Canadian Water Quality Guidelines for the Protection of Aquatic Life

TOTAL PARTICULATE MATTER

For the purposes of this fact sheet, guidelines for total particulate matter in freshwater, estuarine, and marine environments will be derived for suspended sediments, turbidity, deposited bedload sediments, and streambed substrate.

Background Information

Turbidity

Turbidity is a measure of the lack of clarity or transparency of water caused by biotic and abiotic suspended or dissolved substances. The higher the concentration of these substances in water, the more turbid the water becomes. Technically, when passing light through a water sample, turbidity is an expression of the optical properties of substances that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample (Wetzel 1975). The most reliable method for determining turbidity is nephelometry (light scattering by suspended particles), which is measured by means of a turbidity meter giving nephelometric turbidity units (NTUs). Environmental samples vary within the normal range of 1 to 1000 NTUs (Chapman 1992).

Suspended Sediments

The type and concentration of suspended matter controls the turbidity and transparency of the water. Suspended matter consists of silt, clay, fine particles of organic and inorganic matter, soluble organic compounds, plankton, and other microscopic organisms. Suspended matter is

Table 1. Water quality guidelines for total particulate matter for the protection of aquatic life (Caux et al. 1997).

Aquatic life — Freshwater, estuarine, and marine	Guideline value
Suspended sediments	
clear flow	Maximum increase of 25 $mg \cdot L^{-1}$ from background levels for any short-term exposure (e.g., 24-h period). Maximum average increase of 5 $mg \cdot L^{-1}$ from background levels for longer term exposures (e.g., inputs lasting between 24 h and 30 d).
high flow	Maximum increase of 25 $mg \cdot L^{-1}$ from background levels at any time when background levels are between 25 and 250 $mg \cdot L^{-1}$. Should not increase more than 10% of background levels when background is >250 $mg \cdot L^{-1}$.
Turbidity	
clear flow	Maximum increase of 8 NTUs from background levels for a short-term exposure (e.g., 24-h period). Maximum average increase of 2 NTUs from background levels for a longer term exposure (e.g., 30-d period).
high flow or turbid waters	Maximum increase of 8 NTUs from background levels at any one time when background levels are between 8 and 80 NTUs. Should not increase more than 10% of background levels when background is >80 NTUs.
Deposited bedload sediment	Insufficient information to derive guideline.
*Streambed substrate**	
fine sediments	The quantity in streambed substrates should not exceed 10% <2 mm, 19% <3 mm, and 25% <6.35 mm.
geometric mean diameter	Geometric mean diameter should not exceed 12 mm.
Fredle number	Fredle number should not exceed 5 mm.
intergravel dissolved oxygen	Minimum of 6.5 $mg \cdot L^{-1}$.

*Guideline values apply to actual and potential spawning sites.

Table 2. A standard terminology for sediment particle size (Newcombe 1996).

Sediment particle size		Size-class of sediment particle		Velocity of settling particle ($mm \cdot s^{-1}$)
(mm)	(µm)			
2000–4000		Boulders	very large	
1000–2000			large	
500–1000			medium	
250–500			small	
130–250		Cobbles	large	
64–130			small	
32–64		Gravel	very coarse	
16–32			coarse	
8–16			medium	
4–8			fine	
2–4			very fine	
1–2	1000–2000	Sand	very coarse	100–200
0.5–1	500–1000		coarse	53–100
	250–500		medium	26–53
	125–250		fine	11–26
	62–125		very fine	3–11
	31–62	Silt	coarse	1–3
	16–31		medium	0.18–0.66
	8–16		fine	0.044–0.18
	4–8		very fine	0.011–0.044
	2–4	Clay	coarse	< 0.011
	1–2		medium	
	0.5–1		fine	
	0.24–0.5		very fine	

measured in the laboratory by both filterable and nonfilterable residues of a water sample. Undissolved particles make up the nonfilterable residues, these varying in size from approximately 10 nm to 0.1 mm in diameter, although it is usually accepted that the suspended solids are the fraction that will not pass through a 0.45-µm pore diameter glass fibre filter (Caux et al. 1997). For the purpose of deriving water quality guidelines, the nonfilterable residues, containing both biotic and abiotic components, will be referred to as total suspended sediments. A sediment particle grade scale and the settling velocities of these particles in water (Cooke et al. 1993) will be used as standard sediment terminology for guideline development (Table 2).

