteration of vegetation	Chronic

Case Studies

Several researchers have examined the effect of clear cutting on stream temperatures by recording maximum temperature increases for streams flowing through clear cuts and have found increases ranging from 7-13°F (3.9-7.2°C) (Greene 1950, Meehan et al. 1969, Patric 1970, Swift and Messer 1971 all as cited in Brown 1985).

Holtby (1988) found that clear cut logging of 41% of the basin of Carnation Creek on Vancouver Island, B.C. resulted in increased stream temperatures in all months of the year. Increases above prelogging temperatures ranged from 0.7° C in December to 3.2°C in August. For streams in the coastal hemlock zone, revegetation takes 15-30 year's (Summers 1982 as cited in Holtby 1988) and therefore the increased stream temperatures were expected to persist for at least 10 years

Levno and Rothacher (1967 as cited in Brown 1985) compared two watersheds in the Oregon Cascades. One stream had been denuded of stream side vegetation by a flood, and flowed through a clear cut. Mean monthly maximum temperatures increased by 7-12°F (3.9-6.7°C) during midsummer. The other watershed had been completely clear cut, however, logging debris collected in the stream channel and provided some shade. Mean monthly maximum temperatures increased by only 4°F (2.2°C) during the same period.

The Alsea Watershed Study compared two clear cut treatments. One watershed was patch cut such that approximately 25% of the area was clear cut in three small sections with buffer strips left along the stream The other watershed was completely clear cut and burned (Brown and Krygier 1970). The first watershed showed no significant increases in temperature. The second watershed (in the first summer after the cutting, debris clean out and burning) showed an increase in mean monthly maxima of 14°F (7.8°C) and an increase in annual maximum temperature of 28°F (15.5°C).

Beschta et al. (1987) present a review of research findings on temperature changes associated with forest management activities on forested catchments and show a range of 0.7°C per 100 meters to 15.8°C per 100 meters. The greatest differences in temperature occurred in Oregon streams, while the changes between average summer temperature maxima on Vancouver Island, B.C. showed the lowest differences.

Hatten and Conrad (1995) compared unmanaged and managed, low elevation sub.-basins in temperate rain forests of the Olympic Peninsula, Washington. Significant differences were found between the group means of water temperature of the managed and unmanaged sub-basins. Of the environmental variables measured, the greatest correlation with water temperature was shown by the proportion of the sub-basin classified as late seral stage forest.

Models

Several models for water temperature prediction or water temperature changes due to forest management activities were tested in Sullivan et al. (1990) for use by TFW (Timber, Fish and Wildlife) cooperators and readers should refer to that document for a thorough discussion. Table 5.3 presents the brief overview of three models thought to be useful to the preparation of temperature monitoring strategies.

Table 5.3. Water Temperature Models

Researcher	Objective	]Input Variables	Output Variables	Assumptions	Caveats
Adams and Sullivan 1989	To investigate the basic physics of stream temperature.	]Mean air temperature, air temperature fluctuations, daily average solar insolation, cloudiness, view factor (water to sky), air velocity, water vapor in air, stream depth, groundwater influx and temperature	Daily mean stream temperature, stream temperature fluctuations	Stream temperature is uniform in vertical and lateral directions.	

Researcher	Objective	Input Variables	Output Variables	Assumptions	Caveats
Brown 1985	To predict maximum temperature change for a stream running	Water travel time through proposed reach, midday solar angle, discharge, average wetted	Change in temperature (△T) in °F	Only applies for areas clearcut to stream edge, for gravel bottom	1) Frequent cross sections for streams with irregular

Management Induced Disturbance and Recovery

Temperature change produced by a given amount of heat is inversely proportional to the volume of water heated, or in other words, the discharge of the stream. Thus small streams should heat up faster than larger ones. The magnitude of the temperature change also varies directly with the surface area exposed to the sun by clear cutting, thus a wide shallow stream will heat up faster than a narrow, deeper one with the same discharge. The stream bed may affect the amount of energy that the stream will absorb. Much of the solar radiation striking the stream may be transmitted to the bottom, particularly when the stream is shallow and clear. Some of this energy is absorbed by the bed, especially if it is Solid rock. Heat flow into the bed of such streams may be as high as 15 - 20% of the incident heat (Brown 1985).

Where shade is reduced during harvesting, recovery to full mature forest shade levels may take approximately 5 to 10 years to reach 50 and 75% shade respectively according to a riparian study conducted by Summers (1982 as cited in Sullivan et al. 1990). Old growth forest sites averaged approximately 84% shade and recovery to this level of shading was estimated to take approximately 14 years.

