## Appendix A
## Suspended Sediment Effects on Fish: A Literature Review

The first section of Appendix A is a literature review prepared by CH2M HILL on the effect of suspended sediment in the water column on fish. The literature review is presented verbatim from CH2M HILL (2000). The second subsection discusses predictive models available for assessing effects of suspended sediment on aquatic resources.

***Literature review*** This literature review was conducted to gain pertinent literature information regarding the potential effects of suspended sediments on fish, primarily salmonids. Effects of suspended sediments on fish include effects on fish behavior, effects on fish physiology, and effects on fish habitat.

Suspended sediments are usually silt and clay particles that are between 2 and 60 micrometers (:m) in diameter. Suspended sediments can be directly measured as total suspended sediment (TSS) in milligrams per liter (mg/l) but are frequently measured indirectly as turbidity. Turbidity is the optical property of water resulting in a loss of light transmission caused by absorption and scattering. Turbidity is typically measured in Nephlometric Turbidity Units (NTUs). Regression equations correlating turbidity and TSS (Sigler et al. 1984; Lloyd et al. 1987; Scannell 1988) have been published, but these correlation's are typically site-specific (Rowe et al. 2003; Duchrow and Everhardt 1971; Kunkle and Comer 1971). While suspended sediments are often the main contributors to turbidity, other nonsediment sources that affect light transmission (that is, natural tannins and algae) can also influence turbidity. Most recent literature studies on suspended sediment effects report TSS.

The scientific data regarding the effects of suspended sediments on fish have been derived from laboratory experiments (for example, artificial channels with variable TSS conditions); observations of natural systems (for example, population comparisons between habitats differentially influenced by TSS); and in situ experiments (for example, caged fish exposed to variable TSS conditions). Because of the variable approaches and methods used in these studies, generalization and extrapolation of their results to specific areas of concern must be made with caution.

Influences on individual fish, fish populations, and fish communities have been associated with stream TSS loads and turbidities. The TSS influences on fish reported in the literature range from beneficial to detrimental. Elevated TSS conditions have been reported to enhance cover conditions and reduce piscivorous fish and bird predation risks. Elevated TSS conditions have also been reported to cause physiological stresses, reduce growth, and adversely affect survival. Significant suspended sediment levels have been observed to alter fish community composition from salmonid to nonsalmonid fish (for example, creek chub), which better tolerate or prefer more turbid water (Gradall and Swenson 1992).

Of key importance in considering the effects of TSS on fish are the frequency and the duration of the exposure, not just the TSS concentration (Newcombe and Jensen 1996). Adverse effects can become more pronounced with increased TSS concentrations and longer exposure durations in aquatic systems where elevated TSS conditions occur infrequently. In systems where elevated TSS conditions occur more frequently, fish can become acclimated to increased TSS levels and adverse affects can be less pronounced or nullified. Newcombe (2003) created a model that takes into account duration of exposure and suspended sediment concentration to project possible effects on fish. The model is:

$$SEV = -4.49+0.92(\log_e x)-2.59(\log_e y)$$

where SEV is severity of ill effect, x is duration of exposure (hours), and y is black disk sighting range (meters), a vertical measure of optical water quality. SEV is ranked 0 to 14 on a 15 step scale, where 0 represents nil effect and 14 represents 100 percent mortality (Newcombe and Jensen 1996). Table 1 describes the SEV scale and corresponding effects.

Table 1. Severity of Ill Effects Scale and Corresponding Effects on Salmonids.

| SEV | Severity of effect |
|---|---|
| | **Ill effect** |
| 0 | No behavioral effects |
| | **Behavioral effects** |
| 1 | Alarm reaction |
| 2 | Abandonment of cover |
| 3 | Avoidance response |
| | **Sublethal effects** |
| 4 | Short-term reduction in feeding rates; short-term reduction in feeding success |
| 5 | Minor physiological stress; increase in rate of coughing; increased respiration rate |
| 6 | Moderate physiological stress |
| 7 | Moderate habitat degradation; impaired homing |
| 8 | Indications of major physiological stress; long-term reduction in feeding rate; long-term reduction in feeding success; poor condition |
| | **Lethal and paralethal effects** |
| 9 | Reduced growth rate; delayed hatching; reduced fish density |
| 10 | 1-20% mortality; increased predation; moderate to severe habitat degradation |
| 11 | >20 to 40%mortality |
| 12 | >40 to 60% mortality |
| 13 | >60 to 80% Mortality |
| 14 | >80 to 100% mortality |

The size and type of suspended particles can also influence the degree of effects on fish (e.g., larger particles [>75 µm] can be more abrasive and have more adverse effects). Interpretations of TSS influence on aquatic organisms can also be confounded if the suspended sediments contain toxins (e.g., metals or pesticides).