Relationships between turbidity and suspended sediments are site-specific, as turbidity is affected by factors such as the concentration, size, shape, and refractive index of suspended sediments and the water colour (Allen 1979; Singleton 1985; Lloyd et al. 1987; Gippel 1995). Relationships vary from stream to stream and between seasons in the same stream. At sites where the relationship between suspended sediment concentration and turbidity is known, turbidity can be used as a surrogate to predict suspended sediment concentrations. An example of a regression developed for streams in interior Alaska (Lloyd et al. 1987) is

$$\log_{10}T = 0.045 + 0.9679 \log_{10}SSC$$

where T is the turbidity (NTU) and SSC the suspended sediment concentration ($mg \cdot L^{-1}$). As turbidity measurements change along a downstream gradient from a sediment source, turbidity and suspended sediment relationships only apply to specified stream reaches (Lloyd 1987).

Bedload Sediments

Bedload sediment refers to that portion of the total sediment load that is carried by the streambed. Particles in this phase move by sliding, rolling, or saltating on the streambed. Bedload generally consists of coarse sand or larger-sized particles (Leopold and Wolman 1964). Fine to coarse sand is also frequently transported as bedload, but can also be carried as part of the suspended load at higher water velocities.

The transport of bedload sediment requires greater hydraulic energy than does the transport of suspended sediment. Even more hydraulic energy is required to disrupt the armour layer of gravel streams sufficiently to mobilize the sediments stored in streambed substrates (Sidle 1988). For this reason, the transport of significant quantities of bedload sediment may be limited to only a few days a year in many streams, typically during the peak of freshet when streamflows are the highest (Parker and Andrews 1985). It is during these periods that long-term changes in channel morphology and the composition of streambed substrates can occur.

Deposited Sediments

Deposited sediments are those that settle out of the flow and become associated with the streambed substrate. The factors influencing the deposition of sediments include the characteristics of the material (particle sizes and volumes), hydraulic forces (stream size, discharge, and velocity), and the occurrence of roughness elements (Parker and Andrews 1985). Roughness elements, such as large organic debris (i.e., large trees and root systems), boulders, and bedrock outcroppings, are important because they enhance streambed stability, alter flow patterns and velocities, and create sediment storage sites in stream channels (Swanson and Lienkaemper 1978).

Local hydraulic conditions dictate which process, sediment transport or sediment deposition, predominates in any stream reach and period of time (Norton 1986). Because of differences in the hydraulic conditions (i.e., resulting from differences in gradient, instream debris, etc.), sedimentation and resuspension rates vary substantially between reaches in any stream system (Platts et al. 1979).

Sediment Sources

Natural erosion of geological formations is the most common source of suspended sediment to a waterbody. The rate of erosion depends on climate, geology, exposure, slope, soil type, and vegetation cover. Deposited sediments may remain stored in the channel bed and banks until critical velocities are exceeded, mobilizing the bedload. Movement of streambed materials in turn generates additional smaller particles through abrasion. Sediments in streams and rivers can originate from glacial lacustrine deposits. Some sediment is eroded from stream or river banks or is scoured off the bottom to be deposited further downstream or remain suspended. Natural levels of suspended sediments vary widely from water body to water body, and can have large daily and seasonal variations (Singleton 1985).

