

Effects of Turbidity and Suspended Solids on Salmonids

By
Jeff Bash, Cara Berman, and Susan Bolton

Center for Streamside Studies
University of Washington

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Abstract

Human activities in Northwestern watersheds, including logging, grazing, agriculture, mining, road building, urbanization, and commercial construction contribute to periodic pulses or chronic levels of suspended sediment in streams. Suspended sediment is associated with negative effects on the spawning, growth, and reproduction of salmonids. Effects on salmonids will differ based on their developmental stage. Suspended sediments may affect salmonids by altering their physiology, behavior, and habitat, all of which may lead to physiological stress and reduced survival rates. A sizable body of data (laboratory and field-based) has been gathered in North America focusing on the relationship between turbidity, total suspended sediments, and salmonid health. The controlled environment of laboratory studies tends to give clearer results than field studies.

Understanding the relationship between turbidity measurements, suspended sediments, and their effects on salmonids at various life stages will assist agencies implementing transportation projects to devise techniques to reduce temporary and chronic erosion and sedimentation associated with these activities. There are three primary ways in which sediment in the water column is measured: turbidity, total suspended solids, and water clarity. While these measures are frequently correlated with one another, the strength of correlation may vary widely between samples from different monitoring sites and between different watersheds. Turbidity is currently in widespread use by resource managers, partially due to the ease of taking turbidity measurements. In addition, current state regulations addressing suspended sediment are usually NTU-based. The disadvantage of turbidity is that it is only an indicator of suspended sediment effects, rather than a direct measure, and may not accurately reflect the effect on salmonids.

Protection of Washington State's salmonids requires that transportation officials consider the effect of suspended sediments released into streams during transportation projects. Many state and provincial criteria are based on a threshold of exceedance for background levels of turbidity. However, determining natural background levels of turbidity is a difficult endeavor. Turbidity measures may be affected by 1) differing physical processes between watersheds including geologic, hydrologic and hydraulic conditions; 2) legacy issues (activities historically conducted in the watershed); and 3) problems with instrumentation and repeatability of turbidity measurements. Altered systems may not provide accurate baseline conditions.

The inconsistent correlation between turbidity measurements and mass of suspended solids, as well as the difficulty in achieving repeatability using turbidimeters contributes to concerns that turbidity may not be a consistent and reliable tool determining the effects of suspended solids on salmonids. Other factors, such as life stage, time of year, size and angularity of sediment, availability of off-channel and tributary habitat, and composition of sediment may be more telling in determining the effect of sediment on salmonids in Northwestern rivers.

Although salmonids are found in naturally turbid river systems in the Northwest, this does not necessarily mean that salmonids in general can tolerate increases over time of suspended sediments. An understanding of sediment size, shape, and composition, salmonid species and life history stages, cumulative and synergistic stressor effects, and overall habitat complexity and availability in a watershed is required.

For short-term construction projects, operators will need to measure background turbidities on a case by case basis to determine if they are exceeding regulations. However, transportation projects may also produce long-term, chronic effects. Short-term pulses will presumably have a different effect on salmonids than chronic exposure.

To adequately protect salmonids during their freshwater residence, TSS data on physiological, behavioral, and habitat effects should be viewed in a layer context incorporating both the spatial geometry of suitable habitat and the temporal changes associated with life history, year class, and climate variability. Spatial and temporal considerations provide the foundation to decipher legacy effects as well as cumulative and synergistic effects on salmonid protection and recovery.

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I. Introduction

Human activities in Northwestern watersheds, including logging, grazing, agriculture, mining, road building, urbanization, and commercial construction have often resulted in periodic pulses or chronic levels of suspended sediment in streams. Suspended sediment is associated with negative effects on the spawning, growth, and reproduction of salmonids (e.g., Noggle 1978, Berg 1982, Lloyd et al. 1987, Reid 1998).

Effects on salmonids will differ based on their developmental stage. Suspended sediments may affect salmonids by altering their physiology, behavior, and habitat, all of which may lead to physiological stress and reduced survival rates. A sizable body of data has been gathered in North America focusing on the relationship between turbidity, total suspended sediments, and salmonid health.

Recent listings of salmonids under the Endangered Species Act (ESA) and the desire to protect and restore declining stocks have increased interest in the relationship between the release of fine sediment and salmonid productivity and survival. The purpose of this report is to provide an analysis of the current state of the science regarding the relationship between turbidity levels and the survival, reproduction, and growth functions of salmonids. We will also examine research that measures the effect of total suspended sediment on the health of salmonids.

Transportation projects often include activities that may negatively affect water quality, via disturbance of instream sediments for bridge and culvert construction or stormwater runoff from transportation construction sites (E. Molash, pers. commun.). Road-related erosion may significantly increase chronic turbidity levels in streams (Reid 1998). Road-related erosion may also affect subsurface flows, affecting upwelling in the stream (Sedell et al. 1990). It should be noted that much of the research on the effects of roads on suspended sediment and turbidity has focused on unpaved forest roads.

Understanding the relationship between turbidity measurements, suspended sediments, and their effects on salmonids at various life stages will assist agencies implementing transportation projects to devise techniques to reduce temporary and chronic erosion and sedimentation associated with these activities. Methods such as soil covers, project staging, land clearing windows, and water treatment systems could be implemented to prevent occurrence of critical turbidity levels (E. Molash, pers. commun.).

II. Definitions

Measurements

There are three primary ways in which sediment in the water column is measured: turbidity, total suspended solids, and water clarity. Although these three metrics measure different aspects of suspended sediments, they are often incorrectly used in research papers (A. Steel, pers. commun.). While these measures are frequently correlated with one another, the strength of correlation may vary widely between samples from different

monitoring sites and between different watersheds (Duchrow and Everhart 1971, A. Steel, pers. commun.). For example, parent material in a basin, weathering rate, texture of sediment and soils produced through weathering and erodibility all have a great influence on the amount, texture, and behavior of fine sediments in streams (Everest et al. 1987).

Turbidity is an optical property of water where suspended and dissolved materials such as silt, clay, finely divided organic and inorganic matter, chemicals, plankton, and other microscopic organisms cause light to be scattered rather than transmitted in straight lines. Measurements of turbidity have been developed to quickly estimate the amount of sediment within a sample of water and to describe the effect of suspended solids blocking the transmission of light through a body of water (Lloyd 1987).

Turbidity is usually measured by nephelometry – the relative measurement of light scattering through a restricted range of angles to the incident light beam. Typically, nephelometers detect light scattered by a water sample usually at 90° to the incident beam. Nephelometric turbidity units (NTUs) are used as a rough index of the fine suspended sediment content of the water (Davies-Colley and Smith 2000). In the past, turbidity was measured using Jackson Turbidity Units (JTUs). The Jackson Candle Turbidimeter was limited in that it could not measure turbidities lower than 25 JTU and was dependent on human judgment (Web Site Ref. #3). At high turbidities, JTUs and NTUs are roughly equivalent (Lloyd 1987). Please note that JTUs are only used in this report in tables culled from previous literature reviews.

Total Suspended Solids (TSS) represents the actual measure of mineral and organic particles transported in the water column. TSS is an important measure of erosion, and is linked to transport of nutrients, metals, and industrial and agricultural chemicals through river systems. Suspended sediment consists primarily of silt and clay-size particles that may be rapidly transported downstream and locally deposited on floodplains and overbank storage locations or may infiltrate into gravel interstices of the bed (Everest et al. 1987). Note that in older literature, TSS may also be referred to as suspended sediment concentration (SSC). This term will be used in the literature review where appropriate. Fluctuating TSS levels may influence aquatic life from fish to phytoplankton. Fine particles may carry substances that are harmful or toxic to aquatic life.

TSS is determined by measuring the residue in a well-mixed sample of water which will not pass a standard (glass fiber) filter. The residue trapped on the filter is dried (103-105 °C) and reported in units of weight per volume (typically mg/l) (Sorenson et al. 1977).

Water clarity, a direct measure of visible distance through water is another important measure related to the presence of sediment in the water column. Visual water clarity describes the distance that an organism can see underwater. Water clarity is affected by suspended and dissolved materials (Davies-Colley and Smith 2000). Correlations

between visual water clarity and turbidity (NTU) or TSS may vary dramatically between watersheds.

Changes in water clarity alter the balance between predators and prey and may have a strong effect on individual behaviors (A. Steel, pers. commun.). Historically, water clarity has been measured with a Secchi disk, a black and white disk submerged vertically into the water until it can no longer be seen (Davies-Colley and Smith 2000).

Three water quality tests related to sedimentation in streams.

Turbidity	Total Suspended Solids	Water Clarity
Measure of the refractory characteristics of material in the water. Not always correlated with total suspended solids	Actual measure of the amount of sediment suspended in the water column	Measure of visual distance in the water column

Limitations of Using Turbidity as a Measurement

The widespread use of turbidity as a water quality standard and indicator of suspended solid concentration can, at least in part, be attributed to the ease and cost of using a nephelometric turbidity meter in the field (Davis-Colley and Smith 2000) in comparison to the direct measurement of suspended solids. Duchrow and Everhart (1971) noted that direct measurement of settleable solids is difficult and time consuming.

Turbidity cannot always be correlated with suspended solid concentrations due to the effects of size, shape, and refractive index of particles (Sorenson et al. 1977). Duchrow and Everhart (1971) noted that turbidity measurements are primarily useful if: 1) a major portion of the total turbidity is contributed by settleable solids; 2) a relationship exists between turbidity readings and weight per unit of volume of suspended sediment and; 3) if a reliable meter is available.

Duchrow and Everhart (1971) tested different materials to determine if similar turbidity readings were obtained at the same concentration. At higher turbidity readings, they found a poor correlation between readings and suspended sediment concentrations (SSC) for all materials tested. Duchrow and Everhart (1971) questioned the use of turbidity as a parameter for establishing water quality standards, as too many factors must remain constant before a turbidity measurement can be converted to a corresponding SSC.

The relationship between turbidity and SSC may also change along a downstream gradient from a sediment source. Larger particles, which generally produce less turbidity per unit concentration than smaller particles, gradually settle out, thus shifting the turbidity versus SSC relationship to a higher NTU per unit SSC in reaches progressively farther down stream (Lloyd 1987).

Davies-Colley and Smith (2000) have suggested that water clarity is a more useful measure for determining the effect of suspended solids. These researchers suggest that turbidity is only a relative measurement that has no environmental relevance in itself, unless calibrated to clarity or some other absolute optical quantity or to suspended sediment mass concentration, at each site of interest.

This research implies that turbidity may not be a reliable tool for determining the effects of suspended solids on salmonids. The inconsistent correlation between turbidity measurements and mass of suspended solids, as well as the difficulty in achieving repeatability using turbidimeters contributes to concerns regarding this technique.

Turbidity Meters

The consistency of turbidimeters is an issue of concern. Duchrow and Everhart (1971) tested three different turbidimeters and found that there was a highly significant difference between readings on the same sample of suspended sediment. Further examination revealed increasing variance between readings with an increase in turbidity. Highly significant differences were also present between readings obtained on the seven materials for each meter. Recent studies in King County also noted problems with reliability and consistency of turbidimeters (D. Booth, pers. commun.)

Summary

Turbidity, TSS and water clarity are three common measures used to determine the effect of suspended sediment on salmonids. Turbidity is currently in widespread use by resource managers, partially due to the ease of taking turbidity measurements. In addition, current state regulations addressing suspended sediment are usually NTU-based. The disadvantage of turbidity is that it is only an indicator of suspended sediment effects, rather than a direct measure, and may not accurately reflect the effect on salmonids.

Other factors, such as life stage, time of year, size and angularity of sediment, availability of off-channel and tributary habitat, and composition of sediment may be more telling in determining the effect of sediment on salmonids in Northwestern rivers. In addition, many watersheds have been affected by land use that alters sediment input and transport, and therefore do not provide accurate baseline conditions. Unaltered systems display wide ranges of turbidity over space and time, and therefore long-term data are needed to understand baseline conditions.

III. Natural Background Levels of Turbidity in the Pacific Northwest

Determining natural background levels of turbidity is a difficult endeavor. Turbidity measures may be affected by 1) differing physical processes between watersheds; 2) legacy issues (activities historically conducted in the watershed); and 3) problems with instrumentation and repeatability of turbidity measurements (as mentioned in the previous section).

Turbidity can vary between watersheds, based on the geology of each particular basin. For example, systems fed by glacial meltwater often have higher turbidities than other systems (Lloyd et al. 1987). In addition, tributaries and stream segments within the same system may have widely divergent background turbidities. Headwater streams tend to be less turbid than mainstems or estuaries – faster flowing water transports suspended sediment downstream quickly. The patchiness of turbidity, both spatially and temporally, influences how salmonids use a river system in various life stages (Sedell et al. 1990).

In Northwestern watersheds, natural background turbidity varies on a seasonal basis depending on when precipitation and runoff occur (higher in spring in the Fraser River, Servizi and Martens 1987) and depends on the hydrologic regime (lowland Washington streams typically see higher turbidity in fall and winter; **Appendix A**). Increased rainfall and storm events usually produce an increase in erosion and transport of sediments deposited in streams. Monitoring at specific sites throughout a watershed would allow managers to understand the range of change that occurs at a particular site and across the watershed. Methods of monitoring turbidity vary in quality and convenience and their effectiveness changes with stream size (E. Ritzenthaler, pers. commun.).

The State of Washington's 1999 Water Quality Data Report provides water quality data points for a number of Washington state creeks and rivers, including turbidity measurements (Web Site Ref. #11). Twelve measures were taken between the end of 1998 and September of 1999. Monthly values for turbidity from this report for four sites (two on the Stillaguamish, one on the Skagit, one on the Samish) are in **Appendix A**. Note the fluctuation in turbidity at some of these monitoring stations over a twelve month period. In order to determine "natural background turbidity," continuous measurements would be necessary over time and across space. Historical and current changes to the system affecting sediment input and processes, load, and transport must also be understood. This data set does not provide enough context to determine "natural background turbidity." In addition to state water quality data, a sample of data collected by King County METRO is included in **Appendix A**. Three rivers were sampled in 1988-1999 to determine where turbidity and total suspended solids were of concern.

Without continuous monitoring throughout a basin, turbidity data only provides a series of scattered data points that are not linked to temporal or spatial parameters of the watershed. Without this context, it is difficult to make a determination regarding how turbidity levels are affecting the system. This problem is inherent in the collection of water quality data and development of water quality criteria.

Summary

In order to develop "natural" background turbidities, a stratified sample allowing one to differentiate between different physical and biological processes affecting watersheds is necessary. Continuous sampling across these systems may also provide information on how salmonids persist within highly variable systems. The historical legacy of systems is also an important and necessary factor to consider in evaluating this information.

IV. Effects of Turbidity and Suspended Solids on Salmonids

Sedimentation derived from land use activities is recognized as a primary cause of habitat degradation in the range of west coast chinook, steelhead, cutthroat, and bull trout (USFWS 1998, Web Site Ref. #6). Land-use practices, through alteration of vegetation, hydrology and soil structure can alter the delivery of fine and coarse sediments to streams, thus affecting salmonid habitats. Sediment delivery rates and composition are controlled by topography, climate, geology, hydrology, and vegetation (Spence et al. 1996).

The alteration of upslope hydrological and erosional processes with associated changes in instream hydrological, erosional, and depositional processes has resulted in a reduction in channel depth and increased fine and coarse sediment load. Logging, grazing, irrigation, stream channelization, chemical and nutrient applications, mining, agriculture, road construction, dam development and operation, and urban and rural development have played a role in altering upslope and instream physical and biological processes (Berman 1998).

Range of Effects on Salmonids

A range of studies have illustrated the effect of turbidity levels beyond natural background on the physiology and behavior of salmonids (Lloyd 1987, Everest et al. 1987, Newcombe and MacDonald 1991, Gregory and Northcote 1993). Lloyd (1987) suggested that high levels of suspended solids may be fatal to salmonids, while lower levels of suspended solids and turbidity may cause chronic sublethal effects such as loss or reduction of foraging capability, reduced growth, resistance to disease, increased stress, and interference with cues necessary for orientation in homing and migration.

Salmonid populations not normally exposed to high levels of natural turbidity or exposed to anthropogenic sediment sources may be deleteriously affected by levels of turbidity considered to be relatively low (18-70 NTU) (Gregory 1992). Low levels of turbidity appear to correspond to sediment concentrations that may adversely affect coldwater salmonids (Lloyd 1987).