In general, elevated TSS conditions can influence fish in the following ways:

- Behavioral effects: avoidance (holding or migration changes), attraction (TSS as cover;

reduced predation risk), reduced feeding success, increased "coughing" or "gill flaring"

- Physical effects: stress, tissue damage, reduced growth, mortality
- Habitat effects: increased sedimentation, fill gravel interstitial spaces, decrease intergravel dissolved oxygen concentrations, decrease residual pool volumes, decrease spawning and emergence success

***Behavioral Effects*** High levels of sediment can reduce light penetration and inhibit primary production, abrade and clog fish gills, prevent feeding by sight feeders, stop migration, and cause fish to avoid the use of turbid reaches. Increased turbidity generally reduces visibility and decreases the ability of sight-feeding fish to obtain food (Berg and Northcoat 1985) and thus reduces feeding habitat. Avoidance is the primary fish behavioral response to locally turbid water. Avoiding areas with elevated TSS or turbidity may lead to fishless reaches in natural systems (DeVore et al. 1980; Birtwell et al. 1984; Scannell 1988). All life stages of salmonids have been observed to prefer clear water when given the option of clear or turbid water (Bisson and Bilby 1982). Salmonids move laterally (Servizi and Martens 1992) and/or downstream to avoid turbid areas (McLeay et al. 1984, 1987). Avoidance of turbid water may begin as turbidities approach 30 NTU (Sigler et al. 1984; Lloyd 1987). Servizi and Martens (1992) noted a threshold for the onset of avoidance at 37 NTU (300 mg/l TSS). However, Berg and Northcoat (1985) provide evidence that juvenile coho salmon did not avoid moderate turbidity increases when background levels were low, but exhibited significant avoidance when turbidity exceeded a threshold that was relatively high (>70 NTU). At turbidities of between 10 and 30 NTUs there is generally altered behavior, avoidance and a reduction in feeding rates over the course of 24 hours (Rowe et al. 2003). At chronic (continuous) exposures as low as 15 NTUs survival rates of some species have been effected. Other species have experienced reduced growth rates at chronic exposures of 22 NTUs (Rowe et al. 2003).

Salmonids experience a loss of habitat by avoiding turbid water. High turbidity levels may cause abandonment of traditional spawning habitat, displacement from current habitat, and underutilization or avoidance of available habitat. Salmonid migration may be interrupted or blocked in the fish's attempt to avoid turbid water (Newcombe and Jensen 1996).

Turbid water can be beneficial in somewhat low concentrations and act as cover to protect fish from predation. Fish that remain in turbid water experience a reduction in predation from piscivorous fish and birds (Gregory and Levings 1988). In systems with intense predation pressure, this provides a beneficial trade-off (e.g., enhanced survival) to the cost of potential physical effects (e.g., reduced growth). A study done regarding the effects of turbidity on predation showed that prey are more active in turbid water and utilize areas in the turbid water column that would otherwise be unsafe in clear water. The results of this study show that turbid water acts as protective cover and allows fish to exist in otherwise more "riskier" habitat (Gregory 1993). Turbidity levels of about 23 NTU have been found to minimize bird and fish predation risks (Gregory 1993).

Other effects of turbidity on the predator-prey relationship are reaction distance and prey recognition (Rowe et al. 2003). Reaction distance is a negative linear function of turbidity, decreasing 2-2.3 percent for each increase in turbidity unit (Barrett 1992). Turbidities greater than 25 NTU or suspended sediment concentrations from 2,000 to 3,000 mg/l can decrease the visual acuity of predatory fish, leading to reduced feeding rates (McLeay et al. 1984, 1987; Redding et al. 1987; Reynolds et al. 1989) and reduced growth (Sigler 1984). Researchers hypothesized that turbidity lowers prey-background contrast so predators cannot see prey as well (Rowe et al. 2003; Miner and Stien 1993). Perceived lack of recognition may be attributed to feeding desperation. Due to lower encounter rates, and consequently lower predator feeding rates, predators may be more desperate for food and pursue anything that resembles prey (Crowl 1989).