Sediment transport models relating sediment load and streamflows exhibit high variability especially in small streams. Empirical relationships are often the most practical sediment transport models. In British Columbia, correlations between stream discharges and sediment concentrations varied tremendously; higher correlations, however, were found at high discharges (>1.0 $m^3 \cdot s^{-1}$) (e.g., snowmelt). At low flows, spawning salmon were found to contribute to the variability of suspended sediment concentrations by winnowing fine sediment from the gravels during construction of redds (Cheong et al. 1995). Other factors affecting the variability in concentrations are pools, gravel bars, and debris jams acting as sediment storage sites during low flows and as supply sources during high flows. River ice breakup can dramatically increase downstream water levels and velocities. Ice scour of bed and banks can significantly augment the quantities of suspended sediments that induce changes in stream morphology and fish habitat (Milburn and Prowse 1996; Newcombe and MacDonald 1991).

In estuarine waters a substantial proportion of suspended sediments come from the resuspension of fine, unconsolidated sediments and detritus by wave action and currents (Appleby and Scarratt 1989). Concentrations of estuarine suspended sediments can far exceed those levels coming from freshwater sources. Apart from algal blooms, turbidity maxima in estuaries correlate with hydrodynamic conditions and flocculation and deflocculation of riverborne sediment. As sediments enter denser saline water below the saltwater/freshwater interface (halocline), there is a net upstream movement initiated by the saltwater component, which resuspends particles in the upper freshwater component. This vertical mixing repeats itself and localized high concentrations (1.2 $g \cdot L^{-1}$) of suspended sediment may occur (Appleby and Scarratt 1989).

Anthropogenic activities such as forest harvesting, road building, construction, dredging, and gravel pit operations can cause marked changes in the physical, chemical, and biological characteristics of the watercourses located nearby and those located downstream. Other major sources of anthropogenic sediment loading in streams are contaminant and navigational dredging, construction (urbanization), agriculture, industrial wastewater discharge, and mining activities.

Water Quality Guideline Derivation

In order to protect aquatic life in fresh, estuarine, and coastal marine waters from excessive suspended sediments originating from anthropogenic sources, the Canadian water quality guidelines for total particulate matter are established according to the amount of suspended sediment and the turbidity of the aquatic system. Guidelines for streambed substrate and deposited bedload sediment specific to salmonid spawning and mariculture areas have also been developed. As the biotic, physical and chemical conditions describing aquatic ecosystems are diverse, the recommended guidelines will need to be compared to natural background levels (Caux et al. 1997).

Turbidity and Suspended Sediments

In general, the deposition of fine sediment in stream ecosystems is detrimental to aquatic organisms because of reductions in streambed substrate composition, permeability, and stability (Young et al. 1991; Cobb et al. 1996). These alterations in the physical environment can decrease egg-to-fry survival rates in fish and can affect stream and benthic macroinvertebrate production and periphyton communities (Erman and Erman 1984; Noel et al. 1986; Valiela et al. 1987; Culp 1996). Even greater habitat degradation can occur under reduced sediment transport regimes if flushing flows are decreased or eliminated (Burt and Mundie 1996; Nelson et al. 1996).

There are a number of direct and indirect ways by which excessive suspended sediment levels in water affect fish. Effects on trophic interactions at the primary and secondary level of productivity will indirectly affect fish community structure. Direct effects include clogging and abrasion of gills, behavioural effects (e.g., movement and migration), resistance to disease, blanketing of spawning gravels and other habitat changes, the formation of physical constraints disabling proper egg and fry development, and reduced feeding (Singleton 1985).

Newcombe (1994a) described the more subtle and difficult to measure behavioural effects as easily reversible and not long lasting. A study by Berg and Northcote (1985) demonstrated that the territorial, gill-flaring, and feeding behaviour of juvenile coho salmon was disrupted by exposure to suspended sediment pulses. High turbidities (30 and 60 NTUs) broke down the dominance hierarchies with the result of territories not being defended. Social organization was re-established with the return of normal turbidities (0–20 NTUs) (Berg and Northcote 1985). It was shown by an analysis of feeding and reproductive guilds that fish species with similar ecological requirements had a common response (e.g., decreased diversity) to habitat degradation by siltation (Berkman and Rabeni 1987). In another investigation, it was shown that the relationship between fine sediment and chinook salmon abundance in streams during the winter is an indication of the importance of winter habitat to their production. This suggests a cause for the fall–winter exodus in streams with high sediment loads (Hillman and Griffith 1987). The authors suggest that as the interstitial spaces between cobble are filled, juvenile fish may leave redds or take cover in less protected areas.