Newcombe and MacDonald (1991) grouped effects of sediment on salmonids into three categories: lethal, sublethal and behavioral.

Lethal effects kill individual fish, cause overall population reductions, and damage the capacity of the system to produce future populations. This category includes reductions caused by sublethal or behavioral effects.

Sublethal effects relate to tissue injury or alteration of the physiology of an organism. Effects are chronic in nature and while not leading to immediate death, may produce mortalities and population decline over time.

Behavioral effects are described by any effect that results in a change of activity usually associated with an organism in an undisturbed environment. These changes may lead to immediate death or population decline or mortality over time.

It is apparent that salmonids have the ability to cope with some level of turbidity at certain life stages (Gregory and Northcote 1993). Evidence of this is illustrated by the presence of juvenile salmonids in turbid estuaries prior to leaving for the ocean and in local streams characterized by high natural levels of glacial silt, and therefore high turbidity and low visibility (Gregory and Northcote 1993).

Table 1. Effects of turbidity on salmonids

Physiological	Behavioral	Habitat
gill trauma	avoidance	reduction in spawning habitat
osmoregulation	territoriality	effect on hyporheic upwelling
blood chemistry	foraging and predation	reduction in BI habitat
reproduction and growth	homing and migration	damage to redds

Cumulative Effects

Ecological setting, landscape and evolutionary processes, and the physiological and behavioral response to sediment regime alteration are each important and contribute to our understanding of species response to turbidity. Therefore, it is important to examine a system as opposed to single effects or sites – without ecosystem based options for salmonids, species flexibility is diminished in responding to variable sediment loading (Berman 1998).

Anthropogenic disturbances often differ from natural disturbances in magnitude, frequency, and duration of events. Cumulatively, anthropogenic disturbances may decrease system heterogeneity, as well as connectivity. This reduces refuge options available to species during disturbance events. Altered levels of turbidity are just one of many conditions that may have a cumulative effect on the health and survival of salmon stocks.

While many laboratory studies have been performed to determine the effect of sediments on salmonids, the cumulative effect on salmonids is difficult to capture. Many of the effects on salmon are synergistic in nature; one effect can lead to a host of other effects that may affect the growth, reproduction, and survival of the fish. The following factors mediate effects of sediment on salmonids.

Environmental Factors Affecting the Effect of Sediment on Salmonids

- Duration of exposure
- Frequency of exposure
- Toxicity
- Temperature
- Life stage of fish

- Angularity of particle
- Size of particle
- Type of particle
- Severity/magnitude of pulse
- Natural background turbidity of area (e.g. watershed position, legacy)
- Time of occurrence
- Other stressors and general condition of biota
- Availability of and access to refugia

Salmonid response (often measured in terms of physical stress) is dependent on environmental factors such as duration of exposure and temperature (Servizi and Martens 1992). Rogers (1969) suggested that the variability in tolerance to suspended sediment could be explained by sediment particle characteristics, water temperature, species differences and other stressors that might have synergistic effects.

An example of a synergistic effect of sediment can be illustrated by examining the avoidance response of salmonids to turbid water. Life history stages and populations sensitive to sediment loads may be forced to move to other areas of the system to avoid negative effects on survival. These “turbidity refugia” must be available and accessible. Stream reach or segment emigration is a bioenergetic demand that may affect the growth or reproductive success of the individual.

To illustrate seasonal and population differences, an example from the Western Olympic Peninsula is provided. H. Michael (pers. commun.) suggested that fish respond differentially to TSS in summer and winter. He noted that protective mucous secretions are inadequate during summer months and thereby expose individuals to increased risks. There are also salmonid populations that thrive in glacially turbid streams. However, biological and physical mechanisms related to these systems are unclear. Finally, “turbidity refugia” such as tributaries, sloughs, off-channel habitat, and lakes are important during different parts of the year. Organismic response to variables such as TSS require further understanding and evaluation.

Reduction in Buffering Capacity

The overall buffering capacity of a system may be reduced by frequent sediment loading. Salmonids are known to use refugia in a river system to escape negative water quality conditions, such as high temperatures (Berman and Quinn 1991). For example, bull trout seek out side channels in the winter during high flow periods for protection (USFWS 1998). Sediment may also cover intergravel crevices fish use for shelter (Waters 1995). In laboratory experiments, it has been shown that salmonids will move to less turbid waters, if available, after a short-term pulse (Berg and Northcote 1985). Bisson and Bilby (1982) illustrated the displacement of salmonids in water with turbidities greater than 70 NTU. These results suggest that salmonids in a river system might seek out turbidity refugia when subjected to short-term pulses of sediment.

Loss of acceptable habitat and refugia as well as decreased connectivity between habitat reduces the carrying capacity of streams for salmonids. In systems lacking adequate number, distribution, and connectivity of refugia, fish may travel longer distances or to less desirable habitat and may encounter a variety of other conditions including increased bioenergetic demands.

Reid (1998) summed up the cumulative effect created by turbidity upon salmonids in a disturbed system:

“Salmonid strategies for coping with high turbidity are likely to include use of off-channel, clean-water refugia and temporary holding at clean-water tributary mouths. These coping strategies are partially defeated by the spatial distribution of roads: road runoff discharges into low-order channels that once would have provided clean inflows, and riparian roads restrict access to flood-plain and off-channel refugia. The temporal distribution of the high-turbidity inflows also decreases the effectiveness of coping strategies: turbidities are high even during low-magnitude events when flows may not be sufficient to allow access to refugia. The combined influences of increased turbidity and restricted opportunities for escape from the effect constitute a cumulative effect. Further, traffic-related turbidity is highest during the day, when salmonids feed, and traffic produces high turbidity even during small and moderate storm flows of autumn and spring, when water is warmer than during winter floods. Because salmonid metabolic rates are temperature-dependent, salmonids may be particularly sensitive to these unseasonable bouts of high turbidity.”

In consideration of the effect of increased turbidities upon salmonids, the current state of available habitat and refugia must be examined. Can a watershed, given past management practices, provide the protection needed to salmonids at various life stages if additional sediment pulses are released?

It is also important to note in reviewing the following section that much of the research undertaken to examine turbidity effects on salmonids was performed in laboratories, where control turbidities do not necessarily reflect field conditions, such as prey quantities and other potential synergistic effects.

Research Summary

The purpose of this section is to review recent research regarding the effect of turbidity and suspended sediments on salmonids. The research is summarized in three sections:

- A. Physiological effects**
- B. Behavioral effects**
- C. Habitat effects**

Physiological effects cover stressors to the physical health of salmonids attributed to the presence of high turbidity or high levels of suspended solids. Some indicators of stress to

salmonids that have been studied include gill trauma, blood sugar levels, and osmoregulatory function.

Behavioral effects cover changes in activity attributed to increased sediment in the water column. Behavioral effects reviewed here include avoidance, changes in foraging ability, responses to predation risk, and reduced territoriality.

Habitat effects cover changes to spawning and rearing habitat of salmonids.

Note on Turbidity and Sediment Studies

Most laboratory studies examine the effect of sediment on salmonids in a controlled environment, where individual variables are tested. Everest et al. (1987) note that there are significant difficulties in extrapolating laboratory findings to the field. Many laboratory survival studies use simplified unnatural gravel mixtures to test incubation and emergence of salmonid fry. Other factors that may affect results include disease organism presence, temperature, and prey availability.

The authors note that factors in streams, such as structural roughness and spawning behavior of females complicate field application of laboratory studies. Studies dealing with effects of sediment from forest management in natural environments have been less conclusive, as increased fine sediment from forest management is almost always accompanied by other environmental effects (Everest et al. 1987).

In general, studies focusing on physiological effects (gill trauma, blood chemistry, osmoregulation, and reproduction and growth) were conducted in a laboratory environment. Research on behavioral effects included both laboratory and field studies. Studies related to avoidance, territoriality, foraging and predation were primarily performed in artificial holding tanks. Field studies, however, were conducted in projects focused on abundance and diversity of prey, primary production, and homing and migration. Research related to the effect of sediment inputs on habitat were primarily performed in the field.

A. Physiological effects

Turbidity is associated with a number of physiological effects in Pacific salmon (Berg 1982). Researchers have used several physiological indicators to determine the effect of incremental increases of suspended sediment on salmonids. The outcome of a stress response is dependent on synergistic factors such as duration of exposure, frequency, magnitude, temperature, and other environmental variables (Servizi and Martens 1992). Some physiological indicators used by researchers include gill trauma (Berg 1982; Berg and Northcote 1985), increased levels of blood glucose, plasma glucose, plasma cortisol, and osmoregulatory ability (Redding et al. 1987; Servizi and Martens 1987). The stress response itself may compromise the organism's immune system (increasing disease susceptibility) thereby affecting mortality rates (USFWS 1998).

Among salmonids, some species may be more sensitive to suspended sediment than others, and the sensitivity of the egg and juvenile stages of most species seemingly exceed that of adults (Lloyd 1987). Owing to their extended fresh water residency, juvenile chinook, coho, and steelhead may be more sensitive to increases in suspended sediment (Noggle 1978), as opposed to pinks and chum, which spend very little time in streams after hatching.

Gill Trauma

The presence of suspended sediments in the water column has been shown to produce gill trauma in sockeye underyearlings (Servizi and Martens 1987), gill flaring in response to short term sediment pulses (Berg 1982; Berg and Northcote 1985), and increased coughing frequency (Servizi and Martens 1992).

Fish gills are delicate and easily damaged by abrasive silt particles. As sediment begins to accumulate in the filaments, fish excessively open and close their gills to expunge the silt. If irritation continues, mucus is produced to protect the gill surface, which may impede the circulation of water over gills and interfere with fish respiration (Berg 1982).

Laboratory Studies

Servizi and Martens (1987) found that the lethality of Fraser River sediments on underyearling sockeye salmon (*Oncorhynchus nerka*) increased with increasing particle size. Fines (0-740 μm) lodged in gills and caused gill trauma at 3,148 mg/l or 0.2 of the 96 h LC50 value. This value is consistent with normal levels of suspended solids measured at Hell's Gate on the Fraser River. Particle size and shape may also affect the degree of damage to the gills (Servizi and Martens 1992). The LC50 decreased as particle size increased, for particles described as angular to subangular, in their work with Fraser River sediments. Sockeye exposed to volcanic ash by Newcomb and Flagg (1983) experienced greater mortality at lower concentrations, indicating that the combination of slightly larger, more angular particles in volcanic ash may cause higher mortality.

Cough frequency is a sublethal effect that impairs the respiratory ability of salmonids. Servizi and Martens (1992) examined the effect of sublethal concentrations of Fraser River suspended sediments on underyearling coho salmon. Cough frequency was elevated eightfold over control levels at 240 mg/l (turbidity of 30 NTUs). Berg (1982) examined the effect of a short-term sediment pulse (initially 3 days at 60 NTU, then a reduction on the seventh day to 10 NTU) on coughing frequency of juvenile coho. In two of four tests, coughing rates increased significantly when turbidity was raised to 60 NTU. As turbidity declined to 10 NTU, coughing declined or remained at pretreatment levels. Noggle (1978), upon histological examination, found suspended sediments damaged gill structures. Berg and Northcote (1985) reported increases in gill flaring after a short-term sediment pulse, reaching 60 NTU. Flaring continued as turbidity dropped to 30 and 20 NTU.

Blood Physiology

Measures of elevated blood sugars (Servizi and Martens 1992), plasma glucose (Servizi and Martens 1987), and plasma cortisol have all been used as indicators of stress in fishes. Physiological stress in fishes may decrease immunological competence, growth, and reproductive success.

Laboratory Studies

Servizi and Martens (1987) identified increases in plasma glucose in juvenile sockeye salmon exposed to fine sediment. Plasma glucose levels of adult sockeye increased 150 and 39% as a result of exposures to 1,500 and 500 mg/l respectively of fine sediment. Servizi and Martens (1992) noted elevated blood sugar levels in underyearling coho salmon exposed to sublethal concentrations of Fraser River suspended sediments.

Redding et al. (1987) exposed yearling coho salmon and steelhead to high (2,000-3,000 mg/l) or low (400-600 mg/l) concentrations of volcanic ash, topsoil and kaolin clay for 7-8 days. Plasma cortisol levels were elevated in both species after exposure to high levels of topsoil. Yearling steelhead exposed to high or low concentrations for 2 days also showed elevated plasma cortisol levels.

A change in blood physiology is an indicator that a fish is experiencing some level of stress. At the individual fish level, stress may affect physiological systems, reduce growth, increase disease incidence, and reduce ability to tolerate additional stressors. At the population level, the effects of stress may include reduced spawning success, increased larval mortality, reduced recruitment to succeeding life stages and overall population declines. Stress to salmonids can affect the parr-smolt transformation, resulting in impaired migratory behavior, decreased osmoregulatory competence, and reduced early marine survival (Wedemeyer and McLeay 1981).

Osmoregulation

Laboratory Studies

The process of smolt transformation is critical to successful transfer of juvenile salmonids from fresh to marine waters. Disruptions of this process lead to osmotic imbalances and produce sublethal effects and eventual mortality (Redding et al. 1987). During the smolt transformation process, there appears to be an increased sensitivity to total suspended solids. Noggle (1978) conducted studies to assess the effects of suspended sediment upon juvenile salmonids in the stream environment. Results indicated seasonal changes in tolerance of salmonids to suspended sediment. Bioassays conducted in summer produced LC50's less than 1,500 mg/l, while autumn bioassays showed LC50's in excess of 30,000 mg/l. Spring/summer bioassays were coincidental to smolt transformation periods. Sockeye smolts suffered a slight impairment in hypoosmoregulatory capacity when exposed 96 h to 14,407 mg/l of fine sediment (Servizi and Martens 1987).

Reproduction and Growth

Salmonids require gravels that have low concentrations of fine sediments for successful spawning and incubation (Spence et al. 1996). Chronic turbidity during emergence and rearing of young anadromous salmonids could affect the quantity and quality of fish produced (Sigler et al. 1984). Organic matter entering substrate interstices depletes oxygen and reduces dissolved oxygen concentrations, harming eggs (Spence et al. 1996).

Settleable solids may prevent eggs from receiving necessary oxygen and inhibit removal of waste products within the redd and may create a physical barrier to fry emergence. The greater the proportion of fine sediments in redds, the greater likelihood that fry hatching from normally developed embryos will be entrapped and unable to emerge (Everest et al. 1987). Eggs, larvae, and fingerling fish are generally more susceptible to stress by dissolved or suspended solids than are adult fish. Intrusion of fines may occur initially in the upper 10 cm of the streambed gravels (Beschta and Jackson 1979). The intrusion or infiltration of fines into streambed gravels can thus alter the quality of the bed for spawning by fish or for use by other instream biota (Everest et al. 1987).

Sediments may also alter hyporheic inputs thereby reducing the availability of upwelling areas and potentially decreasing egg to fry survival. Transportation projects may affect these zones both by contribution of sediment and interception of sub-surface flow by road networks (Sedell et al. 1990, Poole and Berman 2001).

Intragravel water flow (Vaux 1962; Cooper 1965) and availability of dissolved oxygen for developing embryos (Cooper 1965; Daykin 1965) is key to egg survival. Low dissolved oxygen can cause direct mortality or delay development of alevins (Shumway et al. 1964; Brannon 1965). Delayed emergence may lead to smaller fry that are less able to compete for environmental resources than their larger cohorts that have undergone normal development and emergence (from Everest et al. 1987). Small size may also affect migration timing and marine survival (Holtby 1988; Holtby et al. 1989).

Researchers have found an inverse relationship between fines (% sediment < 3 mm) and fry survival (Bjornn 1968; Phillips et al. 1975, Everest et al. 1987) with decreases in survival ranging up to 3.4% for each 1% increase in fine sediment < 0.850mm (Cederholm et al. 1981).

Laboratory Studies

Sigler et al. (1984) identified a significant difference in growth rates between steelhead and coho in clear versus turbid water. As little as 25 NTUs of turbidity caused a reduction in fish growth. The implication of this finding is that fish subjected to turbidity in this experiment might experience increased probability of mortality in comparison to those fish experiencing normal growth (Sigler et al. 1984).