Certain environmental factors have been shown to strongly affect or correlate with stream temperatures. A sound monitoring plan would need to measure these variables at the same time and in the same location as the stream temperature measurements. These variables include: shade provided by riparian vegetation, air temperature, discharge, stream width and depth, and groundwater inflow.

Monitoring Variables/Concepts

When monitoring water temperature, one can approach monitoring from several directions, as shown in Table 5.4,

Table 5.4. Monitoring Water Temperature

Process Being Monitored	Delivery	**Routing**	**Salmonid Habitat**
Examples of Potential Parameters	shade provided by riparian vegetation, water surface area, stream depth, solar radiation reaching stream, discharge, water temperature, air temperature, precipitation events	precipitation events, water travel time through delivery area, discharge, water temperature, location and amount of groundwater inflow	water temperature maximums and minimums (freezing)

Recommendations for Habitat Assessment and Monitoring

1. Monitoring Frequency - Determine the natural temperature diurnal and seasonal ranges. This can be done by using historical data, designing a baseline study, or using a comparable control area. The literature suggests that monitoring daily maximums for the months of maximum solar insolation is the sampling frequency that will be most useful for regulatory and comparability purposes. We recommend using the model presented by Brown (1985) for the purpose of establishing the range of months to be monitored.

Scale and Location - Sampling location is thoroughly discussed in Sullivan et al. (1990) and this document is recommended as a guideline for location selection. The TFW temperature screen as presented in Sullivan et al. (1990) is useful for selecting sensitive streams that can then be field ’verified as potential monitoring sites. Temperature changes occur in proportion to the discharge and temperature of the ’individual sources. Temperature changes on a basin scale as related to the history of harvest in the basin have been little studied. Determining the sampling locations and scale of the sampling effort needs to be done to the scale of the conclusions to be drawn from the data, for example, is the temperature study designed to determine temperature changes from one particular stream and harvest unit or is the study aimed at basin wide patterns in ’temperature change.

Recommended parameters for monitoring - As listed in the previous section, parameters need to be chosen to match the process being monitored.

Recommendations for future study - The extent of changes in groundwater temperature flowing through clear cut areas has not been well-documented and warrants further study.

VI. Peak Discharge

Water is the primary factor in the geomorphology of streams and the medium in which salmonids live. It is, therefore, of ultimate interest to the quality of salmonid habitat conditions. In this literature review, though, we will be focusing only on increased peak flows associated with timber management activities, the subsequent effects on salmonid habitat and how to monitor them.

Relation of Peak Flows to Habitat Attributes

Increased peak flows affect survival to emergence of eggs, and juvenile rearing. Salmonids lay their eggs in gravel nests (redds) in streambed gravels. The eggs hatch and develop into alevin while buried in the gravel. Development into free swimming fry takes several months, during which time movement of the gravel (scour and or deposition) can result in injury or death. Gravel scour is part of the :natural process of bed load sediment transport. Increased peak flows, though, increase the water velocity and thus the shear stress on the streambed gravels (Schuett-Hames et al. 1995).

Juvenile salmonids that rear over the winter in freshwater are also impacted by increased peak flows. The impacts can include downstream displacement and increased competition for space and food as the microhabitats with lower water velocities become more densely populated (Morgan and Hinojosa 1996).

Processes Affecting Delivery and Routing of Increased Peak Flows

A peak flow is the highest in--channel discharge level reached for a specific precipitation or storm event. Increased peak flows are caused by a larger proportion of the water reaching the channel sooner. Jones and Grant (1996) have shown that this phenomenon can be caused by the cumulative effects of timber harvest practices. The four major mechanisms speeding delivery and routing of the storm water discharge are (1) increased snow accumulation and melt, (2) decreased evapotranspiration, (3) decreased channel roughness, and (4) road extension of channel network. Mechanisms (1) and (2) affect the hillslope water balance and would be expected to increase peak discharge and storm flow volume, whereas mechanisms (3) and (4) affect flow routing and would be expected to speed storm flow, advancing the peak without changing the volume.

Case Studies

Increases in peak flows have been found to correlate with the type and size of vegetative growth after removal of vegetation through timber harvest and burning. Hicks et al. (1991) found increases in streamflows persisted for eight years following clear cutting and burning of a watershed and for sixteen years following the start of logging in another watershed. The differences were thought to be accounted for by differences in geomorphology; the first watershed had a relatively wide valley floor, allowing for development of hardwood stands in the riparian zone following logging. The other watershed had a narrow valley and limited sediment deposits, thus limiting the establishment of hardwoods.