Growth of fish can be impaired with an excess of suspended sediment via effects through the food chain. In a laboratory experiment where turbidity was simulated with clays, kaolinite, and bentonine, feeding of 30- to 65-mm long steelheads *(Oncorhynchus mykiss)* and coho salmon *(O. kisutch)* was affected, giving rise to growth impairment and emigration of fish from experimental channels. Turbidity as low as 25 NTUs caused a reduction in fish growth. The quality of the light may be altered as large amounts of suspended particles intercept the wavelengths used by fish, thereby reducing their ability to see and secure food (Sigler et al. 1984). Similar effects were shown on under-yearling Arctic graylings (*Thymallus arcticus*) exposed to suspended placer mining sediments (McLeay et al. 1984). Concentrations of suspended sediments that significantly reduced fish growth ranged from 100 to 1000 $mg \cdot L^{-1}$. The time required for naïve fish (previously unexposed to sediment) to detect and consume surface drift increases with increased suspended sediment concentrations. Other symptoms of stress were a palish colouration of fish, which may act as a defense mechanism, and a decrease in tolerance to a reference toxicant as compared to controls (McLeay et al. 1984).

Physiological effects other than growth reduction include alteration in blood chemistry (Servizi and Martens 1987) and histological changes (e.g., gill damage and phagocytosis of sediment) (Goldes et al. 1988). Slightly elevated hematocrit counts (2% above controls), an indication of anoxia, were observed in sockeye salmon exposed for 9 d to 1500 $mg \cdot L^{-1}$ of fines (Servizi and Martens 1987). As well, plasma glucose, an indication of secondary stress, was elevated by 150 and 39% resulting from suspended concentration exposures of 1500 and 500 mg·L^{-1}, respectively. Other effects of suspended sediments (kaolin clay and volcanic ash) on the blood chemistry of salmonid species may be temporarily elevated levels of plasma cortisol (max. 1367% increase at 24 h) and reduced resistance to pathogens (Redding et al. 1985).

Histological effects of suspended sediments on the gill apparatus of fish are well documented. Histopathological effects of high concentrations of suspended sediments (>1400 mg·L^{-1}; <74–740 µm) on fish gills include gill hypertrophy, necrosis, and gill lesions due to protozoan infection (Servizi and Martens 1987; Goldes et al. 1988). The authors suggest that Early Stuart adult sockeye could encounter stress-causing concentrations of suspended sediments during their spawning migration. The 96-h LC_{50}s to sockeye salmon ranged from 1.7 to 17.6 g·L^{-1} (Servizi and Martens 1987).

Generally, effects are observed when the particle sizes of sediments are approximately 75 µm, which matches the space between gill lamellae. Not as well documented, however, are the effects of angularity and hardness of sediment particles to fish gills. Underyearling coho salmon have a reduced tolerance to an increase in angularity and particle size (Servizi and Martens 1987, 1991; Appleby and Scarratt 1989). Natural sediments, however, may be coated with organic material, which would reduce the angularity of the particle (Appleby and Scarratt 1989).

Tolerance to suspended sediments may be related to temperature. While low temperature favours oxygen saturation and a fish's tolerance to suspended sediments, it may also lower the capacity of fish to clear the gills of particles due to inadequate cough reflexes and ventilation rates (McLeay et al. 1987; Servizi and Martens 1991). Sediments accumulate in the buccal cavities of fish when these become too fatigued to continue clearing particles by coughing (Servizi and Gordon 1990). In their experiment, the 96-h LC_{50}s for sockeye and chinook salmon were 17.6 and 31 g·L^{-1}, respectively.