Shelton and Pollock (1966) demonstrated that low survival of chinook eggs in an incubation channel occurred when 15 to 30% of voids in the gravel bed were filled with

sediment. Crouse et al. (1981) used Substrate Score, a visual technique for evaluating stream substrate quality to determine the effect of sediment on juvenile coho salmon production. The authors found that production of juvenile coho salmon was inversely related to quantities of fine sediment. Significant decreases in fish production occurred in streams with 80% and 100% embeddedness where fine sediments (<2.0 mm) were 26 and 31% by volume of the total substrate.

Sediments less than 0.850 mm diameter were inversely correlated with survival of coho salmon in artificial streams. Coho salmon eggs in landslide affected gravels in the East Fork Miller Creek survived only 40% as well to hatching when compared to the control group and survived only 9% as well to the button-up stage of development (Cederholm and Salo 1979).

B. Behavioral effects

A number of research efforts have focused on the effect of turbidity levels on salmonid behavior. Behaviors examined by researchers include avoidance, territoriality, and foraging.

Avoidance

In many cases, salmonids avoid turbid water. In these instances, fish must successfully emigrate to areas of lower TSS. Factors affecting emigration may include availability and connectivity of patches with lower turbidity as well as the developmental stage of the fish (Sedell et al. 1990).

Laboratory Studies

Sigler et al. (1984) conducted tests to determine the point at which juvenile steelhead and coho subjected to continuous clay turbidities would emigrate from an area. Tested turbidities ranged from 57 to 265 NTUs. In tanks with mean turbidities of 167 NTUs or higher, no fish were found. Fish were found in tanks with lower turbidities (57 and 77 NTUs) at numbers near carrying capacity.

Newly emerged fry appear to be more susceptible to even moderate turbidities than are older fish. Turbidities in the 25-50 NTU range (equivalent to 125-175 mg/l of bentonite clay) reduced growth and caused more young coho salmon and steelhead to emigrate from laboratory streams than did clear water (Sigler et al. 1984). Juvenile salmonids tend to avoid streams that are chronically turbid, such as glacial streams or those disturbed by human activities (Lloyd et al. 1987), except when the fish have to traverse them along migration routes.

A mean avoidance of 25% was discovered for juvenile coho exposed to a 7,000 mg/l level of suspended sediment (Servizi and Martens 1992). The authors estimated that the threshold for avoidance by juvenile coho in the vertical plane was 37 NTU.

Berg (1982) found that juvenile coho exposed to a short-term pulse of 60 NTU left the water column and congregated at the bottom of an experimental tank. When the turbidity was reduced to 20 NTU, the fish returned to the water column. Bisson and Bilby (1982) subjected juvenile coho to experimentally elevated concentrations of suspended sediment. In their work, juveniles did not avoid moderate increases in turbidity when background levels were low. Significant avoidance, however, was observed at a level of 70 NTU.

Field Studies

In a study related to deposition of Mt. St. Helens ash in the Columbia River Basin, McCabe et al. (1981) noted a severe decline in the catch of juvenile chinook in upper reaches with highest ash deposition.

In addition to avoidance behavior by juveniles, suspended sediment may affect the reproductive success of returning adults. Physiological, bioenergetic and behavioral alterations stemming from increased suspended sediment loads (such as a delay in return to spawning habitat) may affect egg quality or quantity and subsequent egg development. Previous research on sublethal temperature exposure of adult chinook has illustrated this point (Berman and Quinn 1991). We hypothesize that elevated TSS may lead to similar results.

Territoriality

Laboratory Studies

The presence of turbid water appears to disturb normal social behavior and alter the nature of aggressive interactions. It has been suggested that the loss of territoriality and the breakdown of social structure can lead to secondary effects. Juvenile coho rearing in streams affected by frequent short-term sediment pulses with concomitant loss of territoriality may experience a decrease in growth and feeding rates, which may affect overall mortality (Berg 1982).

Juvenile coho exposed to short-term sediment pulses exhibited altered territory structure and altered feeding behavior (Berg and Northcote 1985). Normally, a dominant fish positioned upstream would consume the majority of the prey. During turbid phases, territories broke down, and subordinate fish captured a greater proportion of the prey. This was most evident at 30 and 60 NTU.

Subsequent to a sediment pulse, a breakdown in social organization among juvenile coho in an artificial stream occurred (Berg, 1982). Territoriality appeared to cease during a short-term sediment pulse, possibly due to the inability of the fish to see the positions of their neighbors. Territory was reestablished when turbidity decreased to 20 NTU. Lateral displays, a territorial action performed by salmonids, were limited under the experimental conditions. Experiments conducted by Noggle (1978) within a turbid artificial stream and clear tributary illustrated avoidance by fish of their established territories.

Foraging and Predation

Turbidity appears to affect a number of factors related to feeding for salmonids, including feeding rates, reaction distance, prey selection, and prey abundance. Changes in feeding behavior are primarily related to the reduction in visibility that occurs in turbid water. Effects on feeding ability are important as salmonids must meet energy demands to compete with other fishes for resources and to avoid predators. Turbidity may lead to a reduction in foraging rates, which has been linked to a decrease in growth and health of fishes (Gardner 1981).

The literature presents two major themes on the effect of turbidity on foraging. Many studies indicate that as visual feeders, the effectiveness of salmonids in obtaining food is reduced by turbidity at levels as low as 20 NTU (Berg 1982). Other research indicates that some species of salmonids (juvenile coho, steelhead, and chinook) appear to prefer slightly to moderately turbid water for foraging, as reported in studies by Sigler et al. (1984) and Gregory (1988). This behavior may represent a trade-off between predation risk and bioenergetic demand and benefits of increased growth. While ability to forage in turbid water may be reduced, the reduction in predation risk may make it worthwhile to operate in partially turbid areas (Gregory and Northcote 1993).

Suspended particulate material reduces the underwater visual range of fish, which may either act as a protective cover from predators or reduce the ability of these species to detect predators (Gregory and Levings 1996). Reduced visual clarity of waters may greatly affect the behavior of visual predators, notably fishes and piscivorous birds (Davies-Colley and Smith 2000). The reaction of salmonids to these factors is variable, as shown by the results reviewed below.

Laboratory Studies

Berg (1982) showed a decrease in feeding ability by juvenile coho in response to short-term pulses of suspended sediment in a laboratory environment. At 0 NTU, 100% of the prey items offered to the fish were consumed, whereas at 60 NTU, only 35% of introduced prey were consumed. At a turbidity level of 10 NTU, fish were noted to frequently misstrike prey items. A significant delay in the response of fish to introduced prey was noted at turbidities of 20 and 60 NTU. The acquisition of food resources in turbid waters may be reduced due to the effects of turbidity on behavior and vision. As coho are visual feeders relying on drift, reduction in feeding ability may lead to depressed growth rates (Berg 1982). Reid (1998) reported that published data suggest that feeding efficiency of juvenile coho salmon drops by 45% at a turbidity of 100 NTU. Additionally, prey behavior is also altered by TSS.

Berg and Northcote (1985) showed a reduction in reaction distance by juvenile coho to adult brine shrimp after a sediment pulse (60-20 NTU) was introduced. Prey acquisition increased as the pulse dropped from 60 NTU to 20 NTU, but remained below levels occurring prior to the pulse. The authors suggested that feeding affects were primarily

the result of loss of vision. Ingestion rates decreased to below 50% at higher turbidities (30 and 60 NTU).

Gregory and Northcote (1993) assessed the effects of turbidity on the foraging behavior of juvenile chinook in the laboratory. The reaction distance of the fish to planktonic adult *Artemia* prey was measured by examining the visual ability of the subjects. The foraging rate by juvenile salmonids for surface, planktonic and benthic prey was measured across a range of turbidity levels (<1, 18, 35, 70, 150, 370, 810 NTU). For all three prey types, foraging was reduced at higher turbidities. Foraging rates for surface and benthic prey were also reduced in clear water, with highest foraging rates attained at 35-150 NTU. The authors suggested that the increased feeding rate in turbid conditions may reflect reduced risk from predators.

Gregory (1992) noted that preference for foraging in moderate turbidity appeared to be size dependent, as smaller individuals exhibited greater foraging rates in clear waters. The author suggested that it may be to the advantage of an individual to grow quickly to sizes where it is less vulnerable to predation, even if it may temporarily expose itself to greater risk by foraging in clear water.

Redding et al. (1987) observed reduced feeding rates among yearling coho and steelhead exposed to 2,000-4,000 mg/l of topsoil, kaolin clay and volcanic ash. Less food was found in the stomachs of yearling fish exposed to high concentrations of suspended topsoil, suggesting suspended solids might inhibit feeding. The authors suggested that inhibition may result from a loss of vision in turbid water or may be an indirect consequence of stress.

Boehlert and Morgan (1985) studied the effects of turbidity on feeding abilities of larval Pacific herring. Maximum feeding incidence and intensity occurred at 500 or 1,000 mg/l. Feeding was reduced at concentrations higher than 1,000 mg/l. The authors hypothesized that suspension of sediment may enhance feeding for the larvae by providing visual contrast of prey items.

Gardner (1981) showed reduced feeding rates for bluegills in turbid waters. Feeding rates in a 3 minute period declined from 14 prey per minute in clear water to 11, 10, and 7 per minute in pools of 60, 120, and 190 NTU. Gardner suggested that high (>50 NTU) levels of turbidity would reduce energy intake (through decreased feeding rates) thus reducing production of fish populations.

Vogel and Beauchamp (1999) quantified the reaction distance of adult lake trout (as predators) to rainbow trout and cutthroat as a function of light ($0.17 - 261 \text{ } 1x$; $1x$ is a measurement of light intensity measured with a light meter), prey size (55, 75, and 139 mm) and turbidity (0.09, 3.18, and 7.40 NTU). Reaction distances of adult lake trout to rainbow and cutthroat trout increased with increasing light (25 cm at $.17 \text{ } 1x$, to 100 cm at $17.8x$). Reaction distance decreased as a decaying power function of turbidity. Vogel and Beauchamp (1999) used results to model prey detection capabilities of piscivores at varying depths and times of day in natural environments.

Gregory (1988) examined the foraging behavior of juvenile chinook in elevated turbidity in a series of laboratory experiments. Experiments determined the reaction distance to invertebrate prey, perceived risk to a model predator, and the foraging rate of chinook on benthic Tubifex worms, in turbid conditions ranging from 0 to 800 mg/l. Reaction distance and perceived risk declined inversely with turbidity. Foraging rates on Tubifex worms were highest at intermediate levels (50-200 mg/l) and lowest at 0.0 mg/l (control) and 800 mg/l. The results suggested a tradeoff between perceived risk to predation and the effects of reduced reaction distance.

Gregory (1993) illustrated this consideration with research simulating predation in both clear and turbid environments. In the absence of risk, fish occupied the bottom in clear conditions (<1 NTU). In turbid conditions (NTU = 23), fish were randomly distributed throughout the tank. In the presence of risk (bird and fish models to simulate predators), the juveniles occupied the deep parts of the tank regardless of turbidity. However, responses to simulated predation were less marked and of shorter duration in the turbid conditions. Each simulation elicited a similar response – a distinct rapid movement into deep water.

Gregory and Levings (1996) studied the effect of turbidity and artificial vegetation (as cover types) on the predation mortality of juvenile salmonids in concrete ponds. Adult coastal cutthroat trout were used as predators on juvenile chinook, chum, sockeye, and cutthroat trout. The daily predation rate was determined for each turbidity and vegetation treatment. In the presence of cover, daily predation rates were 10-75% lower. The effects of turbidity were not significant and not additive with the effects of vegetation – turbidity appeared to reduce the effectiveness of vegetation as cover for chinook and sockeye. The authors suggested that the two forms of cover affected predation risks by different mechanisms.

Ginetz and Larkin (1976) examined the predation of rainbow trout on migrant sockeye fry. Feeding rates were higher on fry at lesser turbidities and at lower stream velocities. The authors suggested that this information could be used to improve the timing of hatchery releases of fry.

Abundance and Diversity of Prey

The presence of fine sediment in the substrate affects the benthic community, especially those species living and feeding in the riverbottom. Effects on the benthic community may negatively affect salmonids, as they are an important food source for the fish. (Tebo 1955; Rosenberg and Wiens 1978; Cederholm and Salo 1979; Brzezinski and Holton 1983). Decreased prey abundance may affect growth rate, susceptibility to predation, competition, and susceptibility to disease.

As most experimental studies occur in a laboratory, prey abundance is controlled, usually providing more than adequate prey quantity for salmon present. In natural systems, salmonids may not be fed to satiation and stressor effects may therefore be different. It is

difficult to ascertain systemic effects on both fish feeding and benthic health from these results.

Newcombe and MacDonald (1991) note that a change in sediment concentration can adversely affect secondary production by affecting algal growth, biomass, and species composition. Sediment can clog feeding structures, reducing efficiency and growth rates of filter feeders. Benthic macroinvertebrates living in the substrate are subject to scouring, which can damage respiratory organs and expose organisms to predation through dislodgement. High sediment levels and high flow rates can scour algae and reduce periphyton biomass.

Turbidity and siltation causes an overall reduction in the number of bottom organisms, which results in changes to community structure, density, and diversity. (Sorenson et al. 1977). Lloyd (1987) suggested that turbidity can account for the decrease in primary production in shallow interior Alaskan streams, and subsequent reductions in abundance of zooplankton and macroinvertebrates.

Field Studies

Tebo (1955) pointed to erosion and sedimentation produced by logging roads as a factor in the decrease of benthic macroinvertebrates in a river system in North Carolina. Two stations were used, above and below a logged watershed to determine effects of sedimentation on bottom fauna. At the lower station there were 7.3 organisms per square foot, in comparison to 25.5 organisms per square foot at the upper station.

Rosenberg and Wiens (1978) examined the responses of macroinvertebrates to sediment addition. Increased sediment led to an increased number of macrobenthos drifting in comparison with invertebrates in the control. Total drift was more than 3 times higher in August (sediment addition of 28.27 kg or 138,000 mg/m²) and more than 2 times higher in September (sediment addition of 35.88 kg or 153,000 mg/m²). No significant difference was found in standing crops of macrobenthos in the substrate in the control or sediment channels after sediment addition. The researchers suggested that future efforts focus on the quantitative response of macrobenthos to settled rather than suspended sediments. It was also suggested that highway and pipeline construction undertaken in watersheds of this region resulting in sediment addition be performed in the summer rather than spring or fall, providing discharge is adequate to transport added sediment.

Brzezinski and Holton (1983) examined the relationship between abundance of benthic taxa and the presence of ash in river sediments. The abundance was dependent on distribution of ash within the sediment column. When ash is the top sediment layer, amphipod abundance was zero. Amphipods were present if there were a distinct ash layer at depth (12,500 individuals/m²) or if ash were mixed with sediment (13,300 individuals/m²). The authors concluded that the ash affects the fauna through some physical effect, possibly related to fine grain size.

Gammon (1970) studied substrate types and their relation to benthic macroinvertebrate numbers. Moss, gravel and rubble were the most occupied substrates. Substrates with silt rated fairly low. Benthic populations residing below and above a limestone quarry which contributed approximately 40 mg/l suspended solids to the stream were examined. Suspended sediments above the quarry ranged from 13-52 mg/l, and from 21 – 250 mg/l below. Drift rates increased linearly with increasing suspended solids up to 160 mg/l. An increase of 40 mg/l suspended solids above normal resulted in a 25% increase in drift. A 90% increase in drift occurred at an increase of 80 mg/l suspended solids above normal.

Microfauna

The response of daphnia to suspensions of several types of solids was reviewed by EIFAC (1965). The following results were reported:

Daphnia – harmful levels of solids

- Kaolinite - 102 ppm
- Montmorillonite - 82 ppm
- Charcoal - 82 ppm
- Pond sediment – 1458 ppm

Reproduction rate increased for Daphnia at lower rates of suspended sediment.

Sorenson et al. (1977) assumed that as turbidity limits light penetration and hence aquatic algae and plant productivity, the grazing microfauna would also be limited. The abrasive action of suspended solids would also be expected to have an adverse effect on attached protozoans and micrometazoans (Sorenson et al. 1977).