Berris and Harr (1987) measured water outflow- from a clear-cut plot during a rain-on-snow event and found the it to be 21% greater than in the forested plot (both were at 900 meters above sea level).

Three small watersheds were examined for a large period of time (34 years) in the western Oregon Cascades at elevations ranging from 460 to 1070 meters above sea level. Watershed 1 (100% clear-cut) had significant increases in peak discharges and storm volumes for 22 years after treatment, significantly later peak times for 5 years after treatment, and significantly earlier begin times for 10 years after treatment. Watershed 3, had significantly higher peak discharges and earlier begin times and Watershed 3 (6% roads and 25% clear-cut) had significantly higher peak discharges, higher storm volumes and earlier begin times for 25 years after treatment (Jones and Grant 1996). The combination of roads and clear-cutting in the small basins produced a markedly different hydrologic response than clear-cutting alone, leading to significant increases in peak discharges in all seasons, and especially prolonged increases in peak discharges of winter events. These findings support the hypothesis that roads interact with clear-cutting to modify water flow paths and speed delivery of water to channels during storm events, producing greater changes in peak discharges than either clear-cutting or roads alone. They concluded that the gradual recovery time for peak discharges was attributable to changes in evapotranspiration and that the slower recovery of Watershed 1 was attributable to the fact that conifer cover had reached only 44%, 17 years after cutting versus the 63% coverage attained in Watershed 3.

Jones and Grant (1996) also looked at 6 large watersheds and found that road interactions with clear-cuts also appeared to increase peak discharges in large basins. Despite differences in basin size, geology, and elevation, all six basins had the same rate of response to cumulative cutting Differences in peak discharges were detectable when basins differed by only 5% in cumulative area cut.

The data to strongly suggest that there has been a large increase in peak discharges attributable to forest harvest in both small and large basins in the western Cascades of Oregon. The major mechanism responsible for these changes is the increased drainage efficiency of basins attributable to the integration of the road/patch clear-cut network with the pre-existing stream channel network (Jones and Grant 1996).

Management Induced Disturbance and Recovery

Increased peak flows have been shown in case studies to correlate with increased road and clear-cut patch densities, especially clear cut in conjunction with rain-on-snow events. The disturbance involves, then, both the removal of vegetation and the increased interception and routing of groundwater. Recovery involves the growth of vegetation. As long as the roads are active, they will continue to act as additional conduits for water to enter the stream channel system. From the case studies, we also learn that the type of vegetation grown will affect the rate of recovery, with conifers speeding recovery more than hardwoods and hardwoods speeding it more than low shrubs. Recovery times ranged from 5 to 25+ years, depending on local conditions.

Monitoring Variables/Concepts

In order to monitor for increased peak flows and the associated habitat effect of gravel scour, Table 6.1 shows some examples of potential parameters.

Table 6.1. Monitoring Increased Peak Flows and Habitat Effects

Process being monitored	**Potential Indices**	**Examples of Potential Parameters**
Hydrograph changes	• percentage of total basin area involved in different land uses • land use history • elevation • vegetation coverage changes • basin area	• discharge and time, • precipitation event type, and time
Gravel scour/ redistribution	• salmonid species and extent of use	• discharge, • scour depth, • scour locations, • gravel deposition, • redd locations

Recommendations for Habitat Assessment and Monitoring

1. Scale - Monitoring for increased peak flows should be done on a watershed basis in a watershed for which a multi-year record of flows exists. If baseline or historical data set does not exist, paired watershed studies are recommended. Pairing should be done by comparable basin area, climate, and vegetation associations. A pair should have a treated and an untreated basin or some variation thereof

2. Frequency and Length of Record - When monitoring for increased peak flows, the first step should be determining how to establish that a change has occurred. For this purpose, one can use historical (pre-treatment) data, a baseline study, or a comparable control watershed. These data- can be used to determine the recovery level that will signal the end of the monitoring effort. The monitoring should be done in conjunction with precipitation events of a predetermined recurrence interval or with discharge levels of a certain minimum size.

Parameters to be monitored - As in the previous section, parameters need to correlate with the process being monitored. Paired.-basin studies need to account for potential confounding variables.

References

Adams, T. N. and K. Sullivan. 1989. The physics of forest stream heating: a simple model, Prepared for the Washington Department of Natural Resources under the TFW Agreement, TFW-WQ3-90-007. Olympia, WA 39 pp.