Turbid water may also have indirect effects on salmonid feeding rates. Cloudy water diminishes the extent to which light can penetrate and decreases the volume of the photic zone (Rowe et al. 2003; Lloyd 1987). Decreased light penetration reduces local primary production, which can trigger a cascade of impacts from one trophic level to the next, involving phytoplankton, zooplankton, insects, freshwater mollusks, and fishes (Rowe et al. 2003; Newcombe 2003). Furthermore, Rowe et al. (2003) state that in slow moving waters suspended materials can increase absorption of solar energy near the surface causing the heated upper layers to stratify, reducing the dispersion of dissolved oxygen and nutrients to lower depths. A study of the effect of clay on a New Zealand stream it was suggested that restriction in light penetration may be an important mechanism by which fine inorganic solids damage streams (Rowe et al. 2003).

Additional behavioral effects include “gill flaring” and “coughing” responses. These responses increase in frequency at higher suspended sediment concentrations (30 to 60 NTU, Berg and Northcote 1985; and at 230 mg/l TSS, Servizi and Martens 1992). It is not clear whether these responses affect long-term salmonid health. It is important to note that while the effects of chronic exposures to increased turbidity are evident – avoidance, reduced feeding resulting in reduced growth, and potentially reduced survival there is evidence that short exposures to very high turbidities (100,000 ppm) have no lasting effect (Rowe et al. 2003). Tolerance to brief periods of high sediment is a trait essential to survival of fish in environments with spring freshets and flood events (Rowe et al. 2003). Rowe et al. (2003) also state that instream construction activities cause short-term spikes in turbidities while construction is occurring but levels generally return to background levels after cessation of work activities and that brief spikes in turbidity may be benign however, frequent or long episodes may not.

***Physical Effects*** TSS exposure frequency, duration, particle size, particle type, and fish life stage are critical in determining the magnitude of physical effects on fish. Research has found that duration of exposure plays a more dominant role than TSS concentration (Anderson et al. 1996). Long-term exposure to elevated TSS conditions may cause endocrine stress responses (elevated plasma cortisol, glucose, and hematocrits), suggesting an increased physiological burden that could influence growth, fecundity and longevity (Redding et al. 1987; Lloyd 1987; Servizi and Martens 1992). In addition, Servizi and Martens (1992) found that blood sugar levels which are a secondary indicator of stress, increased at all levels tested. Fish growth is also inhibited by reduced feeding rates due to the behavioral effects mentioned previously. Elevated TSS concentrations can decrease salmonid fitness by thickening the gill epithelium and reducing respiratory efficiency (Bell 1973, as cited in Waters 1995).

The mechanisms of TSS-related mortality are not well understood. Acute TSS-related mortality has been demonstrated in laboratory or controlled in situ exposures where the fish were unable to avoid the elevated TSS conditions (i.e., the fish were in artificial streams or caged in natural streams). Elevated TSS concentrations alone have not been shown to cause mortality (McLeay et al. 1987; Redding et al. 1987; Reynolds et al. 1989). It has been shown that juvenile salmon and steelhead trout can adapt when exposed to short term increased TSS concentrations. In a laboratory experiment, juvenile coho salmon and steelhead were subjected to 2000 to 4000 mg/l of suspended sediment for several days, showing an immediate increase in stress, then within 5 days of initial exposure, returning to control stress levels (Reeding and Schreck 1987). Elevated suspended sediment concentrations appear to have a synergistic effect with other causes of mortality. For example, salmonids appear to be more prone to bacterial- and viral-induced mortality when exposed to TSS concentrations of 2,000 to 3,000 mg/l for 7 or 8 days (Redding et al. 1987).

Mortality related to TSS in salmonids depends on several factors, such as life stage, particle size, and water temperature. Significant mortality (>50 percent) usually occurs at suspended sediment concentrations in the range of 500 to 6,000 mg/l (Lloyd 1987; Sigler et al. 1984). Older, larger salmonids are generally more tolerant of high suspended sediment concentrations (200 to 20,000 mg/l) than juvenile salmonids, eggs, and larvae (Sigler et al. 1984). Particle size affects mortality, with decreases in lethal tolerance as particle size increases (Servizi and Martens 1987). Finer particles tend to clog gillrakers, erode gill filaments, and reduces growth (Sigler 1984). Tolerance is also temperature related. Survivorship is optimal at about 7 degrees C (44.6 degrees Fahrenheit (F)), with reduced survivorship at higher (18 degrees C [64.4 degrees F]) and lower (2 degrees C [35.6 degrees F]) temperatures (Servizi and Martens 1991).

***Habitat Effects*** Increased turbidity in streams can lead to an increase in sedimentation. The primary concern of increased sedimentation on fisheries resources is the potential for degrading and/or decreasing spawning habitat (Shirazi et al. 1979). Although, rearing habitat can also be degraded and/or decreased by increased sedimentation such as a decrease in residual pool volumes.