Field Studies

McCabe et al. (1981) examined the effects of the deposition of Mt. St. Helens ash on demersal fish populations in the Columbia River estuary. The study revealed a change in diet habits and prey consumption by juvenile salmonids. Reduced feeding intensity and lower diet diversity reflected a reduction in *Corophium salmonis*, an amphipod frequently exploited by juvenile salmonids. The authors identified a reduced number of a normally highly used amphipod, *Corophium salmonis*.

McCabe and O'Brien (1983) determined that turbidity levels as low as 10 NTUs can cause significant declines in feeding rate, food assimilation, and reproductive potential of *Daphnia pulex*. Suspended sediment concentrations of 50-100 mg/l reduced algal carbon ingested by cladocerans to potential starvation levels. These zooplankton are an important food item for salmonid fishes.

Primary Production

Suspended material reduces the amount of light available to illuminate submerged objects and provide energy for plant photosynthesis. A change in light penetration through water may be expected to have far-reaching ramifications for whole aquatic ecosystems because of its influence on photosynthetic fixation of energy by aquatic plants (Davies-Colley and Smith 2000).

Major ecological parameters of suspended solids which affect photosynthesis include reduction in light penetration, abrasive action, and effects of adsorbed toxins. A reduction in light penetration may reduce primary producers, with the exception of those species that are planktonic or living on floating debris. Reduction of light may also alter oxygen relationships in surface waters. A decrease in oxygen production due to excess turbidity might be critical in some large streams (Sorenson et al. 1977). Related effects include decreased production of zooplankton and macroinvertebrates, decreased abundance and production of fish, reduced angler use and success, and decreased efficiency of some fish management techniques (Lloyd 1987).

Field Studies

A 5 NTU increase in turbidity in a clear-water lake may reduce the productive volume of that lake by about 80% and a 25 NTU increase in a clear-water stream 0.5 m deep may reduce plant production by approximately 50% (Lloyd et al. 1987). A 5 NTU increase in turbidity in a clear stream 0.5 m deep may reduce primary production by 13% or more, depending on stream depth.

Summary

The results discussed in this section indicate that TSS and turbidity have the potential to affect salmonids through alteration of prey composition and availability. TSS and turbidity appear to affect prey abundance, diversity, and behavior, in part by reducing habitat available to benthic macroinvertebrates. In addition, feeding efficiency of salmonids may be reduced, as salmon are visual predators and may not easily sight food in turbid waters. Finally, the results indicate that in some cases, a reduced level of predation risk may occur under turbid conditions.

Homing and Migration

Migrating salmonids avoid waters with high silt loads, or cease migration when such loads are unavoidable (Cordone and Kelley 1961). It is unknown to what degree the “bouquet” of each stream may be altered by the addition of exotic chemicals, trans-basin diversions, and increased suspended sediment levels (Bjornn and Reiser 1991).

Field Studies

High turbidity may delay migration, but turbidity alone does not seem to affect homing. Whitman et al. (1982) found that salmon preferred natal stream water without ash, but still recognized natal streams despite ash presence and attempted to ascend natal streams. Quinn and Fresh (1984) reported that the rate of straying of chinook to the Cowlitz River Hatchery was low and unaffected by the 1980 Mt. St. Helens eruption, but that many coho salmon in the Toutle River, the river most affected by the eruption, did stray to nearby streams in 1980 and 1981.

Adult chinook males showed an avoidance response to their home water in the presence of a seven-day exposure to ash suspension of 650 mg/l (Whitman et al. 1982). Experimental fish returns did not differ from control returns, indicating that homing performance was not influenced by ash.

Timing of arrival at spawning grounds by chinook that migrate upstream during snowmelt runoff can vary by a month or more, depending on the concentration of suspended solids in rivers along their migration route (Bjornn 1968). In the lower Columbia River, the upstream migration of salmon may be retarded when Secchi disk readings are less than 0.6 m (Cederholm and Salo 1979). Delays in spawning migration and associated energy expenditure may reduce spawning success (Berman and Quinn 1991).

C. Habitat

In addition to affecting salmonid physiology and behavior, deposited sediments may affect salmonids by altering the physical structure of the stream environment. Sediments pose a direct threat to salmonid embryos through deposition in interstitial spaces, thereby reducing oxygen rich flows and pathways for waste removal as well as potentially entombing emerging fry. Broader systemic effects of sedimentation in streams include the loss of habitat complexity and abundance, loss of refugia, and alterations to hyporheic flow (Sedell et al. 1990; Poole and Berman 2001).

Increased Embeddedness

Intragravel survival of salmonid embryos is dependent on a streambed structure that facilitates the influx of oxygen rich waters and the removal of waste products associated with embryo and alevin development. High levels of fines (less than 0.85 mm in diameter) in or on spawning gravels can reduce intragravel permeability (Cederholm and Salo 1979). The effect of sediment on pre-emergent survival for a particular gravel composition varies, and may depend on the salmonid species as well as hydrologic conditions of the watershed. In addition to indirect mortality, direct mortality may be caused by sediment that physically prevents fry emergence (Cederholm and Salo 1979).

Reduction in Habitat Complexity and Abundance

Salmonids require a variety of habitats throughout their lifetime. Sediment inputs may decrease both habitat complexity and availability. Large pools, consisting of a wide range of water depths, velocities, substrates, temperatures, and cover are characteristic of high quality habitat and channel complexity. Many of these pools have been lost in recent times, at least in part to sediment contributed by timber harvesting, roading, and historical grazing practices (USFWS 1998). Reduction in pool volume decreases rearing habitat for juveniles and holding pools for migrating adults.

Elevated sediment loads also increase frequency of channel scour and fill events, and increase channel width through aggradation. The stability of large woody debris, an important habitat component, is also compromised (Spence et al. 1996). The pool to riffle ratio present in a stream is important for provision of refugia and maintenance of hyporheic flows (see below) (Poole and Berman 2001).

Refugia

Refugia are created and maintained by watershed processes. Systems altered by anthropogenic activities may not contain the necessary distribution and abundance of refugia to maintain salmonid populations in the face of natural and anthropogenic disturbances. Habitat heterogeneity may provide localized refugia against turbidity extremes for fishes and other organisms. Loss of channel structure and streambed heterogeneity leads to decreases in the abundance of suitable habitat and the distribution, abundance, and connectivity of refugia. As suspended solids progressively change geomorphic channel structure, suitable habitat may become marginal and marginal habitat may become unusable (Poole and Berman 2001).

Loss of refugia as well as decreased connectivity between refugia will reduce carrying capacity of streams for salmonids. Fish may be required to travel longer distances or to less desirable habitat in systems lacking adequate number, distribution, and connectivity of refugia. Fish may suffer a variety of secondary effects from meeting these extra energy demands.

Alterations to Hyporheic Inputs

Hyporheic inputs throughout a watershed may contribute upwelling flows that reduce temperatures in areas where streams might normally be too warm for salmonid activity. The presence of hyporheic flows throughout a system contribute to spatial and temporal heterogeneity important to salmonids (Poole and Berman 2001). Upwelling areas are also critical to proper water exchange in salmonid redds. Bull trout have been observed selecting redd sites that correlate to areas of hyporheic exchange (Baxter and Hauer 2000).

Increasing sediment load can clog coarse streambed gravels with fine sediments, thereby decreasing streambed conductivity and reducing the exchange of ground water and surface water across the streambed. Sediment may alter the dynamics of heating, cooling, and temperature buffering. The two-way exchange between the stream channel and the hyporheic zone is perhaps the most important buffer to high stream temperatures (Poole and Berman 2001).

Note on Bull Trout

Bull trout are highly susceptible to sediment inputs. They require the lowest turbidity and suspended sediment levels of all salmonids for spawning, incubation, and juvenile rearing (USFWS 1998). Bull trout are strongly associated with cover, including interstitial spaces in gravel. Additionally, they have protracted embryo/alevin development with approximately 220 days required from egg deposition to fry emergence (USFWS 1998). Thus they are highly susceptible to the effects of sediment deposition and bedload movement.

Bull trout show preference for stream bottoms and deep pools of cold water. This strong association with the substrate makes them susceptible to human activities that directly or indirectly change substrate composition. There is also a strong association between juveniles and streambed cobble, and substrates low in fine sediment. Bull trout also require a large network of suitable freshwater habitat with migratory corridors, and deep pools for thermal refugia (USFWS 1998).

Specific Road and Devegetation Effects

Field Studies

Burns (1972) linked sedimentation with higher temperatures and low dissolved oxygen in streams. The use of bulldozers on steep slopes caused excessive sedimentation in narrow streams. During heavy rainfall after construction, erosion and road slippage caused turbidities of 3,000 ppm and deposition of as much as 0.6 m of sediment in the stream. Brown and Krygier (1971) found that sediment production doubled after road construction but before logging in one watershed, and tripled after burning and clearcutting in another watershed.

Fifteen years of heavy logging and road construction in the South Fork River in Idaho, followed by flood caused massive sedimentation of habitat. Roads were the largest contributor of sediment to the system. Spawning, rearing, and holding habitats of summer chinook and summer steelhead were inundated with fine granitic sediments, and fine sediment filled pools (Platts and Megahan 1975).

Reid (1998) used flow and turbidity data from Caspar Creek, California, to model the potential influence of the presence and use of roads on cumulative duration curves for stream turbidity. Her results suggested that a proportional increase in fine-sediment production equivalent to that measured in coastal Washington (i.e. a 5.8 fold increase due

to road-related erosion) would increase the average annual duration turbidities greater than 100 NTU by a factor of 73 (i.e. from 0.5 day to 36.5 days).

Smedley et al. (1970) found that the percentage of fine sediment <0.83 mm in diameter increased in all study areas for six years during logging, and remained at elevated levels for 3 years after. Fines increased 6-8% as a result of logging. Low survival of pink salmon brood stock from 1966 was attributed to sedimentation of spawning areas (from Everest et al. 1987).

Scrivener and Brownlee (1982) showed an increase in fines between 0.3 and 9.6 mm in diameter within the top 12 cm of riffle gravels 3 years after logging was begun in the Carnation Creek Watershed.

Previous Literature Reviews : Lloyd (1987) and Newcombe and MacDonald (1991)

Lloyd (1987) and Newcombe and MacDonald (1991) examined research on turbidity and suspended solids to illustrate the levels of tolerance to these two measures exhibited by salmonids and other fishes at various life stages. **Table 2** provides the results of Lloyd's (1987) research, developed in an effort to determine possible turbidity criteria for Alaska cold water fisheries. **Table 3** summarizes suspended sediment effects on selected salmonids present in the Yakima basin of Washington State. This table was compiled from Newcombe and MacDonald (1991) for the Yakima River Total Maximum Daily Load (TMDL) Report. **Table 4** includes data derived from 1) research conducted after 1991; and 2) research prior to 1991 not presented by Lloyd (1987) and Newcombe and MacDonald (1991).

Lloyd (1987) examined the use of turbidity as a water quality standard for salmonid habitats in Alaska. Lloyd suggested that evidence of trophic level changes induced by reduction in light penetration, and known direct effects of sediment and turbidity on aquatic life indicates that turbidity constitutes a useful water quality standard for protecting aquatic habitats from sediment pollution.

According to Lloyd (1987), relatively low turbidity or SSC may stress salmonids, alter behavior patterns, or lead to acute mortality. Even low turbidities near 10-25 NTU and suspended sediment concentrations near 35 ppm can have deleterious effects on fish (Berg 1982; Sigler et al. 1984; Berg and Northcote 1985).

Effects of Turbidity and Suspended Sediment on Salmonids (Lloyd 1987)

- 1) Reduced light penetration in lakes and streams
- 2) Associated with decreased production and abundance of plant material (primary production)
- 3) Decreased abundance of fish food organisms (secondary production)
- 4) Decreased production and abundance of fish

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Newcombe and MacDonald (1991) suggested that the use of concentration of suspended solids alone is a poor indicator of physiological and behavioral effects. The authors suggested using both concentration and duration of exposure in a “stress index” to determine relative impacts on salmonids. The authors believe this is a convenient tool for predicting effects for a pollution episode of known intensity. The results of this work can be found in **Appendix B**.

It is important to remember that the listings below are primarily laboratory studies. For example, prey rations, temperature, disease, and intra- and interspecific encounters are controlled. Therefore, it is difficult to clearly illustrate how fish would be affected by high turbidities in the field. In addition to those factors mentioned above, most experiments cited do not account for spatial and temporal factors, such as the distribution, abundance, or availability of suitable habitat, time of year, frequency, duration, and magnitude of events, and cumulative or synergistic effects.

Table 2. Some reported effects of turbidity and suspended sediment concentrations on salmonids outside Alaska (Lloyd 1987).

Effect	Species ^a (life stage)	Location	Reported turbidity ^b or suspended sediment concentration	Reference
Fatal (96-h LC50)	Coho salmon (juveniles)	Washington	1,200 mg/l	Noggle (1978)
Fatal (96-h LC50)	Coho salmon (juveniles)	Washington	509; 1,217 mg/l	Stober et al. (1981)
Fatal (96-h LC50)	Chinook salmon (juveniles)	Washington	488 mg/l	Stober et al. (1981)
Reduced survival (marked)	Chum salmon (eggs)	British Columbia	97 mg/l	Langer (1980)
Reduced survival (marked)	Rainbow trout (eggs)	Great Britain	110 mg/l	Scullion and Edwards (1980)
Reduced survival (marked)	Rainbow trout (eggs)	Oregon	1,000-2,500 ppm	Campbell (1954)
Reduced survival (marked)	Rainbow trout (juveniles)	Great Britain	270 ppm	Herbert and Merkens (1961)
Reduced survival (marked)	Rainbow trout (juveniles)	Great Britain	200 ppm	Herbert and Richards (1963)
Reduced survival (marked)	Rainbow trout (juveniles)	Oregon	1,000-2,500 ppm	Campbell (1954)
Reduced survival (marked)	Rainbow trout (juveniles)	Great Britain	90 ppm	Herbert and Merkens (1961)
Reduced survival (marked)	Coho salmon (juveniles)	Pennsylvania	6; 12 mg Fe/l (15-27 JTU)	Smith and Sykora (1976)
Reduced survival (marked)	Coho salmon (adults)	Washington	1,400-1,600 mg/l	Stober et al. (1981)
Reduced abundance (marked)	Brown trout	Great Britain	1,000; 6,000 ppm	Herbert et al. (1961)
Reduced abundance (marked)	Lake trout	Northwest Territories	<10 FTU	McCart et al. (1980)
Reduced growth (marked)	Brook trout (juveniles)	Pennsylvania	50 mg Fe/l (86 JTU)	Sykora et al. (1972)
Reduced growth (slight)	Brook trout (juveniles)	Pennsylvania	12 mg Fe/l (32 JTU)	Sykora et al. (1972)
Reduced growth (slight)	Rainbow trout (juveniles)	Great Britain	50 ppm	Herbert and Richards (1963)
Reduced growth	Coho salmon (juveniles)	Idaho	25 NTU	Sigler et al. (1984)
Reduced growth (marked)	Arctic grayling (juveniles)	Yukon	1,000 mg/l	McLeay et al. (1984)
Reduced growth (slight)	Arctic grayling (juveniles)	Yukon	100; 300 mg/l	McLeay et al. (1984)

a Arctic grayling (*Thymallus arcticus*)
 Brook trout (*Salvelinus fontinalis*)
 Brown trout (*Salmo trutta*)
 Chinook salmon (*Oncorhynchus tshawytscha*)
 Chum salmon (*Oncorhynchus keta*)

Coho salmon (*Oncorhynchus kisutch*)
 Cutthroat trout (*Salmo clarki*)
 Lake trout (*Salvelinus namaycush*)
 Rainbow trout (*Salmo gairdneri*)
 Steelhead (anadromous *S. gairdneri*)

b Formazin (FTU), Jackson (JTU), and nephelometric (NTU) turbidity units.
 c Information not available.

Table 2 (cont.).

Some reported effects of turbidity and suspended sediment concentrations on salmonids outside Alaska (Lloyd 1987).