Andrus, C.W., B. A. Long, and H.A. Froehlich. 1988. Woody debris and its contribution to pool formation in a Coastal stream 50 years after logging. Canadian Journal of Fisheries and Aquatic Science 45: 2080-2086.

Arnold, J. F. and L. J. Lundeen. 1968. South Fork Salmon River special survey: soils and hydrology. USDA Forest Service, Boise National Forest, Boise, ID.

Benda, L. 1985. Delineation of channels susceptible to debris flows and debris floods, in: International Symposium on Erosion, Debris Flow, and Disaster Prevention. Tsukuba, Japan. pp. 195-201.

Benda, L. 1990. The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA Earth Surface Processes and Land forms. 15:457-466.

Benda, L. 1995. Stochastic geomorphology: monitoring erosion and sediment yields in mountain basins in: Proceedings from a Symposium, Effects of Scale on Interpretation and Management of Sediment and Water Quality. IAHS Publication No. 226.

Benda, L. and T. Dunne. 1987. Sediment routing by debris flows, *In:* R. L. Beschta, T. Blinn, G. E. Grant, G. G. Ice, and F. J. Swanson reds]. Erosion and Sedimentation in the Pacific Rim, IAHS Publication 165. pp. 213-223.

Bender, E.A., T.J. Case, and M.E. Gilpin. 1984. Perturbation experiments in community ecology: theory and practice. Ecology 65: l-. 13.

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 Resources Research 23(1): 135-142.

Beschta, R. 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. Water Resources Research 14:6:1011-1016.

Beschta, R.L, R. E. Bilby, G.W. Brown, L. B. Holtby, and T.D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions, *In* E.O. Salo and T.W. Cundy reds.] Stream side Management: Forestry and Fisheries Interactions. College of Forest Resources, University of Washington, Seattle. pp. 191-223.

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

Bilby, R. E. and J. W. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in Western Washington. Transactions of American Fisheries Society 118: 386-387.

Bilby, R. E. and J. W. Ward 1991. Characteristics and Function of Large Woody Debris in Streams Draining Old-Growth, Clear-Cut, and Second-Growth Forests in Southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences 48:2499-2508.

Bisson, P.A., J.L. Nielson, R.A. Palmason, and L.E. Grove. 1982. A system of naming habitat types in small streams;, with examples of habitat utilization by salmonids during low streamflow, *In* NB. Armantrout [ed.]. Acquisition and utilization of aquatic habitat inventory information. Western Division, American Fisheries Society. Portland, Oregon. pp. 62-73

Bisson, P.A, R. E. Bilby, M. D. Bryant, C.A. Dolloft, G. B. Grette, R.A. House, M. L. Murphy, K V. Koski, and JR. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future, *In:* E. O. Salo and T. W. Cundy [eds.] *Stream side Management, Forestry and Fishery Interactions.* Contribution No. 57, College of Forest Resources, University of Washington, Seattle, WA. pp. 143-190.

Bjornn, T C. and D. W. Reiser, 1991. Hahitat requirements of salmonids in streams. *In:* W. R. Meehan [ed] Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. American Fisheries Society Special Publication 19, Bethesda, MD. pp. 83-138.

Brown, G.W. 1985. Forestry and Water Quality. [2nd edition] Oregon State University Book Stores, Inc. Corvalis, Oregon

Brown, G.W. and J.T. Krygier. 1970. Effects of clear cutting on stream temperature. Water Resources Research 6(4): 1133-1140. (as cited in Brown [1985] - original article not seen)

Bryant, M. D. 1985. Changes 30 years after logging in large woody debris, and its use by salmonids. Riparian Ecosystems and Their Management; Tucson, Arizona, April 16-18, pp. 329-334.

Bryant, M. D. 1983. The rote and management of woody debris in West Coast salmonid nursery streams. North American Journal of Fisheries Management 3: 322-330.

Bryant, M. D. 1981. Organic debris in salmonid habitat in Southeast Alaska: measurement and effects, *In* N.B. Armantrout [ed]. Acquisition and utilization of aquatic habitat inventory information. Western Division, American Fisheries Society. Portland, Oregon. pp. 259-265.

Cairns, Jr., J. 1990. Lack of theoretical basis for predicting rate and pathways of recovery. Environmental Management 14(5):517-526.