A basic necessity for quality fish habitat is freedom from excessive sediment and turbidity (Everest 1987) and retention of desirable channel morphology and stability (Bisson et al. 1987; Sullivan et al. 1987). Persistent long term sediment sources are the most detrimental to fish and fish habitat with low gradient streams being more vulnerable to irreversible clogging than high gradient streams (Chamberlin 1982). Pool volumes may be decreased, resulting in direct loss of living space (Reiser and Bjornn 1979; Toews and Brownlee 1981).

There is considerable literature concerning sedimentation effects on fish. A general conclusion reached by a review of literature is that the greatest adverse impact of sedimentation is on incubating embryos and larval fish. Sedimentation can cause high losses of incubating eggs and fry in redds, particularly by interfering with oxygen exchange. Fine sediment deposits may also seal rubble and gravel substrates, decreasing spawning area, egg survival, emergence of fry, and hiding cover for fingerlings (Hall and Lantz 1969; Satterlund and Adams 1992). Sand, silt, and fines in the makeup of the substrate can reduce intergravel water flow, decrease intergravel dissolved oxygen concentrations, and result in high Biological Oxygen Demand (BOD) over long periods (Chamberlin 1982). A dissolved oxygen concentration of at least 11.0 mg/l is needed in the water column to maintain an intergravel dissolved oxygen concentration of at least 8.0 mg/l (EPA 1987). This is the minimum level required as to not cause a production impairment of salmonid embryos or larvae (EPA 1987). These minimum dissolved oxygen requirements assume a minimum embeddedness. Sedimentation without cleansing and scouring flows can result in permanent rearing and spawning habitat changes (Platts et al. 1989).

Aquatic invertebrates can also be affected by sedimentation resulting in a change of community composition and prey species for fish. Benthic macroinvertebrates tend to drift as turbidity and TSS levels rise. As the duration of the increased turbidity or TSS concentration lengthens and when particles are smaller, macroinvertebrates become especially prone to drift (Rowe et al. 2003). Sensitive benthic herbivores abundances can be reduced when sediment accumulation occurs in algal mats (Rowe et al. 2003). Salmonids do not benefit from increased drift because turbidity reduces sight distances as well as capture rates (Rowe et al. 2003).

***Summary*** The TSS influences on fish reported in the literature range from beneficial to detrimental. Elevated TSS conditions have been reported to enhance cover conditions, reduce piscivorous fish/bird predation rates, and improve survival. Elevated TSS conditions have also been reported to cause physiological stress, reduce growth, decrease feeding rates, and adversely affect survival. Of key importance in considering the detrimental effects of TSS on fish are the frequency and the duration of the exposure, not just the TSS concentration. Most western United States salmonids have evolved in systems that periodically experience short-term (days to weeks) elevated TSS/turbidity events (winter runoff, spring storms and floods) and are adapted to periodically elevated TSS exposures without adverse effects.

Suspended sediments can have behavioral and physical effects on salmonids. Avoidance is the primary fish behavioral response to locally turbid water. Other behavioral responses include attraction (TSS as cover, and enhanced survival because of reduced fish and bird predation); reduced feeding success; and increased “coughing” or “gill flaring.” TSS exposure frequency, duration, particle size, and particle type are critical in determining the magnitude of physical effects. Long-term exposure to elevated TSS conditions may cause endocrine stress responses, decrease the visual acuity of predatory fish (leading to reduced feeding rates and reduced growth), and decrease salmonid fitness.

The mechanisms of mortality related to TSS are not well understood. Acute TSS-related mortality has been demonstrated in laboratory or controlled in situ exposures where the fish were unable to avoid the elevated TSS conditions. TSS-related mortality in salmonids depends on several factors, such as life stage, particle size, and water temperature. Mortality usually occurs at suspended sediment concentrations in the range of 500 to 6,000 mg/l.

Suspended sediments can also reduce fisheries habitat by increasing sedimentation. Sedimentation can decrease or reduce spawning habitat as well as rearing habitat. Increased sedimentation, especially in low valley streams, can smother incubating embryos and emergent fry. Increased sedimentation can seal gravel and decrease intergravel water flow reducing intergravel dissolved oxygen concentrations and result in high BOD. Increased turbidity, especially caused by fine inorganic particles, increase drift of macroinvertebrates. Aquatic invertebrate communities may change as a result of sedimentation or turbidity, which in turn could affect salmonid prey items. In addition, suspended materials in slow moving waters can increase absorption of solar energy near the surface causing the heated upper layers to stratify reducing the dispersion of dissolved oxygen and nutrients to lower depths.