Effect	Species ^a (life stage)	Location	Reported turbidity ^b or suspended sediment concentration	Reference
Reduced food conversion	Rainbow trout (juveniles)	Arizona	< 70 JTU	Olson et al. (1973)
Reduced feeding (cessation)	Coho salmon (juveniles)	Washington	300 mg/l	Noggle (1978)
Reduced feeding	Coho salmon (juveniles)	Washington	100 mg/l	Noggle (1978)
Reduced feeding	Coho salmon (juveniles)	British Columbia	10-60 NTU	Berg (1982), Berg and Northcote (1985) Bachmann (1958)
Reduced feeding (cessation)	Cutthroat trout	Idaho	35 ppm	Bachmann (1958)
Reduced feeding	Brown trout	Pennsylvania	7.5 NTU	Bachman (1984)
Reduced feeding	Rainbow trout (juveniles)	Arizona	70 JTU	Olson et al. (1973)
Reduced feeding	Arctic grayling (juveniles)	Yukon	100; 300; 1,000 mg/L	McLeay et al. (1984)
Reduced condition factor	Rainbow trout (juveniles)	Great Britain	110 mg/l	Scullion and Edwards (1980)
Altered diet (terrestrial instead of aquatic)	Rainbow trout (juveniles)	Great Britain	110 mg/l	Scullion and Edwards (1980)
Stress (increased plasma cortisol, hematocrit, and susceptibility to pathogens)	Coho salmon (juveniles) Steelhead (juveniles)	Oregon	500 mg/l 2,000 mg/l	Redding and Schreck (1980)
Stress (increased metabolic rate, susceptibility to toxicants)	Arctic grayling	Yukon	300 mg/l	McLeay et al. (1984)
Stress (increased plasma glucose)	Arctic grayling (juveniles)	Yukon	50 mg/l	McLeay et al. (1983)
Stress (respiratory distress)	Coho salmon (juveniles)	Pennsylvania	6; 12 mg Fe/l (15-27 JTU)	Smith and Sykora (1976)
Stress (increased ventilation)	Brook trout	Lake Superior	231 NTU	Carlson (1984)
Disease (fin rot)	Rainbow trout (juveniles)	Great Britain	270 ppm	Herbert and Merkens (1961)
Disease (fin rot)	Rainbow trout (juveniles)	Great Britain	100; 200 ppm	Herbert and Merkens (1961)

a Arctic grayling (*Thymallus arcticus*)
 Brook trout (*Salvelinus fontinalis*)
 Brown trout (*Salmo trutta*)
 Chinook salmon (*Oncorhynchus tshawytscha*)
 Chum salmon (*Oncorhynchus keta*)

Coho salmon (*Oncorhynchus kisutch*)
 Cutthroat trout (*Salmo clarki*)
 Lake trout (*Salvelinus namaycush*)
 Rainbow trout (*Salmo gairdneri*)
 Steelhead (anadromous *S. gairdneri*)

b Formazin (FTU), Jackson (JTU), and nephelometric (NTU) turbidity units.
 c Information not available.

Table 2 (cont.).

Some reported effects of turbidity and suspended sediment concentrations on salmonids outside Alaska (Lloyd 1987).

Effect	Species ^a (life stage)	Location	Reported turbidity ^b or suspended sediment concentration	Reference
Avoidance	Chinook salmon (adults)	California	“Natural turbidity”	Sumner and Smith (1940)
Avoidance	Chinook salmon (adults)	Washington	650 mg/l	Whitman et al. (1982)
Avoidance	Chinook salmon (adults)	Washington	350 mg/l	Brannon et al. (1981)
Avoidance (sensitivity)	Lake trout	Lake Superior	6 FTU	Swenson (1978)
Avoidance	Coho salmon (juveniles)	Washington	70 NTU	Bisson and Bilby (1982)
Avoidance	Coho salmon, steelhead (juveniles)	Idaho	22-265 NTU	Sigler (1980), Sigler et al. (1984)
Displacement	Coho salmon, steelhead (juveniles)	Idaho	40-50 NTU	Sigler (1980)
Displacement	Arctic grayling (juveniles)	Yukon	300; 1,000 mg/l	McLeay et al. (1984)
Displacement	Rainbow trout (juveniles)	Great Britain	110 mg/l	Scullion and Edwards (1980)
Altered behavior (feeding)	Trout	c	25 JTU	Langer (1980)
Altered behavior (less use of overhead cover)	Brook trout	Wisconsin	7 FTU	Gradall and Swenson (1982)
Altered behavior (visual)	c	c	25-30 JTU	Bell (1984)
Altered behavior (visual)	Coho salmon (juveniles)	British Columbia	10-60 NTU	Berg (1982), Berg and Northcote (1985)
Altered behavior (loss of territoriality)	Coho salmon (juveniles)	British Columbia	10-60 NTU	Berg (1982), Berg and Northcote (1985)
Altered behavior (listlessness)	Coho salmon (juveniles)	Pennsylvania	6; 12 mg Fe/l (15-27 JTU)	Smith and Sykora (1976)
Change in body color	Arctic grayling (juveniles)	Yukon	300; 1,000 mg/l	McLeay et al. (1984)
Change in body color	Coho salmon (juveniles)	Pennsylvania	6; 12 mg Fe/l (15-27 JTU)	Smith and Sykora (1976)
Reduced tolerance to saltwater	Chinook salmon (juveniles)	Washington	3,109 mg/l	Stober et al. (1981)

a Arctic grayling (*Thymallus arcticus*)
 Brook trout (*Salvelinus fontinalis*)
 Brown trout (*Salmo trutta*)
 Chinook salmon (*Oncorhynchus tshawytscha*)
 Chum salmon (*Oncorhynchus keta*)

Coho salmon (*Oncorhynchus kisutch*)
 Cutthroat trout (*Salmo clarki*)
 Lake trout (*Salvelinus namaycush*)
 Rainbow trout (*Salmo gairdneri*)
 Steelhead (anadromous *S. gairdneri*)

b Formazin (FTU), Jackson (JTU), and nephelometric (NTU) turbidity units.
 c Information not available.

Table 3. Summary of suspended sediment effects on selected salmonids commonly present in the Yakima River basin (Newcombe and McDonald 1991)

(*) indicates estimated concentration.

Species	Concentration (mg/l)	Duration (hours)	Effect
Chinook Salmon	1400*	36	10% mortality of juveniles
	488	96	50% mortality of smolts
	82,000	6	60% mortality of juveniles
	19,364	96	50% mortality of smolts
	1.5-2.0	1,440	Gill hyperplasia, poor condition of fry
	6	1,440	Reduction in growth rate
	75	168	Harm to quality of habitat
	84	336	Reduction in growth rate
	1,547	96	Histological damage to gills
	650	1	Homing performance disrupted
Whitefish	16,613	96	50% mortality of juveniles
	.7	1	Overhead cover abandoned
Salmon (general)	8	24	Sport fishing declines
Steelhead	84	336	Reduction in growth rate
Rainbow Trout	19,364	96	50% mortality of smolts
	157	1728	100% mortality of eggs
	21	1152	62% reduction in egg to fry survival
	37	1440	46% reduction in egg to fry survival
	7	1152	17% reduction in egg to fry survival
	90	456	5% mortality in sub-adults
	171	96	Histological damage
	50	1848	Reduction in growth rate
	100	1	Avoidance response

Compiled by the Washington State Department of Ecology for "A Suspended Sediment and DDT Total Maximum Daily Load Evaluation Report for the Yakima River."
(Web Site Ref. #10)

Table 4. Some reported effects of turbidity and suspended sediment concentrations on salmonids: 2001 Update. This table is derived from Lloyd (1987).

Effect	Species (life stage)	Location	Reported turbidity or suspended sediment concentration	Reference
Activity	Creek Chubs, Brook Trout	Wisconsin	Increase in moderately turbid waters	Gradall and Swenson (1982)*
Avoidance	Coho salmon (underyearling)	British Columbia	After 60 NTU pulse, fish move to substrate	Berg (1982)*
Avoidance	Coho salmon (underyearling)	British Columbia	Approx 25% at 7,000 mg/l – estimated that the threshold for avoidance in the vertical plane was 37 NTU	Servizi and Martens (1992)*
Avoidance	Creek Chubs	Wisconsin	Preferred 56.6 FTU	Gradall and Swenson (1982)*
Blood Sugar	Coho salmon (underyearling)	British Columbia	Elevated, proportional to SS exposure	Servizi and Martens (1992)*
Capture success per strike	Coho salmon (juvenile)	British Columbia	30 and 60 NTU	Berg and Northcote (1985)*
Cough Frequency	Coho salmon (underyearling)	British Columbia	Elevated eightfold over control levels at 240 mg/l	Servizi and Martens (1992)*
Feeding rates	Pacific herring (larval stage)	Oregon	Maximum feeding potential at 500 and 1000 mg/l	Boehlert and Morgan (1985)*
Feeding rates	Coho salmon (juvenile)	British Columbia	Prey consumption only 35% of feeding in clear water at 60 NTU	Berg (1982)*
Feeding rates	Coho salmon and steelhead (yearlings)	Oregon	When exposed to 2,000-3,000 mg/l of topsoil, kaolin clay, volcanic ash, 7-8 days	Redding et al. (1987)*
Feeding rates	Chinook salmon (juvenile)	British Columbia	Reduced at higher turbidities, highest rates at intermediate turbidity 35-150 NTU for surface and benthic prey	Gregory and Northcote (1993)*

* laboratory study

** field study

Table 4 (cont.).

Some reported effects of turbidity and suspended sediment concentrations on salmonids: 2001 Update. This table is derived from Lloyd (1987).

Effect	Species (life stage)	Location	Reported turbidity or suspended sediment concentration	Reference
Feeding rates	Chinook salmon (juvenile)	British Columbia	Increased rates on surface and benthic prey in conditions of moderate turbidity (18-150 NTU) compared with lower (<1 NTU) or higher 370-810 NTU	Gregory (1992)*
Feeding rates	Chinook salmon (juvenile)	British Columbia	Above 150 NTU, juvenile chinook exhibit reduced feeding regardless of prey type and forager size	Gregory (1992)*
Feeding rates	Bluegills	North Carolina	14 prey per minute in clear water to 1, 10, 7 per minute in pools of 60, 120, and 190 NTU. Size selectivity independent	Gardner (1981)*
Gill trauma	Sockeye salmon (underyearling)	British Columbia	3,148 mg/l or 0.2 of the 96 h LC50 Value	Servizi and Martens (1987)*
Homing	Chinook salmon (adult)	Washington	Strong baseline preference for clean (ash-free) home water over a clean non-natal water source	Whitman et al. (1982)**
Impairment in hypo-osmoregulatory capacity	Sockeye salmon (underyearling)	British Columbia	Exposed 96 h to 14,407 mg/l of fine sediment	Servizi and Martens (1987)*
Percentage of prey ingested	Coho salmon (juvenile)	British Columbia	30 and 60 NTU	Berg and Northcote (1985)*
Plasma glucose increase	Sockeye salmon (underyearling)	British Columbia	Increased 150 and 39% from exposure to 1,500 and 500 mg/l of fine sediment	Servizi and Martens (1987)*

* laboratory study

** field study

Table 4 (cont.) . Some reported effects of turbidity and suspended sediment concentrations on salmonids: 2001 Update. This table is derived from Lloyd (1987).

Effect	Species (life stage)	Location	Reported turbidity or suspended sediment concentration	Reference
Predation rates	Chinook salmon (juvenile), chum, sockeye, cutthroat trout	British Columbia	Mean predation rates were 10-75% lower than those in controls (no vegetation and clear water); addition of turbidity reduced effect	Gregory and Levings (1996)*
Predator avoidance	Chinook salmon (juvenile)	British Columbia	In absence of risk, juvenile chinook were distributed randomly in 23 NTU, at bottom in clear water– with risk, all at bottom, and responses less marked and of shorter duration	Gregory (1993)*
Prey abundance	N/A	Columbia River Estuary	Reduction in amphipods in substrate with surface layer of ash	Brzezinski and Holton (1981)**
Prey abundance	N/A	Northwest Territories	Sediment addition increased total drift of invertebrates (avoidance reaction)	Rosenberg and Wiens (1978)**
Reaction distance	Coho salmon (juvenile)	British Columbia	30 and 60 NTU	Berg and Northcote (1985)*
Reaction distance	Chinook salmon (juvenile)	British Columbia	Decline with increasing turbidity	Gregory and Northcote (1993)*

* laboratory study

** field study

Table 4 (cont.).

Some reported effects of turbidity and suspended sediment concentrations on salmonids: 2001 Update. This table is derived from Lloyd (1987).

Effect	Species (life stage)	Location	Reported turbidity or suspended sediment concentration	Reference
Reaction distance	Adult lake trout	Utah	Reaction distance increased w/ increasing light - <25 cm at .17 lx to about 100 cm at light threshold of 17.8 lx., declined with turbidity - > 80% of decline in reaction distance occurred over 0-5 NTU	Vogel and Beauchamp (1999)*
Reactive Distance	Rainbow Trout	Georgia	Reactive distances in 15 and 30 NTU treatments were only 80 and 45% respectively of those observed at ambient turbidities 4-6 NTU.	Barrett and Rosenfeld (1992)*
Reduced Growth	Coho salmon (juvenile)	Oregon	Significant decrease in fish production when fine sediments were 26-31% by volume	Crouse et al. (1981)*
Reduction in prey	Chinook salmon (juvenile)	Washington	Reduced appearance of highly utilized amphipod <i>Corophium salmonis</i> .	McCabe et al. (1981)**
Relation of turbidity and suspended solids	N/A	Alaska	Depth to which 1% of subsurface light penetrates has inverse correlation with sediment-induced turbidity	Lloyd et al. (1987)**
Stress (Gill Flaring)	Coho salmon (juvenile)	British Columbia	Increased at 30 and 60 NTU	Berg and Northcote (1985)*

* laboratory study

** field study

Table 4 (cont.).

Some reported effects of turbidity and suspended sediment concentrations on salmonids: 2001 Update. This table is derived from Lloyd (1987).

Effect	Species (life stage)	Location	Reported turbidity or suspended sediment concentration	Reference
Stress (increased plasma cortisol)	Coho salmon and steelhead (yearlings)	Oregon	When exposed to 2-3 g/L of topsoil, 7-8 days	Redding et al. (1987)*
Stress (blood hematocrits and plasma cortisol)	Coho salmon and steelhead (yearlings)	Oregon	Increased in fish exposed to high concentrations for two days, topsoil, kaolin clay, or ash.	Redding et al. (1987)*
Stress (resistance to bacterial pathogen)	Yearling steelhead and coho	Oregon	Vibrio anguillarum	Redding et al. (1987)*
Territoriality	Coho salmon (juvenile)	British Columbia	Territoriality ceases with 60 NTU pulse – re-established at 20 NTU – lateral displays minimized	Berg (1982)*

* laboratory study

** field study

V. Assessment of Whether Emulsion Characteristics of Turbidity have a Significant Differential Effect on Salmonid Survival, Growth, and Reproduction.

Salmonids encounter “naturally” turbid conditions in estuaries and glacially-fed streams. Managers are interested in determining whether there is something inherent in “natural” turbidity sources that make them somehow less harmful to fish than anthropogenic sediment inputs. A pertinent question is the relationship between sediment size, shape, and composition and salmonids viability.

It is difficult to determine the effect of sediments of various sizes and shapes based on laboratory experimentation owing to the complexity of natural systems. In addition to the character of the material, a number of other factors must be considered in evaluating salmonid response to suspended sediments. These factors include the life history stage, presence of cumulative stressors, availability of refugia that are well distributed, connected, and accessible, condition of biotic community, frequency and magnitude of exposure to the sediments, and the physical processes associated with hydrology, sediment input, transport, and storage present in a particular watershed. Past land use practices within a watershed are also of import.

Various types of sediment have been used in experiments developed to test the effect of suspended solids on salmonid health. Very few studies, however, provide a comparison of the effect of different sediment types and sizes on salmonids.

Davies-Colley and Smith (2000) noted that the physical and chemical, and therefore optical, character of suspended particles can vary widely between stream systems as well as within the same system. The important attributes of aquatic particles in addition to optical character include settling velocity and particle size, shape, and composition.

Based on current studies, it appears that gill injuries increase as angularity and particle size increase. Servizi and Martens (1987) studied gill injuries among underyearling sockeye exposed to fine and medium coarse sediments. The size and shape of particles appeared to affect the yearlings differentially. The study demonstrated that tolerance decreased as particle size increased, specifically for particles described as “angular to subangular.” Underyearling sockeye experienced gill trauma at 3,143 mg/l, levels that have been measured at Hell’s Gate on the Fraser River.