Fish eggs are very susceptible to the settling of suspended particles. Fine particles can disrupt normal gas exchanges and metabolic wastes between the egg and water with coverings as thin as a few millimetres (Anderson et al. 1996). The 48-d LC_{40} for rainbow trout was 7 mg·L^{-1} (Slaney et al. 1977). Juvenile and adult fish are more resilient to high concentrations of suspended sediment than the eggs or larvae of fish (Newcombe 1994a), as these early life stages cannot use avoidance behaviour (Anderson et al. 1996). Marine fish LC_{50}s are similar to those for freshwater fish (Cyrus and Blaber 1987). Lethal effects of turbidity on fish require concentrations far above the highest naturally occurring turbidity concentrations. Physical effects of suspended solids on marine and estuarine fish and shellfish have been summarized by Appleby and Scarratt (1989).

In summary, fish (all life stages) are sensitive to low levels of suspended sediment. The LC_{50}s for adults and juvenile fish range from 0.27 to 35 g·L^{-1}. In estuarine waters, LC_{50}s range from 0.19 to 330 g·L^{-1} (Newcombe and Jensen 1996).

Invertebrate populations depend on the condition and abundance of primary producers. Their numbers and composition will be affected if suspended sediment concentrations affect periphyton communities. More direct effects of suspended sediments on invertebrates include (1) physical habitat changes due to scouring of streambeds and dislodgement of invertebrates; (2) smothering of benthic communities; (3) clogging of interstices between gravel, cobbles, and boulders affecting invertebrate microhabitat; and (4) abrasion of respiratory surfaces and interference of food intake for filter-feeding invertebrates (Singleton 1985).

The effect of streambank clear-cutting on benthic macroinvertebrate communities was a decrease in the abundance of benthos due to increased inputs of fine sediments (amounts not given) originating from clear-cut areas without adequate buffer zones around streams. It was shown that sediment saltation is a significant mechanism by which macroinvertebrates are scoured from the streambed substrate thereby reducing macroinvertebrate densities (Culp et al. 1985; Culp 1996). Another study emphasized that reduced sediment size and stream velocity are major factors influencing the macroinvertebrate community structure in streams. Upper reaches of logged streams have an abundance of shredder and predator taxa whereas downstream sites are lacking these (Hachmöller et al. 1991). Addition of fine sediments to a coastal stream from a drinking-water filtration plant had similar effects (Erman and Ligon 1988). It was also suggested that sedimentation ponds were insufficient to protect macroinvertebrate diversity in streams when impoverishment of benthic communities was due to deposition of particles on benthic habitats and particle movement at the streambed surface (Vuori and Joensuu 1996).

Embeddedness, or the degree to which the dominant particles are surrounded by fine inorganic sediments, and the presence of coarse woody debris were found to have the strongest correlations with macroinvertebrate assemblage richness and composition (Richards and Host 1994). Other subtle effects of suspended sediment (silt) deposition on streambeds include the elimination of the predation of stoneflies on benthic invertebrates, demonstrating that turbidity can override the effects of predation by predators in stream communities (Peckarsky 1985).

The macroinvertebrate community structure in streams is correlated with the average size of particles in the stream's substrate (Erman and Erman 1984). When median particle size was held constant, heterogeneity of substrate composition was not an important component structuring macroinvertebrate communities. Thus, an increase in the deposition of fines could create an imbalance of the median particle size and affect species abundance and richness.

Studies reporting the effects of suspended sediments on aquatic invertebrates are more abundant than those for aquatic plants. The information gathered suggests that invertebrates are as sensitive to high levels of suspended sediments as salmonid fishes (Newcombe and MacDonald 1991). The LC_{50}s range from 0.72 to 5.11 $mg{\cdot}L^{-1}$ (Newcombe and Jensen 1996).