The scientific data regarding the effects of suspended sediments on fish have been derived from laboratory experiments, observations of natural systems, and in situ experiments. Due to the variable approaches and methods used in these studies, the generalization and extrapolation of their results to specific areas of concern must be made with caution.

Suggested or existing TSS standards typically range from 25-80 mg/l. The higher end of this range seems to have been derived from the impacts of TSS on adult fish, whereas the low-end concentrations seem to have come from the impacts and protection of juveniles, larvae, and eggs. Again, suspended sediment concentrations must be considered in conjunction with frequency and duration of exposure to predict effects on fish. Short-term spikes in turbidities may be benign however, frequent or long episodes may not. Tolerance to brief periods of high sediment is a trait essential to survival of fish in environments with spring freshets and flood events.

***Predictive Models for Assessing Suspended Sediment on Aquatic Resources*** Development of a stress index for predicting suspended sediment effects on fish has been described and reviewed in the literature over the past decade. Newcombe and MacDonald (1991) described a concentration-duration response model as a tool for assessing environmental effects caused by suspended sediment on salmonid fishes. Gregory et al. (1993) commented on the utility and limitations of this particular model for predicting suspended sediment effects. Newcombe and MacDonald (1993) responded to these comments, defending their stress index but acknowledging its limitations as a predictor of general effects and the need for additional data to more precisely predict suspended sediment effects on fishes. This predictive tool was subsequently refined by Newcombe and Jensen (1996) who developed a quantitative approach for assessing the acute and chronic effects of channel suspended sediment on a variety of fish species.

Newcombe (2003) recently described an impact assessment model for clear water fishes exposed to excessively cloudy water, which was described above in the literature review. This model is optimized for sediment pollution events where loss of visual clarity is the primary mode of harmful effect in systems that are relatively clear and free of excessive suspended sediment most of the year. Newcombe (2003) stated that this model is suitable for determining the impact status of a sediment pollution event in relation to the threshold of ill effects, but requires black disk measurements at the time of the event to predict magnitude of effect. He also noted that the model requires further testing and refinement of postulated scores aided by data yet to be generated and published in peer reviewed sources. For these reasons, the quantitative model described by Newcombe and Jensen (1996) and discussed below is used to assess potential project-related TSS effects on fish.

Newcombe and Jensen (1996) summarized the acute and chronic effects of channel suspended sediment on a variety of fish species, and used these data in developing a method for synthesizing and quantitatively assessing the resulting degree of risk and impact to fish. In determining the severity of ill effect to fish, the authors stressed the importance of considering both the duration of exposure and the concentration of suspended sediment (the sediment dose). Newcombe and Jensen (1996) described four categories of severity of ill effects associated with excess suspended sediment, beginning with no effects and progressively worsening through behavioral effects, sublethal effects, and paralethal and lethal effects (see Table 1). Behavioral effects include alarm reaction, abandonment of cover, and avoidance response, while sublethal effects include short-term to long-term reduction in feeding rate and success, increased rate of coughing and respiration, impaired homing, poor condition, and moderate habitat degradation. Paralethal and lethal effects include reduced fish growth rate and density, delayed hatching, increased predation, moderate to severe habitat degradation, and stepwise incremental rates of mortality increasing from 0 to 20 percent to 80 to 100 percent.

Newcombe and Jensen (1996) used results of previous suspended sediment studies on fish to predict the severity of effect for different species' groups and life stages of fish. Because of the wide range of results of these previous studies, the predicted thresholds for different levels of severity of effect vary widely over a range of suspended sediment concentrations and durations of exposure. For example, Newcombe and Jensen's (1996) model for juvenile and adult salmonids predicts that paralethal effects will begin at the following suspended sediment concentrations (mg/l) and durations of exposure: 59,874 mg/l for 1 hour; 8,103 mg/l for 7 hours; 2,981 mg/l for 1 day; 403 mg/l from 6 days to 2 weeks; 148 mg/l for 7 weeks; 55 mg/l for 4 months; and 20 mg/l for 11 months. Lethal effects at a mortality rate of 0 to 20 percent for these same durations of exposure are predicted to occur at the following suspended sediment concentrations: 162,755 mg/l for 1 hour; 22,026 mg/l for 7 hours; 8,103 mg/l for 1 day; 2,981 mg/l for 6 days; 1,097 mg/l for 2 weeks; 403 mg/l for 7 weeks; and 148 mg/l for 4 months and 11 months. Mortality rates are predicted to increase as suspended sediment concentrations increase for the same durations of exposure (Newcombe and Jensen 1996). The predicted threshold for sublethal effects to juvenile and adult salmonids consists of the following suspended sediment/exposure duration relationships: 55 mg/l for 1 hour; 7 mg/l for 7 hours; 3 mg/l for 1 day and 2 days; and 1 mg/l for exposures of 6 days or longer. In discussing different possible applications of their dose-response models, Newcombe and Jensen (1996) observed that the models are only a beginning, that thresholds of sublethal and lethal effects must be known more precisely, and that research is needed on the effects of sediment particle quality, particle toxicity, and water temperature.