Cederholm, C. J. and Reid, 1.,. M. 1987. Impact of forest management on coho salmon *(Oncorhynchus kisutch)* populations of the Clearwater River, Washington: a project summary. *In:* E. O. Salo and T. W. Cundy [eds.] Stream side Management, Forestry and Fishery Interactions. Contribution No. 57, College of Forest Resources, University of Washington, Seattle, WA pp. 373-398.

Cederholm, C.J., L.M. Reid, and E.O. Sale. 1981. Cumulative effects of logging road sediment on salmonid populations' in the Clearwater River, JeffErson County, Washington. *In* Proceedings, Conference on Salmon Spawning Gravel: a Renewable Resource in the Pacific Northwest? Washington State University, Water Research Center Report 39, Pullman, WA. pp. 38-74.

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

Dolloff, C. A. 1986. Effects of stream cleaning on juvenile coho salmon and Dolly Varden in Southeast Alaska. Transactions of American Fisheries Society 115: 743-755.

Fausch, K. D. and T. G. Northcote. 1992. Large woody debris and salmonid habitat in a small Coastal British Columbia Stream. Canadian Journal of Fisheries and Aquatic Science 49: 682-693.

Fisher, S.G. 1990. Recovery processes in k)tic ecosystems: limits of successional theory. Environmental Management 14(5):725-736.

Furniss, M. J., T. D. Roelofs, and C. S. Yee, 1991. Road construction and maintenance. *lin:* W. R. Meehan [ed.] Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats American Fisheries Society Special Publication 19, Bethesda, Maryland. pp. 297-323.

Gippel, CJ. 1995. Environmental hydraulics of large woody debris in streams and rivers. Journal of Environmental Engineering 12l(5): 388-395.

Grant, G. E. 1986. Downstream effects of timber harvest activities on the channel and valley floor morphology of western Cascade streams. Ph.D. dissertation for Johns Hopkins University. Baltimore, MD. 246 pp.

Greene, G. E. 1950. Land use and trout streams. J. Soil and Water Cons. 5: 125-126. (as cited in Brown [1985] - original article not seen)

Grette, G. B. 1985. The role of large organic debris in juvenile salmonid rearing habitat in small streams. M.S. Thesis. University of Washington, Seattle.

Groot, C. and L. Margolis. 1991. Pacific Salmon Life Histories. UBC Press, University of British Columbia, Vancouver, British Columbia, Canada. 564 pp.

Grossman, G.D., J.F. Dowd, and M. Crawford. 1990. Assemblage stability in stream fishes: a review. Environmental Management 14(5):661-671.

Hatten, J. and R. Conrad 1995. A comparison of summer stream temperatures in unmanaged and managed sub-basins of Washington's Western Olympic Peninsula. Northwest Fishery Resource Bulletin, Project Report Series No. 4. Olympia, Washington. 52 pp.

Hicks, B. J., R. L. Beschta, and R. D. Hart. 1991. Long-term changes in streamflow following logging in Western Oregon and associated fisheries implications. Water Resources Bulletin 27(2): 217-226.

Holtby, L. B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon *(Oncorhynchus kisutch).* Canadian Journal of Fisheries and Aquatic Sciences 4.5:502-515.

House, R. A. and P. L. Boehne. 1987. The effect of stream cleaning on salmonid habitat and populations in a Coastal Oregon drainage. Western Journal of Applied Forestry 2(3): 84-87.

Johnson, A. C. 1991. The effects of landslide-dam-break floods on stream channel morphology. Unpublished M.Sc. Thesis, University of Washington, Seattle, WA. 90 pp.

Jones, J. A. and G. E. Grant. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. Water Resources Research 32(4): 959-974.

Kelly, J.R. and M. A. Harwell. 1990. Indicators of ecosystem recovery. Environmental Management 14(5):527-546.

Kelsey, H. M., R. Lamberson, and M. A. Madej. 1987. Stochastic model for the long-term transport of stored sediment in a river channel. Water Resources Research. 23(9):1738-1750.

Kennard, P., G. Pess, T. Beechie; R. Bilby, and D. Berg. 1997. *In press.* Riparian-in-a-box: a manager's tool to predict the impacts of riparian management on fish habitat. *In:* Forest-Fish Conference: Land Management Practices AffEcting Aquatic Ecosystems. Calgary, Alberta, Canada. May 1-4, 1996.