Newcomb and Flagg (in Servizi and Martens 1987) reported a 36 h LC₅₀ of Mt. St. Helens ash to be 6,100 mg/l for sockeye smolts, whereas there were no mortalities when smolts were exposed to 14,407 mg/l of Fraser River sediments. These data suggest that sockeye smolts may be more sensitive to slightly larger, largely angular ash particles than subangular to angular particles. The 96 h LC₅₀s of four Fraser River sediments to underyearling sockeye ranged from 1,674 to 17,560 mg/l and were related to particle size (Servizi and Martens 1987).

Table 5. Classification of suspended solids and their probable major effects on freshwater ecosystems (from Sorenson et al. 1977).

	Biochemical, Chemical, and Physical Effects	Biological Effects*
Clays, silts, sand	Sedimentation, erosion and abrasion, turbidity (light reduction), habitat change	Respiratory interference, habitat restriction, light limitation
Natural organic matter	Sedimentation, DO utilization	Food sources, DO effects
Wastewater organic particles	Sedimentation, DO utilization, nutrient source	DO effects, eutrophication
Toxicants sorbed to particles	All of the above	Toxicity

* Biological effects may result directly from pollutants (primary effect), changes due to biochemical, chemical, or physical changes (secondary), or biological interactions (tertiary effects).

Table 6. Sediment particle size (modified from Waters 1995)

Category	Size Range	Phi scale
Boulder	> 256 mm	-8
Cobble	64-256 mm	-6,-7
Pebble	16-64 mm	-4,-5
Gravel	2-16 mm	-1,-2,-3
Very coarse sand	1-2 mm	0
Coarse sand	0.5-1 mm	1
Medium sand	0.25-0.5 mm	2
Fine sand	0.125-0.25 mm	3
Very fine sand	0.0625-0.125 mm	4
Silt	4-62 um	5,6,7,8
Clay	< 4 um	9

Summary

Additional research needs to be undertaken in this area. Laboratory results indicate that size, shape, and composition of sediment particles may have differential effects on salmonids. It is important to understand all of the mechanisms by which suspended sediments affect salmonids in order to reduce effects associated with land use.

VI. Current State and Provincial Turbidity Standards

This section provides a review of the current turbidity requirements in Alaska, Idaho, Oregon, Washington, and British Columbia. The standards reviewed here require that turbidity be measured against a “background turbidity,” established at a point upstream of the affected area. Only two of the five standards reviewed include a limit on the duration of exposure to a certain turbidity level (Idaho and British Columbia).

Best Available Technology (BAT) TSS requirements are commonly used in writing National Pollutant Discharge Elimination System (NPDES) discharge permits in Washington State. For many industrial applications, the BAT standard is 45 mg/l for a long-term average and 90 mg/l for a daily maximum (E. Molash, pers. commun.). To address watershed scale turbidity or total suspended solid issues, the four states have the option of using the Total Maximum Daily Load (TMDL) process to assess the need for overall reductions in turbidity levels and suspended sediments.

The TMDL process was established by section 303(d) of the Clean Water Act. Federal law requires states to identify sources of pollution in waters that fail to meet state water quality standards after all point sources have been permitted, and to develop cleanup plans to address pollutants of concern. A TMDL is a calculation of the maximum amount of a pollutant that a water body can receive and still meet state water quality standards. Percentages of the total maximum daily load are allocated to the various pollutant sources (Web Site Ref. #10). More detailed information on TMDLs in Washington, Oregon, and Idaho can be found in Appendix D.

A number of researchers analyzed existing state regulations for turbidity and total suspended solids to determine if the level of protection afforded to salmonids is adequate. Bisson and Bilby (1982) noted that state regulations at that time did not consider acclimation of stream biota to high turbidity, as regulations permitted only minor increases in suspended sediment when background turbidity was low, but allowed greater absolute increases as background levels rise.

Lloyd (1987) examined the use of turbidity as a water quality standard for salmonid habitats in Alaska. Lloyd’s (1987) review indicated that water quality standards allowing increases in coldwater habitats of 25 NTU above ambient turbidity would provide “moderate” protection, while a standard allowing a 5 NTU increase above ambient turbidity would provide “high” protection for salmonids. This determination was based on a number of studies which indicated that turbidities as low as 10-25 NTUs can have deleterious effects on fish (Berg 1982; McCabe and O’Brien 1983; Sigler et al. 1984; Berg and Northcote 1985).

Lloyd (1987) suggested that an acceptable turbidity standard must do two things to protect aquatic habitats: prevent loss of aquatic productivity and cause no lethal or chronic sublethal effects on fish and wildlife. Other researchers have suggested the need for standards other than simple turbidity criteria to control pollution by sediment. The National Academy of Sciences and National Academy of Engineering (1973)

recommended that depth of light penetration not be decreased by more than 10% and that suspended sediment concentrations be limited to specific values.

Sorenson et al. (1977) cited concern over the difficulty in setting rigid standards for suspended solids. The concentration of suspended solids in natural waters is influenced by such factors as topography, geology, soil condition, intensity and duration of rainfall, type and amount of vegetation in the drainage basin, and past and current human activity. Flowing waters may have considerable variation in SSC from day-to-day and year-to-year. Since natural variation in suspended solids is so great, the authors suggested that it is not desirable to have fixed rigid standards.

Duchrow and Everhart (1971) and Bisson and Bilby (1982) called for consideration of standards for settleable solids, as they are of primary concern in the protection of aquatic fauna. As sediment type and aquatic fauna vary across and between watersheds, specific standards might have to be applied depending on conditions within and between watersheds.

Table 7 provides a summary of current turbidity standards for states in the Northwestern United States and British Columbia, Canada. **Table 8** provides standards for the year 1987. This is provided to show changes in regulations between 1987 and 2001.

Appendix C provides detailed information on turbidity standards for each state and province.

Table 7. 2001 Comparison table of state and provincial turbidity standards

State/Province	Standard	Notes
Alaska (Web Site Ref. #1)	May not exceed 25 NTU above natural conditions. For all lake waters, may not exceed 5 NTU above natural conditions.	Standard for growth and propagation of fish, shellfish, other aquatic life, and wildlife. <i>End-of-pipe unless a mixing zone has been approved.</i>
British Columbia (Web Site Ref. #2)	Maximum Induced Turbidity – NTU or % of background: 8 NTU in 24 hours when background is less than or equal to 8 Mean of 2 NTU in 30 days when background is less than or equal to 8 8 NTU when background is between 8 and 80 10% when background is greater than or equal to 80	Standard for aquatic life, fresh, marine, estuarine BC regulations also include limits on Maximum Induced Suspended Sediments –mg/L or % of background and limits on streambed substrate composition (% fines at spawning sites, geometric mean diameter not less than 12 mm) <i>Edge of mixing zone.</i>
Idaho (Web Site Ref. #5)	Turbidity, below any applicable mixing zone set by the Department, shall not exceed background turbidity by more than (50) NTU instantaneously or more than twenty-five (25) NTU for more than ten (10) consecutive days.	Standard for aquatic life use designations. <i>Edge of mixing zone</i> (Exceedance limited to 5 NTU if a point source)
Oregon (Web Site Ref. #7)	No more than ten percent cumulative increase in natural stream turbidities, as measured relative to a control point immediately upstream of the turbidity causing activities.	Limited duration activities that exceed requirements may be authorized (see Oregon Turbidity Standards Section). <i>End-of-pipe unless a mixing zone has been approved.XX</i>
Washington (Web Site Ref. #12)	Turbidity shall not exceed 5 NTU over background turbidity when the background turbidity is 50 NTU or less, or have more than a 10 percent increase in turbidity when the background is > 50 NTU	For Class A Waters; for Class B waters, turbidity shall not exceed a 10 NTU increase over background turbidities of 50 NTU or less, or a 20% increase when background turbidity is greater than 50 NTU <i>Edge of mixing zone</i>

Table 8. Numerical turbidity standards for protection of fish and wildlife habitats in Alaska and other states (as cited by Lloyd 1987).

State	Turbidity (NTU or JTU) ^a
Alaska	25 units above natural in streams 5 units above natural in lakes
California	20% above natural, not to exceed 10 units above natural
Idaho	5 units above natural
Minnesota	10 units
Montana	10 units (5 above natural) ^b
Oregon	10% above natural
Washington	25 units above natural (5 and 10 above natural) ^c
Wyoming	10 units above natural

a Nephelometric (NTU) and Jackson (JTU) turbidity units are roughly equivalent (USEPA 1983).

b Montana places the more stringent limit on waters containing salmonid fishes.

c API (1980) reports different values in Washington for “excellent” and “good” classes of water.

Summary

Each state and province in the northwest attempts to control sediment input to rivers by placing limits on turbidity increases above “natural background levels.” Natural background turbidity levels may vary widely between watersheds due to factors such as base geology, legacy conditions, and land-cover and within a system (e.g. headwaters versus estuary). In addition, turbidity may change daily, seasonally, and annually depending on physical and biological changes in the system. This variability makes it difficult to quantify natural background turbidity.

To adequately protect salmonids during their freshwater residence, TSS data on physiological, behavioral, and habitat effects should be viewed in a layer context incorporating both the spatial geometry of suitable habitat and the temporal changes associated with life history, year class, and climate variability. Spatial and temporal considerations provide the foundation to decipher legacy effects as well as cumulative and synergistic effects on salmonid protection and recovery.

VII. Turbidity Requirements for Hatcheries

In Washington State, hatcheries do not follow specific turbidity requirements regarding water used for hatchery operations. However, hatchery operators often have unstated guidelines to determine when turbidity levels pose a risk to eggs and juvenile salmonids. In many cases, hatchery managers rely on visual measurement rather than numeric guidelines to determine risk to developing salmonids.

Upland hatcheries are subject to regulations regarding the water released from facilities and the byproducts of hatchery operations. Hatcheries must obtain NPDES permits to address discharges from their facilities into streams.

Controlling Turbidity and Suspended Solids in Hatchery Water

In general, hatcheries in Washington State receive water supplies from nearby creeks and rivers. In a minority of cases, groundwater or springs are used where available (H. Michael, pers. commun.). The advantage of groundwater and spring sources is 1) lower concentrations of suspended solids and 2) reduced pathogen presence from river water. There are additional costs, however, associated with using groundwater and spring sources, such as pumping the water from the source to the facility.

Hatchery operators must monitor the sediment concentration of the water and determine the point at which the condition will be deleterious to fish at various life stages. It is important for hatchery managers to determine when to “clean” eggs that are exposed to suspended sediments. Even when the water supply contains low levels of suspended sediment, operations must be observed carefully. Over a period of 3 or 4 months even a low level of sediment could eventually smother eggs (H. Michael, pers. commun.).

The Soos Creek Hatchery in Auburn does not adhere to specific turbidity criteria during operation. The staff use professional knowledge to identify when the water supply is turbid to the point of endangering the eggs. In these cases, the eggs are temporarily removed from their tanks until turbidity decreases. This emergency measure most often occurs as the result of rainfall and a subsequent storm surge. The hatchery uses water from Soos Creek for raising coho, and spring water for raising steelhead (T. Sorbo, pers. commun.).

At a hatchery on the Cowlitz River in Southwestern Washington, glaciated river water occasionally creates conditions where juveniles cannot see their food. H. Michael (pers. commun.) stated that fish require 12-18” of visibility for feeding during rearing. Reduced feeding can lead to reduced growth rates. Additionally, if glacial water slows enough in the hatchery, glacial sediment may settle and pose a risk to eggs.

Outflow from Hatcheries

Washington State upland hatcheries (as opposed to netpens) require NPDES discharge permits to account for all materials released from hatcheries back into the stream. The

amount of settleable solids allowed from normal hatchery operations is a monthly average of 0.1 mg/l. For total suspended solids, the monthly average allowed is 5 mg/l. The instantaneous maximum allowed is 15 mg/l (H. Michael, pers. commun.).

Off-line settling basins are used to contain settleable solids from hatchery operations. These ponds are drawn down and sediments are removed on a regular basis. Dredged material is then removed for upland disposal. For the water returned to the creek from off-line settling ponds, the NPDES requirement calls for monthly release rates of 1 mg/l settleable solids, and 100 mg/l total of suspended solids.

Summary

Turbid water and related suspended sediment concentrations pose a threat to the health of hatchery fish. Excessive sediment in hatchery water may smother eggs by depriving them of oxygen, and reducing the ability of juveniles to capture prey. While there appears to be no specific measurement guideline for determining when the suspended sediment levels are a danger to eggs and juveniles, hatchery managers have developed methods of visually estimating risk and acting accordingly. Hatcheries are subject to discharge permits which limit the amount of sediment they may release downstream of the facility.

VIII. Recommendations

Based on this literature review, there are a number of areas where additional research would help managers better assess the effects of suspended sediment on salmonid health, growth, and reproduction.

Regulatory requirements often force managers to focus on meeting a specific requirement at a specific location and point in time. It is difficult to quantify the direct effect of turbidity on salmonids by looking at the effect of one particular disturbance in a watershed. This does not account for cumulative sediment loading throughout the basin nor synergistic effects. If possible, transportation project managers should consider watershed-scale effects in addition to the effect of their particular project. The key questions for managers are: 1) whether there are various scale refugia accessible in the system that will allow salmonids to cope with short term sediment effects; and 2) whether other cumulative and synergistic effects magnify short-term sediment alterations.

Another important consideration is the inconsistency of turbidity measurements. When devising monitoring strategies for transportation projects, Washington State Department of Transportation (DOT) might want to consider collecting baseline TSS data, which then may be correlated with turbidity readings for future monitoring.

Research, Monitoring, and Management Recommendations

Measurement

- Conduct baseline studies measuring “natural” background levels in undisturbed systems and disturbed systems, stratified by biophysical parameters.
- Prior to conducting construction projects, determine TSS concentrations and gather information on size, shape, and composition of sediment.
- Develop new exposure metrics that account for sublethal effects (as opposed to direct mortality).
- Conduct research in the field if possible – most work to date has been performed in laboratories, which may not provide an accurate picture of the effects of suspended sediment on salmonids.
- Consider use of other measurement tools, such as water clarity to determine levels of suspended sediments.

Sediment Effects

- Examine the effect of frequent short-term pulses of suspended sediment on salmonids.
- Conduct additional research on correlations between particle size, shape, and composition of sediments to sensitivity effects on salmonids.
- Evaluate how loss of groundwater/surface water interactions affect availability and abundance of salmonid habitat.
- Study relationships between seasonal timing and effect of sediment load on salmon.
- View TSS data on physiological, behavioral, and habitat effects in a layered context, incorporating both the spatial geometry of suitable habitat and the temporal changes associated with life history stage, year class, and climate variability. Spatial and temporal considerations provide the foundation to decipher legacy effects as well as cumulative and synergistic effects on salmonid protection and recovery.

Management

- Consider watershed condition when evaluating projects. Examine legacy of land use in watershed and determine how planned disturbance will contribute to cumulative effects.
- Analyze other sources of sediment contribution to the watershed, such as grazing allotments, roads and culverts, and timber harvest areas. Reduce sediment loads from these areas if possible.
- Restore tributaries and off-channel habitat to create potential turbidity refuges.
- Determine whether knowledge of salmonid survival responses to turbid flows can be used to develop mixing zones, work windows, treatment systems, and buffers that will allow fish to perform their necessary life functions during project construction and operation.
- Test a variety of existing and new technologies used to reduce TSS during road construction projects. Collect quantitative data.

Given that salmonids encounter “naturally” turbid conditions in estuaries and glacially-fed streams, as well as during flood events and have developed survival responses for those turbid conditions there are some additional critical questions for consideration . Is there something inherent in “natural” turbidity sources that makes exposure less harmful to fish? For instance, is the “angularity” of suspended sediments a factor? How about particle size ranges? During flood events, does available habitat provide “turbidity” refugia?

Establishing Baseline Turbidity Values

The difficulty of establishing overall “natural background turbidities” was discussed earlier in this paper. One possibility for setting baseline turbidity ranges is to measure background turbidity levels in unmanaged or “natural” areas of basins with differing morphologies. Continuous sampling would be required to define turbidity fluctuations under various hydrological conditions (such as a storm event). Once a range of conditions has been identified for the watershed, a distribution may be plotted. This distribution can be used to establish guidelines for similar watersheds.