Newcombe and Jensen's predictive models were developed using regression equations and empirical data that are more conservative than predicted values in estimating the severity of TSS threshold effects to juvenile and adult salmonids. Newcombe and Jensen (1996) noted that the empirical data can be used to estimate (infer) the minimum concentrations and durations that trigger sublethal and lethal effects in salmonids. They define the category of lethal effects as including paralethal effects (reduced fish growth, delayed hatching, and reduced fish density) as well as lethal effects (incremental mortality rates to 100 percent). Newcombe and Jensen (1996) noted that thresholds estimated from empirical data often are lower than thresholds predicted by regressions fit to meta-analytical data, and stated that they viewed empirical thresholds as "an approximated response of the more 'sensitive' individuals within a species group." For purposes of comparison to predictive values listed above and for later reference in the effects analysis section of this BA, empirical TSS lethal (paralethal/lethal) thresholds presented by Newcombe and Jensen (1996) for the most sensitive juvenile and adult salmonids include the following: 22,026 mg/l for 1 hour; 2,981 mg/l for 3 hours; 1,097 mg/l for 7 hours; 148 mg/l for 1 day and 2 days; 55 mg/l for 6 days; 7 mg/l for 2 weeks; and 3 mg/l for 7 weeks to 11 months. Most of these empirical thresholds for paralethal/lethal effects are considerably lower (TSS concentrations are lower and/or durations are shorter) than listed above for predicted paralethal and lethal thresholds.

**Literature Cited**

Anderson, P.G., B.R. Taylor, and G.C. Balch. 1996. Quantifying the Effects of Sediment Release on Fish and their Habitats. Canadian Manuscript Report of Fisheries and Aquatic Sciences No. 2346, Department of Fisheries and Oceans, Vancouver, B.C. and Winnipeg, Manitoba, 1996.

Barret, J.C., G.D. Grossman, and F. Rosenfeld. 1992. "Turbidity-nduced Changes in Reactive Distance of Rainbow Trout". Transactions of the American Fisheries Society 121: 437-443.

Bell, M.C. 1973. Fisheries Handbook of Engineering Requirements and Biological Criteria. U.S. Army Corps of Engineers, Fisheries Engineering Research Program, Portland, Oregon.

Berg, L. and T.G. Northcote. 1985. "Changes In Territorial, Gill-Flaring, and Feeding Behavior in Juvenile Coho Salmon (*Oncorhynchus kisutch)* Following Short-Term Pulses of Suspended Sediment." Canadian Journal of Fisheries and Aquatic Sciences 42: 1410-1417.

Birtwell, I.K., G.F. Hartman, B. Anderson, D.J. McLeay, and J.G. Malick. 1984. A brief Investigation of Arctic Grayling (*Thymallus arcticus*) and Aquatic Invertebrates in the Minto Creek Drainage, Mayo, Yukon Territory: An Area Subjected to Placer Mining. Canadian Technical Report of Fisheries and Aquatic Sciences 1287.

Bisson P.A., Bilby R.E., Mason D.B., Dolloff C.A., Grette G.B., House R.A., Murphy M.L., Koski K.V., and J.R. Sedell. 1987. "Large Woody Debris in Forested Streams in the Pacific Northwest: Past, Present, and Future. In E.O. Salo and T.W. Cundy, eds. Streamside Management: Forest and Fisheries Interactions. Contribution No. 57 College of Forest Resources, University of Washington, Seattle.

Bisson, P.A., and R.E. Bilby. 1982. "Avoidance of Suspended Sediment by Juvenile Coho Salmon. North American Journal of Fisheries Management 4: 371-374.

CH2MHILL. 1999. Background Information Report: Turbidity/Suspended Particulates Study of the Ross Island Area. Prepared for Ross Island Sand & Gravel Company.

CH2MHILL. 1998. Selection of Total Suspended Sediment (TSS) Target Concentration for the Lower Boise River TMDL. Technical Memorandum. March 13.