Koski, K V. 1975. The survival and fitness of two stocks of chum salmon *(Oncorhynchus keta)* from egg deposition to emergence in a controlled-stream environment at Big Beef Creek. Ph.D. dissertation University of Washington. Seattle, WA. 212 pp

Lamberti, G A., S.V. Gregory, L.R. Ashkenas, R.C. Wildman, and K.M.S. Moore. 1991. Stream ecosystem recovery following a catastrophic debris flow. Canadian Journal of Fisheries and Aquatic Science. 48:196-208.

Leopold, L. B., M. G. Wolman, and J. P. Miller, 1964. Fluvial Processes in Geomorphology. San Francisco: W. H. Freeman 522 pp.

Levno, A. and J. Rothacher. 1967. Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. USDA Forest Service. Pacific Northwest Forest and Range Experimental Station, Research Paper PNW-82.45 pp. (as cited in Brown [1985] - original article not seen)

Lichatowich, J.L., L. Mobrand, L. Lestelle., and T. Vogel. 1995. An approach to the diagnosis and treatment of depleted Pacific salmon populations in freshwater ecosystems. Fisheries. 20(1): 10-18.

Lienkaemper, G.W. and F.J. Swanson. 1987. Dynamics of large woody debris in streams in old-growth Douglas fir :forests. Canadian Journal of Forest Research. 17:150-156.

Lisle; T. E., 1982. Channel recovery from recent large floods in North Coastal California. *In:* Proceedings, Symposium on Watershed Rehabilitation in Redwood National Park and Other Coastal Areas. August 25 - 28, 1981, Center for Natural Resource Studies, Sacramento, CA.

MacDonald, A. and K W. Ritland. 1989. Sediment dynamics in type 4 and 5 waters: a review and synthesis. Report prepared for TFW/CMER Sediment, Hydrology & Mass Wasting Steering Committee and Washington Department of Natural Resources, Olympia, WA. 86 pp.

Madej, M. A. 1982. Sediment transport and channel changes in an aggrading stream in the Puget Lowland, Washington. In: F. J. Swanson, R.. J. Janda, T. Dunne, and D. N. Swanston eds. Sediment Budgets and Routing in Forested Drainage Basins. USDA Forest Service PNW Research Station, General Technical Report PNW-141. pp. 5-23.

Madej, M. A. 1992. Changes in channel-stored sediment, Redwood Creek, northwestern California. US Geological Survey Open-File Report 92-34 39 pp.

Madej, M. A. and H. M. Kelsey. 1982. Sediment routing in stream channels: its implications for watershed rehabilitation]n: Proceedings, Symposium on Watershed Rehabilitation in Redwood National Park and Other Coastal Areas. August 25 - 28, 1981, Center for Natural Resource Studies, Sacramento, CA. pp. 17-25.

Madej, M. A. and V. Ozaki. 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. Earth Surface Processes and Land forms. 21:911-927.

McDade, M. H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. VanSickle. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research. 20: 326-330.

McNeil, W. J. 1962. Mortality of pink and chum salmon eggs and larvae in Southeast Alaska streams. Doctoral Dissertation. University of Washington College of Fisheries. Seattle, WA. 270 pp.

McNeil, W. J. 1966. Effect of stream flow on survival of pink and chum salmon in spawning beds. Fisheries Bulletin (U. S.) 6:5: 459-523.

Meehan, W.R., W.A. Farr, D.M. Bishop, and J.H. Patric. 1969. Some effects of clear cutting on salmon habitat of two Southeast Alaska streams. USDA Forest Service. Pacific Northwest Forest and Range Experimental Station. Research Paper PNW-82. 45pp. (as cited in Brown [1985] - original paper not seen)

Megahan, W. F. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho batholith. *In:* F. J. Swanson, R. Janda, T. Dunne, and D. N. Swanston [eds.] Sediment Budgets and Routing in Forested Drainage Basins. USDA Forest Service PNW Research Station, General Technical Report PNW-141. pp. 114-121

Megahan, W.F., W.S. Platts, and B. Kulesza. 1980. Riverbed improves over time: South Fork Salmon. *In:* Symposium on Watershed Management, vol. 1. American Society of Civil Engineers, New York, NY. pp. 380-395.

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. *ln: R. F.* Hadley [ed]. Proceedings of the Albuquerque Symposium, Drainage Basin Sediment Delivery, August 4-8. IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, England. pp. 31-39.

Megahan, W. F., J. P. Potyondy, and K. A. Seyedbagheri. 1992. Best management practices and cumulative effects from sedimentation in the South Fork Salmon River: an Idaho case study. *In:* R.J. Naiman [ed.] Watershed Management: Balancing Sustainability and Environmental Change. Springer-Verlag. New York, NY. pp. 401-414.