Regulatory Suggestions in the Literature

Lloyd (1987) suggested that a turbidity standard could be used to address the effects of turbidity as an optical property of water and as an indicator of SSC. The effects of sedimentation on lake and stream bottoms could be addressed by separate enforceable settleable solid or streambed standards. Lloyd (1987) cites a need to establish or reaffirm the levels of turbidity, and associated suspended solids concentrations that are appropriate

as standards for regulating human-induced effects on aquatic systems. Turbidity standards can be tiered or graded (if necessary) to ambient water quality conditions and the level of protection desired for a body of water (Lloyd 1987).

Lloyd (1987) also suggested that any alternative standards account for the primary aspects of turbidity—extinction of light and presence of suspended sediment. Direct measurement is possible of both, but the measure of turbidity was developed to facilitate suspended sediment estimates. Light penetration can be measured in situ with portable photometers and extinction coefficients calculated with simple graphs or equations, but discrete samples cannot be removed and analyzed separately. Sediment concentration can be sampled in the field and measured gravimetrically in a laboratory. Filtering, drying and weighing procedures are required (Lloyd 1987).

Reasonable turbidity criteria that are established to protect aquatic habitats from decreased light penetration may also protect systems from high concentrations of suspended sediments and heavy metals. Separate settleable solids or streambed standards could then be applied to protect aquatic habitats from effects on benthic substrates (Lloyd 1987).

Cairns (1968) suggested that truly responsive regulations should be developed on a drainage-by-drainage basis, and should change with stream flow and other habitat conditions. Lloyd (1987) noted that this type of standard would require enormous baseline studies and almost continuous surveillance and monitoring, and subsequently questioned whether such an approach is feasible in Alaska or elsewhere.

Lloyd (1987) indicated that for salmonids, a “moderate” level of protection (SSC up to 100 mg/l) roughly translates to turbidity values up to 23 NTUs. Recommendations for a “high” level of protection (0-25 mg/l) roughly translate to turbidity values up to 7 NTUs. Stricter limits might be warranted to protect extremely clear waters, due to the dramatic initial effect of turbidity on light penetration. Naturally turbid systems might need tiered or graded standards based on ambient water quality.

USFWS (1998) suggested that managers avoid new road construction in areas vulnerable to mass wasting and in areas that may initiate or exacerbate stream bank erosion. On a larger scale, it was suggested that managers identify land management activities (upland and riparian) that have potential to contribute sediment to spawning and rearing areas above natural levels (USFWS 1998).

Castro and Reckendorf (1995) suggest that fish are not good indicators of excess sedimentation, as separating the effects of sediment from other environmental factors can be impossible in a natural system. While sometimes obvious effects of excessive fine sediment can be viewed, often effects are not apparent. The authors suggested using another indicator species, such as benthic macroinvertebrates, which are more sensitive to small changes in sediment quality and quantity, less mobile, and have shorter life cycles.

IX. Summary

Protection of Washington State's salmonids requires that transportation officials consider the effect of suspended sediments released into streams during road construction.

Numerous studies have shown that the presence of suspended sediments can have a detrimental effect on the physiology, behavior, and habitat of salmonids. Different species and even different life stages of species are susceptible to adverse effects from different levels of sediment and to sediments of different sizes.

Turbidity is the measure most commonly used by agencies to indicate the level of suspended solids in the water column. It is an indirect measure, however, and may not always be correlated with suspended solid concentrations. Turbidity may vary depending on geomorphic, hydrologic, and hydraulic factors.

Although salmonids are found in naturally turbid river systems in the Northwest, this does not necessarily mean that salmonids in general can tolerate increases over time of suspended sediments. An understanding of sediment size, shape, and composition, salmonid species and life history stages, cumulative and synergistic stressor effects, and overall habitat complexity and availability in a watershed is required.

For short-term construction projects, operators will need to measure background turbidities on a case by case basis to determine if they are exceeding regulations. However, transportation projects may also produce long-term, chronic effects. Short-term pulses will presumably have a different effect on salmonids than chronic exposure.

Turbidity standards developed by several states and provinces in this region attempt to consider natural variability in turbidity by requiring the regulated community to measure "background turbidity" upstream of any proposed activity. The background turbidity measured in these situations represents a measurement at one point in time. Regulating turbidity levels based on this type of measurement may not be protective of salmonid health.

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Appendix A 1999 Washington State Water Quality Data
(Web Site Ref. #11)

Table A-1. Discharge (cfs) and Turbidity (NTUs) Measured in Western Washington Streams During 1988-99 (Web Site Ref. #11)

Sample month	Skagit River @ Marblemount		Samish River near Burlington		NF Stillaguamish @Cicero		Stillaguamish R. near Silvana	
	Cfs	NTU						
October	4390	0.6	150	6.3	1420	6	1400	8.3
November	6330	1.1	450	10	5300	145	5870	60
December	7600	1.4	793	16	6600	100	7710	55
January	8360	0.9	583	7.7	4840	170	8810	55
February	7640	0.5	406	5.5	1050	19	2830	29
March	6190	0.8	359	5.4	2260	22	5210	29
April	6230	1.6	327	9.6	2120	19	5890	60
May	12700	4.8	180	6.3	3690	60	8200	50
June	7080	3.2	107	3.3	2010	8	4480	17
July	10600	2.7	78	2.2	1300	3.1	2460	4.9
August	8550	2.2	62	2.7	641	2.1	1600	4.2
September	4290	0.7	32	1.1	270	1.6	574	1.7

Table A-2. Turbidity (NTUs) Measured in Three Western Washington Streams During 1988-99

	Yearly Average	Summer Range (May-Oct.)	Winter Range (Nov. – Apr.)
Cedar River	1.1	0.4 – 1.2	1.0 – 2.0
Newaukum Creek	2.4	0.7 – 1.5	3.1 – 4.0
Springbrook Creek	22.0	13.0 – 44.0	13.0 – 35.0

Table A-3. TSS (mg/l) Measured in Three Western Washington Streams During 1988-99

	Yearly Average	Summer Range (May-Oct.)	Winter Range (Nov. – Apr.)
Cedar River	3.6	0.6 – 5.0	3.5 – 6.2
Newaukum Creek	5.7	1.6 – 5.1	7.5 – 8.8
Springbrook Creek	19.8	8.0 – 26.0	6.7 – 44.0

Source: Metro 1990. *Quality of Local Lakes and Streams 1988-89 Status Report*. Municipality of Metropolitan Seattle, Water Resources Section, from: Washington Department of Ecology, A Citizen's Guide to Understanding and Monitoring Lakes and Streams. (Web Site Ref. #8)

Appendix B Tables from Newcombe and MacDonald (1991)

Table B-1. Summary of data (in situ observations) on exposures to suspended sediment that resulted in lethal responses in salmonid fishes. Within species groups, stress indices are arranged in increasing order. For exposure, C= concentration (mg/l) and D = duration (h).

Species	<i>Exposure</i>		Stress index (log ^{e*} [CxD])	Effect	Rank of Effect	Source
	C	D				
Arctic grayling	25	24	6.397	6% mortality of sac fry	10	Reynolds et al. (1988)
	23	48	7.007	14% mortality of sac fry	10	Reynolds et al. (1988)
	65	24	7.352	15% mortality of sac fry	10	Reynolds et al. (1988)
	22	72	7.368	15% mortality of sac fry	10	Reynolds et al. (1988)
	20	96	7.560	13% mortality of sac fry	10	Reynolds et al. (1988)
	143	48	8.834	26% mortality of sac fry	11	Reynolds et al. (1988)
	185	72	9.497	41% mortality of sac fry	12	Reynolds et al. (1988)
	230	96	10.002	47% mortality of sac fry	12	Reynolds et al. (1988)
	20,000	96	14.468	10% mortality of age-0 fish	10	McLeay et al. (1987)
	100,000	96	16.077	20% mortality of age-0 fish	10	McLeay et al. (1987)
Chinook salmon	488	96	10.755	50% mortality of smolts (high T°C)	12	Stober et al. (1981)
Coho salmon	509	96	10.797	50% mortality of smolts (high T°C)	12	Stober et al. (1981)
Chinook and sockeye salmon	1,400 ^b	36	10.827	10% mortality of juveniles	10	Newcomb and Flagg (1983)
Coho salmon	1,200	96	11.654	50% mortality of juveniles	12	Noggle (1978)
	1,217	96	11.668	50% mortality of pre-smolts (high T°C)	12	Stober et al. (1981)
Chinook and sockeye salmon	207,000 ^b	1	12.240	100% mortality of juveniles	14	Newcomb and Flagg (1983)
	9,400	36	12.732	50% mortality of juveniles	12	Newcombe and Flagg (1983)
Chum salmon	97	3,912 ^b	12.847	77% mortality of eggs and alevins	13	Langer (1980)

Table B-1 (cont.). Summary of data (in situ observations) on exposures to suspended sediment that resulted in **lethal** responses in salmonid fishes. Within species groups, stress indices are arranged in increasing order. For exposure, C= concentration (mg/l) and D = duration (h).

Species	<i>Exposure</i>		Stress index (log ^{e*} [CxD])	Effect	Rank of Effect	Source
	C	D				
Chum salmon	111	3,912 ^b	12.981	90% mortality of eggs and alevins	14	Langer (1980)
Chinook and sockeye salmon	82,000	6	13.106	60% mortality of juveniles	12	Newcomb and Flagg (1983)
Coho salmon	18,672	96	14.400	50% mortality of presmolts	12	Stober et al. (1981)
Chinook salmon	19,364	96	14.436	50% mortality of smolts	12	Stober et al. (1981)
Chum salmon	28,000	96	14.804	50% mortality of juveniles	12	Smith (1939)
Coho salmon	28,134	96	14.811	50% mortality of smolts	12	Stober et al. (1981)
	29,580	96	14.859	50% mortality of smolts	12	Stober et al. (1981)
	35,000 ^b	96	15.027	50% mortality of juveniles	12	Noggle (1978)
Chinook and sockeye salmon	39,400	36	15.145	90% mortality of juveniles	14	Newcombe and Flagg (1983)
Chum salmon	55,000	96	15.479	50% mortality of juveniles	12	Smith (1939)
Whitefish	16,613	96 ^b	14.282	50% mortality of juveniles	12	Lawrence and Scherer (1974)
Rainbow trout	200 ^c	24	8.476	5% mortality of fry	10	Hebert and Richards (1963)
	7	1,152	8.995	17% reduction in egg-to-fry survival	10	Slaney et al. (1977b)
	21	1,152	10.094	62% reduction in egg-to-fry survival	13	Slaney et al. (1977b)
	200 ^c	168	10.422	8% mortality of fry	10	Herbert and Richards (1963)
	90	456	10.622	5% mortality of sub-adults	10	Herbert and Merkens (1961)
	68	720 ^b	10.799	25% reduction in population size	11	Peters (1967)
	37	1,440	10.883	46% reduction in egg-to-fry survival	12	Slaney et al. (1997b)
	47	1,152	10.889	100% mortality of incubating eggs	14	Slaney et al. (1997b)
	57	1,440	11.315	23% reduction in egg-to-fry survival	11	Slaney et al. (1997b)
	270 ^d	456	11.721	10-35% mortality of sub-adults	11	Herbert and Merkens (1961)

Table B-1 (cont.). Summary of data (in situ observations) on exposures to suspended sediment that resulted in **lethal** responses in salmonid fishes. Within species groups, stress indices are arranged in increasing order. For exposure, C= concentration (mg/l) and D = duration (h).

Species	<i>Exposure</i>		Stress index (log ^{e*} [CxD])	Effect	Rank of Effect	Source
	C	D				
Rainbow trout	270 ^c	456	11.721	80% mortality of sub-adults	13	Herbert and Merkens (1961)
	101	1,440	11.888	98% mortality of eggs (high metals and NH3 levels)	14	Turnpenny and Williams (1980)
Brown trout	110	1,440	11.973	98% mortality of eggs	14	Scullion and Edwards (1980)
Rainbow and brown trout	300	720 ^b	12.283	97% reduction in population size	14	Peters (1967)
Rainbow trout	1,000-2,500	144	12.437	100% mortality of eggs	14	Campbell (1954)
	157	1,728	12.511	100% mortality of eggs	14	Shaw and Maga (1943)
	810 ^d	456	12.820	5-80% mortality of sub-adults	13	Herbert and Merkens (1961)
	810 ^c	456	12.820	80-85% mortality of sub-adults	14	Herbert and Merkens (1961)
	200 ^c	2,352	13.061	50% mortality of fry	12	Herbert and Richards (1963)
	1,000-2,500	480	13.641	57% mortality of fingerlings	12	Campbell (1954)
	4,250	588	14.731	50% mortality (life stage not specified)	12	Herbert and Wakeford (1962)
	160,000	24	15.161	100	14	D.W. Herbert, pers. commun. in Alabaster and Lloyd (1982)
	49,000	96	15.363	50% mortality of juveniles	12	Lawrence and Scherer (1974)
	1,000-6,000	1,440 ^b	15.432	85% reduction in population size	14	Herbert and Merkens (1961)
Brown trout	1,040	8,670	16.024	85% reduction in population size	14	Herbert et al. (1961)
	5,838	8,670	17.750	85% reduction in population size	14	Herbert et al. (1961)

a Scientific names: Arctic grayling, *Thymallus arcticus*, chinook salmon, *Oncorhynchus tshawytscha*, coho salmon, *O. kisutch*; sockeye salmon, *O. nerka*; chum salmon, *O. keta*; whitefish, *Coregonus* sp.; rainbow trout, *Oncorhynchus mykiss*; brown trout, *Salmo trutta*.

b Estimated.

c Wood fiber.

d Kaolin.

e Diatomaceous earth.

Table B-2. Summary of data on exposures to suspended sediment that resulted in sublethal responses in salmonid fishes. Within species groups, stress indices are in increasing order. For exposure, C = concentration (mg/l) and D = duration (h).

Species	<i>Exposure</i>		Stress index (log ^{e*} [CxD])	Effect	Rank of Effect	Source
	C	D				
Arctic grayling	100	1	4.605	Reduction in feeding rate	4	McLeay et al. (1984)
	100	1,008	11.521	6% reduction in growth rate	9	McLeay et al. (1984)
	300	1,008	12.620	Physiological stress	8	McLeay et al. (1987)
	300	1,008	12.620	10% reduction in growth rate	9	McLeay et al. (1987)
	1,000	1,008	13.823	33% reduction in growth rate	9	McLeay et al. (1987)
Coho salmon	14	1	2.639	Reduction in feeding efficiency	4	Berg and Northcote (1985)
	100	1 ^b	4.605	45% reduction in feeding rate	4	Noggle (1978)
	250	1 ^b	5.521	90% reduction in feeding rate	4	Noggle (1978)
	300	1 ^b	5.704	Feeding ceased	4	Noggle (1978)
	53.5	12	6.465	Physiological stress, changes in behavior	8	Berg (1983)
Chinook salmon	1.5-2.0 ^c	1,440	7,832	Gill hyperplasia, poor condition of fry	8	Anderson, USFWS, pers. commun.
	6 ^c	1,440	9.064	Reduction in growth rate	9	MacKinlay et al. (1987)
	75	168 ^b	9.441	Harm to quality of habitat	7	Slaney et al. (1977a)
	84 ^d	336	10.248	Reduction in growth rate	9	Sigler et al. (1984)
	1,547	96	11.908	Histological damage to gills	8	Noggle (1978)
Cutthroat trout	35	2	4.248	Feeding ceased, cover sought	4	Bachmann (1958)
Rainbow trout	500	9	8.412	Physiological ill effects	8	Redding and Schreck (1980)
	171	96	9.706	Histological damage	8	Goldes (1983)
Steelhead	84 ^d	336	10.248	Reduction in growth rate	9	Sigler et al. (1984)
Rainbow trout	50 ^c	960 ^b	10.779	Reduction in growth rate	9	Herbert and Richards (1963)
	50 ^f	960 ^b	10.779	Reduction in growth rate	9	Herbert and Richards (1963)
Trout	270	312 ^b	11.341	Histological damage to gills	8	Herbert and Merkens (1961)

Table B-2 (cont.). Summary of data on exposures to suspended sediment that resulted in **sublethal** responses in salmonid fishes. Within species groups, stress indices are in increasing order. For exposure, C = concentration (mg/l) and D = duration (h).