Chamberlin, T.W. 1982. Influence of Forest Management on Anadromous Fish Habitat in Western North America. Timber Harvest. USDA Forest Service Anadromous Fish Habitat Program. U.S. Department of Agriculture, Pacific Northwest Forest and Range Experiment Station. General Technical Report PNW-136 April. 27pp.

Crowl, T.A. 1989. "Effects of Crayfish Size, Orientation, and Movement on the Reactive Distance of Largemouth Bass Foraging in Clear and Turbid Water. Hydrobiologia 183: 133-140.

DeVore, P.W., L.T. Brooke, and W.A. Swenson. The Effects of Red Clay Turbidity and Sedimentation on Aquatic Life in the Nemadji River System. Impacts of Nonpoint Pollution Control on Western Lake Superior. S.C. Andrews, R.G. Christensen, and C.D. Wilson. Washington D.C., U.S. Environmental Protection Agency, EPA Report 905/9-79-002-B, 1980.

Duchrow, R.M. and W.H. Everhardt. 1971. Turbidity Measurement. Transactions of the American Fisheries Society 100: 682-690.

EPA. 1987. Quality Criteria for Water 1986. EPA 44015-86-001. Updated May 1, 1987.

Everest, F. H. 1987. "Salmonids of Western Forested Watersheds." Pages 3-8. In E. O. Salo and T. W. Cundy, eds. Streamside management: Forest and Fisheries Interactions. Contribution N0. 57 College of Forest Resources, University of Washington, Seattle.

Gradall, K.S., and W.A. Swenson. 1982. Responses of Brook Trout and Creek Chubs to Turbidity. Transactions of the American Fisheries Society 111: 392-395.

Gregory, R.S. 1993. Effect of Turbidity on the Predator Avoidance Behavior of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 50: 241-246.

Gregory, R.S., and C.D. Levings. 1998. Turbidity Reduces Predation on Migrating Juvenile Pacific Salmon. Transaction s of the American Fisheries Society 127: 275-285.

Hall, J.D. and R.L. Lantz. 1969. Effects of Logging on the Habitat of Coho Salmon and Cutthroat Trout in Coastal Streams. In H.R. MacMillan Lectures In Fisheries. A symposium held at the University of British Columbia February 22-24, 1968. University of British Columbia, Vancouver, Canada. pp. 355-375.

Kunkle, S.H., and G.H. Comer. 1971. Estimating Suspended Sediment Concentrations in Streams by Turbidity Measurements. Journal of Soil and Water Conservation 26: 18-20.

Lloyd, D.S. 1987. Turbidity as a Water Quality standard for Salmonid Habitats in Alaska. North American Journal of Fisheries Management. 7: 34-45.

McLeay, D.J., G.L. Ennis, I.K. Birtwell, and G.F. Hartman. 1984. Effects On Arctic Grayling (*Thymallus arcticus*) of Prolonged Exposure to Yukon Placer Mining Sediment: A Laboratory Study. Canadian Technical Report of Fisheries and Aquatic Sciences 1241.

McLeay, D.J., I.K. Birtwell, G.F. Hartman, and G.L. Ennis. 1987. Responses of Arctic Grayling (*Thymallus arcticus*) to Acute and Prolonged Exposure to Yukon Placer Mining Sediment. Canadian Journal of Fisheries and Aquatic Sciences 44: 658-673.

Miner, J.G., and R.A. Stein. 1993. Interactive Influence of Turbidity and Light on Larval Bluegill (*Lepomis macrochirus*) Foraging. Canadian Journal of Fisheries and Aquatic Science 50: 781-788.

Newcombe, C.P. 2003. Impact Assessment for Clear Water Fishes Exposed to Excessively Cloudy Water. Journal of the American Water Resources Association 39(3):529-544.

Newcombe, C.P., and J.O.T. Jensen. 1996. Channel Suspended Sediment and Fisheries: A Synthesis for Quantitative Assessment of Risk and Impact. North American Fisheries Management 16: 693-727.

Platts, W. S., C. Armour, G. D. Booth, M. Bryant, L. Judith, P. Cuplin, S. Jensen, G. W. Lienkaemper, G. W. Minshall, S. B. Monsen, R. L. Nelson, J. R. Sedell, and J. S. Tuhy. 1987. Methods for Evaluating Riparian Habitats with Applications to Management. United States Department of Agriculture, Forest Service. General Technical Report INT-221. Intermountain Research Station, Ogden, Utah. 177 pp.