Minore, D. and H. G. Weatherly. 1993. Riparian trees, shrubs, and forest regeneration in the coastal mountains of Oregon. New Forests. 8:249-263.

Montgomery, D. R. and J. M. Buffington. 1993. Channel classification, prediction of channel response, and assessment of channel condition. Report prepared for TFW/CMER Sediment, Hydrology & Mass Wasting Steering Committee and Washington Department of Natural Resources, Olympia, WA. 84 pp.

Morgan, A. L. and F. Hinojosa. 1996. Literature review and monitoring recommendations for salmonid winter habitat, Prepared for the Washington Department of Natural Resources under the TFW agreement. TFW-AM-9-96-004. Olympia, WA. 26 pp.

Murphy, M. L. 1985. Die-offs of pre-spawn adult pink salmon and chum salmon in southeastern Alaska. North American Journal of Fisheries Management. 5:302-308.

Murphy, M. L. and K V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for stream side management. North American Journal of Fisheries Management. 9:427-436.

Naiman, R. J., T. J. Beechie, L. E. Benda, D. R. Berg, P. A. Bisson, L. H. MacDonald, M. D. O'Connor, P. L Olson, E. A. Steel. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal ecoregion. *In:* R.J. Naiman [ed.] Watershed Management: Balancing Sustainability and Environmental Change. Springer-Verlag. New York. pp. 127-.88.

Niemi, G J., P. DeVore, N. Detenbeck, D. Taylor, A. Lima, J. Pastor, J. D. Yount, and R. J. Naiman. 1990. Overview of case studies on recovery of aquatic systems from disturbance. Environmental Management. 14(5): 571-587.

Patric, J.H. 1970. Changes in streamflow, duration of flow, and water quality on two partially clear cut watersheds in West Virginia. Trans. AGU 50:144 Abstract only (as cited in Brown [1985] - original abstract not seen)

Pentec Environmental. 1991. Methods for testing effectiveness of Washington forest practices rules and regulations with regard to sediment production and transport to streams. Report prepared for TFW/CMER Water Quality Steering Committee and Washington Department of Natural Resources by Pentec Environmental.

Perkins, S,J. 1989. interactions of landslide-supplied sediment with channel morphology in forested watersheds. Unpublished M. Sc. Thesis. University of Washington, Seattle, WA 104 pp.

Peterson, N.P., and L.M. Reid. 1984. Wall-based channels: their evolution, distribution, and use by juvenile coho salmon in the Clearwater River, Washington, *In* J.M. Walton and D.B. Houston [eds.] Proceedings of the Olympic Wild Fish Conference, March 23-25, 1983. Fisheries Technical Program, Peninsula College. Port Angeles, WA. pp. 215-225.

Pitlick, J. 1993. Response and recovery of a subalpine stream following a catastrophic flood. Bulletin of the Geological Society of America. 105: 657-670.

Platts, W. S., R. J. Torquemada, M. L. McHenry, and C K Graham. 1989. Changes in salmon spawning and rearing habitat from increased delivery of fine sediment to the South Fork Salmon River, Idaho Transactions of the American Fisheries Society. 118:274-283.

Ralph, S. C., G. C. Poole, L L. Conquest, and R. J. Naiman. 1994. Stream channel morphology and woody debris in logged and unlogged basins of Western Washington. Canadian Journal of Fisheries and Aquatic Science 51:37-51.

Rashin, E. and C. Graber. 1992. Effectiveness of Washington forest practice riparian management zone regulations for protection of stream temperature. TFW-WQ6-92-001 Washington Department of Natural Resources, Olympia, WA.

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

Reneau, S. L., and Dietrich, W. E. 1987. Size and location of colluvial landslides in a steep forested landscape. *In.' R.L.* Beschta, T. Blinn, G. E. Grant, G. G Ice, and F. J. Swanson [eds.] Erosion and Sedimentation in the Pacific Rim. IAHS Publication 165. pp. 39-48.

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

Robison, E.G. and R.L. Beschta. 1990. Identifying trees in riparian areas that can provide coarse woody debris to streams..Forest Science. 36(3):790-801

Schuett-Hames, D.E., R. Conrad, A.E. Pleus, and K Lautz. 1995. Salmonid spawning gravel scour module. TFW-AM -95-02. Washington Department of Natural Resources. Olympia, WA

Scrivener, J.C and M.J. Brownlee. 1989. Effects of forest harvesting on spawning gravel and incubation survival of chum *(Oncorhynchus keta)* and coho salmon *(Oncorhynchus kisutch)* in Carnation Creek, British Columbia. Canadian Journal of Fisheries and Aquatic Science. 46: 681-696.