	<i>Exposure</i>					
Species	C	D	Stress index (log ^{e*} [CxD])	Effect	Rank of Effect	Source
Rainbow trout	50 ^c	1,848	11.434	Reduction in growth rate	9	Sykora et al. (1972)
Rainbow trout	5,000-300,000	168	13.641-17.736	Fish survived, but gill epithelium harmed	8	Slanina (1962)
Brook trout	12 ^c	5,880	11.164	Reduction in growth rate, reduced condition	9	Sykora et al. (1972)
	100 ^c	1,176 ^b	11.675	Reduction in growth rate	9	Sykora et al. (1972)
	24 ^c	5,280	11.736	Reduction in growth rate	9	Sykora et al. (1972)

a Scientific names: cutthroat trout, *Oncorhynchus clarki*; steelhead = anadromous rainbow trout; brook trout, *Salvelinus fontinalis*

b Estimated

c Lime-neutralized iron hydroxide

d Fire clay

e Coal dust

f Wood fiber

Table B-3. Summary of data on exposures to suspended sediment that resulted in behavioral responses in salmonid fishes. Within species groups, stress indices are in increasing order. For exposure, C = concentration (mg/l) and D = duration (h).

Species	<i>Exposure</i>		Stress index (log ^{e*} [CxD])	Effect	Rank of Effect	Source
	C	D				
Arctic grayling	100 ^a	1	2.303	Avoidance response	3	Suchanek et al. (1984a), Suchanek et al. (1984b)
Coho salmon	54	0.02	0.077	Alarm reaction	2	Berg (1983)
	88	0.02	0.565	Alarm reaction	2	Bisson and Bilby (1982)
	4.3 ^b	1	1.447	Avoidance response	3	Updegraff and Sykora (1976)
	88	0.08	1.952	Avoidance response	3	Bisson and Bilby (1982)
	25	4	4.605	Sport fishing declines	4	Phillips (1970)
Salmon	8	24	5.257	Sport fishing declines	4	A.H. Townsend, unpublished, cited in Lloyd (1985)
Chinook salmon	650	1	6.477	Homing performance disrupted	5	Whitman et al. (1982)
Coho salmon	6,000 ^a	0	8.700	Avoidance response	3	Noggle (1978)
Whitefish	0.7	1	-0.416	Overhead cover abandoned	3	Lawrence and Scherer (1974)
Rainbow trout	100 ^a	1	2.303	Avoidance response	3	Suchanek et al. (1984a), Suchanek et al. (1984b)
	100 ^c	0.25	3.219	Coughing rate increased	1	Hughes (1975)
	250 ^d	0.25	4.135	Coughing rate increased	1	Hughes (1975)
	66	1	4.190	Avoidance response	3	Lawrence and Scherer (1974)
Trout	8	24 ^a	5.257	Sport fishing declines	4	A.H. Townsend, unpublished, cited in Lloyd (1985)
Rainbow trout	665	1 ^a	6.500	Overhead cover abandoned	3	Lawrence and Scherer (1974)
Brook trout	4.5	168 ^a	6.628	Overhead cover abandoned	3	Gradall and Swenson (1982)

a Estimated.

b Lime-neutralized iron hydroxide.

c Coal dust.

d Wood fiber.

Appendix C Individual State Turbidity Standards

The following section illustrates specific turbidity regulations for the states of Alaska, Idaho, Oregon and Washington, and the Province of British Columbia.

Alaska State Turbidity Standards

According to Lloyd (1987), Alaska does not have a numerical standard for suspended solid concentrations in drinking water supplies. The state has a narrative standard for sediment.

“No measurable increase in concentrations of sediment including settleable solids, above natural levels.” [AAC 1985].

Alaska has a sediment standard for the propagation of fish and wildlife:

“The percent accumulation of fine sediment in the range of 0.1 mm to 4.0 mm in the gravel bed of waters utilized by anadromous or resident fish for spawning may not be increased more than 5% by weight over natural condition (as shown from grain size accumulation graph). In no case may the 0.1 mm to 4.0 mm fine sediment range in the gravel bed of waters utilized by anadromous or resident fish for spawning exceed a maximum of 30% by weight (as shown from grain size accumulation graph).” [AAC 1985], taken from (Lloyd 1987)

Table C-1. Alaska State Turbidity Standards (Web Site Ref. #1)

(1) Fresh Water Uses	Turbidity (not applicable to groundwater)
(A) Water Supply (i) drinking, culinary, and food processing	May not exceed 5 nephelometric turbidity units (NTU) above natural conditions when the natural turbidity is 50 NTU or less, and may not have more than 10% increase in turbidity when the natural turbidity is more than 50 NTU, not to exceed a maximum increase of 25 NTU.
(A) Water Supply (ii) agriculture, including irrigation and stock watering	May not cause detrimental effects on indicated use.
(A) Water Supply (iii) aquaculture	May not exceed 25 NTU above natural conditions. For all lake waters, may not exceed 5 NTU above natural conditions.
(A) Water Supply (iv) industrial	May not cause detrimental effects on established water supply treatment levels.
(B) Water Recreation (I) contact recreation	May not exceed 5 NTU above natural conditions when the natural turbidity is 50 NTU or less, and may not have more than 10% increase in turbidity when the turbidity is more than 50 NTU, not to exceed a maximum increase of 15 NTU. May not exceed 5 NTU above natural turbidity for all lake waters.
(B) Water Recreation (I) secondary recreation	May not exceed 10 NTU above natural conditions when natural turbidity is 50 NTU or less, and may not have more than 20% increase in turbidity when the natural turbidity is greater than 50 NTU, not to exceed a maximum increase of 15 NTU. For all lake waters, turbidity may not exceed 5 NTU above natural turbidity.
(C) Growth and Propagation of Fish, Shellfish, Other Aquatic Life, and Wildlife	Same as (1)(A)(iii).

Idaho State Turbidity Standards

The Idaho Division of Environmental Quality adopted turbidity criteria for the protection of cold water biota in 1994. The criteria focus on requirements of salmon as an indicator species. The 50 NTU background turbidity is based on data suggesting that displacement of salmonids occurs at 50 NTU (Lloyd et al. 1987). The 25 NTU for 10 days limit is based on literature showing that salmonid feeding and growth are affected by prolonged exposure to turbidity over 25 NTU (Sigler et al. 1984).

Surface Water Quality Criteria for aquatic life use designations – turbidity, below any applicable mixing zone set by the Department shall not exceed background turbidity by

more than fifty (50) NTU instantaneously or more than twenty-five (25) NTU for more than ten (10) consecutive days.

For comparison, turbidity criteria for water supply (measured at a public water intake) is as follows:

- (1) No increase by more than five (5) NTU above natural background, measured at a location upstream from or not influenced by any human induced non-point source activity, when background turbidity is fifty (50) NTU or less.
- (2) No increase by more than ten percent (10%) above natural background, measured at a location upstream from or not influenced by any human induced non-point source activity, not to exceed twenty-five (25) NTU, when background turbidity is greater than fifty (50) NTU (Web Site Ref. #5).

Oregon State Turbidity Standards

Oregon turbidity standards are applied to all watersheds in the state. The requirement may be applied to temporary projects affecting a stream or activities responsible for long-term sediment inputs.

In all basins, no more than 10% cumulative increase in natural stream turbidities shall be allowed, as measured relative to a control point immediately upstream of the turbidity causing activity. The criteria for listing a water body as 303(d) limited due to turbidity is a systematic or persistent increase (of greater than 10%) in turbidity due to an operational activity that occurs on a persistent basis (e.g., dam release, irrigation return). The requirements for listing a water body include collection of TSS data since water year 1986 (10/85) on a frequent enough basis (e.g., daily) to establish a relationship between water quality and a turbidity causing activity (Oregon Administrative Code).

Limited duration activities necessary to address an emergency or to accommodate essential dredging, construction, or other legitimate activities and which cause the standard to be exceeded may be authorized provided “practicable” turbidity control techniques have been applied and one of the following has been granted:

- (A) Emergency activities: Approval coordinated by the Department of Environmental Quality with Department of Fish and Wildlife under conditions they may prescribe to accommodate response to emergencies or to protect public health and welfare;
- (B) Dredging, Construction or other Legitimate Activities: Permit or certification authorized under terms of Section 401 or 404 (Permits and Licenses, Federal Water Pollution Control Act) or Oregon Administrative Rule 141-085-0100 et seq. (Removal and Fill Permits, Division of State Lands), with limitations and

conditions governing the activity set forth in the permit or certificate (Web Site Ref. #7).

Washington State Turbidity Standards

Table C-2. Washington State Turbidity Standards

Class A Waters	Class B Waters
Turbidity shall not exceed 5 NTU over background turbidity when the background turbidity is 50 NTU or less, or have more than a 10 percent increase in turbidity when the background is more than 50 NTU.	Turbidity shall not exceed 10 NTU over background turbidity when the background turbidity is 50 NTU or less, or have more than a 20 percent increase in turbidity when the background is more than 50 NTU

(Web Site Ref. #12)

British Columbia Standards

Table C-3 British Columbia Turbidity and Suspended Sediment Standards

Water Use	Maximum Induced Turbidity – NTU or % of background	Maximum Induced Suspended Sediments –mg/l or % of background	Streambed Substrate Composition
Drinking Water – raw untreated	1 NTU when background is less than or equal to 5	No guideline	No guideline
Drinking Water – raw treated	5 NTU when background is less than or equal to 50	No guideline	No guideline
Recreation and Aesthetics	Maximum 50 NTU secchi disc visible at 1.2 m	No guideline	No guideline
Aquatic Life -fresh- -marine- -estuarine-	8 NTU in 24 hours when background is less than or equal to 8 Mean of 2 NTU in 30 days when background is less than or equal to 8	25 mg/l in 24 hours when background is less than or equal to 25 Mean of 5 mg/l in 30 days when background is less than or equal to 25	Fines not to exceed -10% as less than 2mm- -19% as less than 3mm- -25% as less than 6.35mm- at salmonid spawning sites
Aquatic Life -fresh- -marine- -estuarine-	8 NTU when background is between 8 and 80 10% when background is greater than or equal to 80	25 mg/l when background is between 25 and 250 10% when background is greater than or equal to 250	Geometric mean diameter not less than 12 mm Fredle number not less than 5mm
Terrestrial Life -wildlife- -livestock water- Irrigation Industrial	10 NTU when background is less than or equal to 50 20% when background is greater than or equal to 50	20 mg/l when background is less than or equal to 100 20% when background is greater than or equal to 100	No guideline

(Web Site Ref. #2)

European Inland Fisheries Advisory Committee (EIFAC)

EIFAC (1965) presented five pathways that fine sediments may harm freshwater fishes:

1. By acting directly on the fish swimming in water in which solids are suspended, and either killing them or reducing their growth rate, affecting their resistance to disease
2. Preventing the successful development of fish eggs and larvae
3. By modifying natural movements and migrations of fish
4. By reducing the abundance of food available to the fish
5. By affecting the efficiency of methods of catching fish

Subsequent EIFAC recommendations:

<u>Level of Protection</u>	<u>Maximum Concentration of Suspended Solids</u>
High	25 mg/l
Moderate	80 mg/l
Low	400 mg/l
Very Low	over 400 mg/l

(Protective levels established based on EIFAC Study.)

Appendix D Total Maximum Daily Loads

The Total Maximum Daily Load (TMDL) process was established by section 303(d) of the Clean Water Act. Federal law requires states to identify sources of pollution in waters that fail to meet state water quality standards after all point sources have been permitted and to develop cleanup plans to address pollutants of concern. A TMDL is a calculation of the maximum amount of a pollutant that a water body can receive and still meets state water quality standards. Percentages of the total maximum daily load are allocated to the various pollutant sources. (Web Site Ref. #11).

Uses are identified for each water body, such as drinking water, contact recreation, and aquatic life support. The TMDL is meant to reflect the sum of allowable loads from a single pollutant for all point and non-point sources. TMDL calculations include a “margin of safety” to ensure protection in the case of unforeseen events or unknown sources of the pollutant. Calculation must also account for seasonable variation in background water quality (Web Site Ref. #11).

In Oregon and Washington, few rivers to date have TMDL requirements for 1) turbidity levels or 2) suspended solids.

Umatilla TMDL (Oregon)

The Umatilla TMDL for turbidity requires that measurements not exceed 30 NTU for 48 hours. The state collected TSS and turbidity data with automated ISCO samplers in the Umatilla, and determined that the Umatilla needed improvement in this area. The state did not focus on background concentrations. High turbidity levels in the Umatilla are associated with agricultural practices in the watershed. Upstream forested areas did not require a sediment load allocation. The TSS requirement for the Umatilla is 80-110 mg/l, except when stream flow is high (greater than 1.5 times bank) (Wiltsey, pers. commun.).

Lower Yakima TMDL (Washington)

The Washington State Department of Ecology conducted a TMDL evaluation of the lower Yakima River basin in 1994 and 1995. The process was conducted with the cooperation of the Yakama Nation and the USEPA. The evaluation focused on total suspended sediment (TSS) and DDT loads from irrigated agricultural areas during the irrigation season. Historical and TMDL data indicated significant correlations between TSS and turbidity, and TSS and DDT. It was assumed reductions in TSS would decrease DDT levels. Turbidity targets were recommended for mainstem and tributary sites on a 15-year implementation schedule (Web Site Ref. #10).

The Department of Ecology needed to build a “narrative criteria” argument because the state water quality criteria were written exclusively for point source rather than non-point source control. There are few turbidity (under 10) listings on the state 303(d) list because the criteria require a “background” turbidity measurement. Few monitoring agencies are

equipped to establish a background NTU value when turbid conditions arise from a diffuse set of streams affected by non-point sources. The Palouse River is an example of a river with TSS concentrations in the hundreds and thousands that has escaped 303(d) listing. Glacial headwaters are not helpful in some systems either, as they may produce a high level of natural background turbidity (Joy, e-mail).

The Washington State Class A turbidity criterion was applied to the mainstem to control TSS loading. In-stream turbidity will be limited to a 5 NTU increase in the 86.4 mile reach between the confluence of the Yakima and Naches River and Benton city. A 90th percentile turbidity target of 25 NTUs (56 mg/l TSS) for the tributaries and return drains was recommended to significantly reduce t-DDT loads and to protect aquatic communities from TSS effects. The target will require the largest return drains to reduce TSS loads 70% or more during an irrigation season with normal water availability. Based on the current correlation equation, tributary TSS concentrations will need to be further reduced to 7 mg/l to meet the 1 mg/l DDT chronic toxicity criterion for protection of aquatic life. However, more data from tributaries for TSS and t-DDT at lower TSS concentrations are needed to confirm this target (Web Site Ref. #10).

Currently, two systems in Washington State with turbidity problems are targeted for TMDL work: the upper Yakima River and tributaries, and Portage Creek in the Stillaguamish River System. The state is applying narrative type criteria for protection of aquatic life where it is unable to provide background conditions for applying turbidity criteria. (Joy, e-mail).

Idaho TMDLs

The State of Idaho has developed a number of TMDLs focused on reducing sediment as a pollutant. (Web Site Ref. #4)

Watershed/Sub-Basin with sediment	TMDLs done for sediment
Paradise Creek (1997)	1 segment
Lower Boise River (1998)	3 segment
MF Payette River (1998)	1 segment
Winchester Lake (1998) and Upper Lapwai (2003)	1 lake for sediment, 1 river segment for sediment
Portneuf River (1998)	26 segments
Lake Walcott (1999)	3 segments
Upper Snake-Rock (1999)	34 segments
Lemhi River (1998)	7 segments
Coeur d'Alene Lake/Lower River (1999)	7 segments
Pend Oreille (1999)	4 segments
Jim Ford Creek (1999 & 2003)	1 segments
Cottonwood Creek (1999 & 2003)	6 segments
Little Lost (1999)	3 segments
Bruneau (2000)	3 segments
Palisades (2000)	2 segments

Summary

TMDLs offer an opportunity for regulators and stakeholders in a watershed to reduce pollutant loads in the system. In Washington, Oregon, and Idaho, control of sediment is of concern, particularly in agricultural areas. Sediment is a concern both for its direct physical effect on aquatic life and its ability to transport pesticides through the river system.