Quinn, P. 2001. Preliminary Assessment of Potential Effects on Salmonids Associated with Turbidity Caused by Dredging in the Columbia and Willamette Rivers. Technical Memorandum, Ellis Ecological Services Inc., 30 August 2001.

Redding, J.M., C.B. Schreck, and F.H. Everest. 1987. Physiological Effects on Coho Salmon and Steelhead of Exposure to Suspended Solids. Transactions of the American Fisheries Society 116:

Department of Agriculture, Forest Service. General Technical Report INT-221. Intermountain Research Station, Ogden, Utah. 177 pp.

Quinn, P. 2001. Preliminary Assessment of Potential Effects on Salmonids Associated with Turbidity Caused by Dredging in the Columbia and Willamette Rivers. Technical Memorandum, Ellis Ecological Services Inc., 30 August 2001.

Redding, J.M., C.B. Schreck, and F.H. Everest. 1987. Physiological Effects on Coho Salmon and Steelhead of Exposure to Suspended Solids. Transactions of the American Fisheries Society 116: 737-744.

Reynolds, J.B., R.C. Simmons, and A.R. Burkholder. 1989. Effects of Placer Mining Discharge on Health and Food of Arctic Grayling. Water Resources Bulletin 25: 625-635.

Reiser, D.W. and T.C. Bjornn. 1979. Influence of Forest and Rangeland Management on Anadromous Fish Habitat in Western United States and Canada. Part 1: Habitat Requirements of Anadromous Salmonids. USDA Forest Service General Technical Report PNW-96. Pacific Northwest Forest and Range Experiment Station, Portland, OR. 54 pp.

Rowe, M., D. Essig, and B. Jessup. 2003. Guide to Selection of Sediment Targets for Use in Idaho TMDLs. Idaho Department of Environmental Quality. Boise, Idaho. 89 pp.

Satterlund, D. R., Adams, P. W. 1992. Wildland Watershed Management. Second Edition. John Wiley & Sons, New York.

Scannell, P.O. 1988. Effects of Elevated Sediment Levels from Placer Mining on Survival and Behavior of Immature Arctic Grayling. Alaska Cooperative Fisheries Unit, University of Alaska, Unit Contribution 27.

Servizi, J.A., and D.W. Martens. 1985. Some Effects of Suspended Fraser River Sediments on Sockeye Salmon (*Oncorhynchus nerka*). Conference International Sockeye Salmon Symposium-Sockeye 1985, Nanaimo, B.C. (Canada), November 19.

Servizi, J.A., and D.W. Martens. 1991. Effects of Temperature, Season, and Fish Size on Acute Lethality of Suspended Sediments to Coho Salmon. Canadian Journal of Fisheries and Aquatic Sciences 49: 1389-1395.

Servize, J.A., and D.W. Martens. 1992. Sublethal Responses of Coho Salmon (*Oncorhynchus kisutch*) to Suspended Sediments. Canadian Journal of Fisheries and Aquatic Sciences 49: 1389-1395.

Shirazi, M.A., Seim, W.K., and Lewis, D.H. 1979. Monitoring Spawning Gravel in Managed Forested Watersheds, a Proposed Procedure. EPA-600/3-79-014. Feb. 1979. USEPA, Corvallis Environmental Research Laboratory, Corvallis, Oregon. 13 pp.

Sigler, J.W., T.C. Bjornn, and F.H. Everest. 1984. Effects of Chronic Turbidity on Density and Growth of Steelheads and Coho Salmon. Transactions of the American Fisheries Society 113: 142-150.

Sullivan, K., Lisle, T. E., Dolloff, C. A., Grant, G. E., and L. M. Reid. 1987. Stream Channels: The Link between Forests and Fishes." In E. O. Salo and T. W. Cundy, eds. Streamside Management: Forest and Fisheries Interactions. Contribution No. 57 College of Forest Resources, University of Washington, Seattle.

Toews, D.A. and M.J. Brownlee. 1981. A Handbook for Fish Habitat Protection on Forest Lands in British Colombia. D.F.O. Vancouver, B.C. 180pp.

Sullivan, K., Lisle, T. E., Dolloff, C. A., Grant, G. E., and L. M. Reid. 1987. "Stream Channels: The Link between Forests and Fishes." In E. O. Salo and T. W. Cundy, eds. *Streamside Management: Forest and Fisheries Interactions*. Contribution No. 57 College of Forest Resources, University of Washington, Seattle.

Toews, D.A. and M.J. Brownlee. 1981. A Handbook for Fish Habitat Protection on Forest Lands in British Colombia. D.F.O. Vancouver, B.C. 180pp.