Sedell, J.R., GH. Reeves, F.R. Hauer, J.A Stanford, and C.P. Hawkins. 1990. Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems. Environmental Management. 14(5):711-724.

Sidle, R. C., A. J. Pearce and C. L. O'Loughlin. 1985. Hillslope Stability and Land Use. Water Resource Monograph 11, American Geophysical Union. 140 pp.

Sonnevil, R. A. and W. E. Weaver, 1982. The evolution of approaches and techniques to control erosion on logged lands in Redwood National Park, 1971 - 1981. In: Proceedings, Symposium on Watershed Rehabilitation in Redwood National Park and Other Coastal Areas. August 25 - 28, 1981, Center for Natural Resource Studies, Sacramento, CA. pp. 258-2'72

Sullivan, K., J. Tooley, K. Doughty, J. E. Caldwell, P. Knudsen. 1990. Evaluation of prediction models and characterization of stream temperature regimes in Washington. TFW-WQ-90-006. Washington Department of Natural Resources, Olympia, Washington. 224p

Sullivan, K, T. E. Lisle, C. A. Dollof, G. E. (kant, and L. M. Reid. 1987. Stream channels: the link between forests and fishes *In:* E.O. Salo and T.W. Cundy [eds.] Stream side management: forestry and fishery interactions. College of Forestry Resources, University of Washington. Seattle, WA. pp. 39-97.

Summers, RP. 1982. Trends in riparian vegetation regrowth following timber harvesting in Western Oregon watersheds· M. Sc. thesis. Oregon State University, Corvallis, Oregon.

Swanson, F. J., R. L. Fredriksen, and F. M. McCorison. 1982. Material transfer in a · western Oregon forested watershed. *In:* R. L. Edmonds [ed.] Analysis of Coniferous Forest Ecosystems in the Western United States. Hutchinson Ross, Stroudsburg, PA. pp. 233-266

Swanson, F. J., L. E. Benda, S. H. Duncan, (G. E. Grant, W. F. Megahan, L. M. Reid, and R. R. Zimmer. 1987a. Mass failures and other processes of sediment production in Pacific Northwest forest landscapes. *In:* E. O. Salo and T. W. Cundy [eds.] Stream side Management, Forestry and Fishery Interactions. Contribution No. 57, College of Forest Resources, University of Washington, Seattle, WA. pp. 39-97.

Swanson, F. J., G. E. Grant, and G. W. Lienkaemper. 1987b. 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., M. D. Bryant,, G.W. Lienkaemper, and J.R. Sedell. 1984. Organic debris in small streams, Prince of Wales Island, Southeast Alaska. United States Department of Agriculture, Forest Service, General Technical Report PNW-166. Pacific Northwest Forest and Range Experiment Station. Portland, Oregon.

Swanson, F. J. and G. W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific Northwest streams. United States Department of Agriculture Forest Service, General Technical Report, PNW-69. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. 15 pp

Swanston, D. N. 1991. Natural processes. American Fisheries Society Special Publication 19:139-179.

Swift, L. W. and J. B. Messer. 1971. Forest cuttings raise temperatures of small streams in the southern Appalachians. Journal of Soil and Water Conservation 26(3): 111-116. (as cited in Brown [1985] - original article not seen)

Tagart, J. V. 1976. The survival from egg deposition to emergence of coho salmon in the Clearwater River. Unpublished M.Sc. Thesis, University of Washington, Seattle, WA. 101 pp.

Tripp, D. B. and V. A. Poulin. 1986. The effects of mass wasting on juvenile fish habitats in streams on the Queen Charlotte Islands. BC. Ministry of Forests and Lands.

VanSickle, J. and S.V. Gregory. 1990. Modeling inputs of large woody debris to streams from falling trees. Journal of ForeSt Research 20:1593-1601.

Wickett, W. P. 1958. Review of certain environmental factors affecting the production of pink and chum salmon. Journal of the Fisheries Research Board. Canada. 15(5) 1103-1126.

Wolman, M. G. and J. P. Miller. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology. 68:54-74.

Yount, J. D. and G. J. Niemi. 1990. Recovery of lotic communities and ecosystems from disturbance: a narrative review of case studies. Environmental Management 14(5):547-570.