The effects of suspended sediments on algae are associated with reduced primary productivity (Singleton 1985). Increased or excessive suspended sediments can reduce productivity by (1) inhibiting photosynthesis, due to decreased light penetration; (2) physically smothering benthic communities; (3) removing periphyton by scouring; and (4) affecting community composition (Singleton 1985). Notwithstanding these general patterns, temporary resuspension (e.g., dredging and logging) of sediments and nutrients in the water column can temporarily augment algal productivity (Bilby and Bisson 1992).

Natural or anthropogenic events leading to disturbances in aquatic systems and elevated suspended sediments affect whole ecosystems (Lloyd et al. 1987). Effects on algae are the first consequence of perturbation. For example, logging practices may produce shifts in the sources of food supply originating within the stream (autochthonous) and from the riparian landscape (allochthonous) energy inputs. These shifts have the effect of changing the amount and quality of available food resources in streams (Culp 1996). With increased suspended sediments and nutrients and less shading of streams resulting in higher temperatures and more light available for photosynthesis, algal biomass may flourish, temporarily giving rise to increased invertebrate (Behmer and Hawkins 1996) and fish abundance (Bilby and Bisson 1992). This may not be the case, however, as other factors essential to primary productivity (e.g., phosphorus) may be limiting (Shortreed and Stockner 1996). In a study where logging practices brought about changes in stream bottom particle size, it was found that green algae and flowering plants were more abundant in clear-cut streams than in reference streams where diatoms dominated. In logged areas, streams had relatively higher amounts of sand and gravel than reference streams, which had more of a pebble, cobble, and boulder bottom composition (Noel et al. 1986).

It has been shown in laboratory experiments that mineral particles (e.g., silica, kaolin, and bentonite) affect many physical and biotic processes such as algal–clay flocculation and sedimentation (Threlkeld and Soballe 1988). These in turn would have an effect on trophic interactions.

Guidelines for Suspended Sediments

For suspended sediments and turbidity, in most lotic systems, background levels are to be monitored in clear flow periods. Clear flow must not be confused with low flow periods, which give a much smaller window of opportunity for sampling background levels. Clear flow periods are determined on a site-specific basis. Even though most sediment load in streams is transported during spring freshets and storm events, these high flow periods have been excluded from the determination of background levels due to the extreme variability found in relationships between suspended sediment concentrations and discharge flows (MacDonald et al. 1991). The clear and turbid flow periods for individual stream systems should be defined using data on the background concentrations of suspended sediment at the site-specific level.

During clear flow periods, anthropogenic activities should not increase suspended sediment concentrations (or nonfilterable residue levels) by more than 25 $mg{\cdot}L^{-1}$ over background levels during any short-term exposure period (e.g., 24-h). For longer term exposure (e.g., 30 d or more), average suspended sediment concentrations should not be increased by more than 5 $mg{\cdot}L^{-1}$ over background levels.

During high flow periods, anthropogenic activities should not increase suspended sediment concentrations by more than 25 mg·L^{-1} at any time when background levels are between 25 and 250 mg·L^{-1}. When background levels exceed 250 mg·L^{-1}, suspended sediment concentrations should not be increased by more than 10% of the measured background level at any one time (Singleton 1985; CCREM 1987).

This two-pronged approach to guideline setting for suspended sediments recognizes that exposure duration plays a key role in the toxicity response. The guideline is based on the severity-of-ill-effects (SEV) concentration-duration-response curve approach (Newcombe 1994b; Newcombe and Jensen 1996). The approach is based on the change in suspended sediment concentration causing an increase of one in a SEV score for the most sensitive taxonomic group of aquatic organisms. The steepest slope representing a change in response of one SEV score was for adult salmonids (24–48 h; slope 2.08), which represents a 25 mg·L^{-1} increase in suspended sediments (Caux et al. 1997).

In clear stream systems, small induced exceedances in suspended sediment concentration above a 25 mg·L^{-1} change from background levels for short-term exposure (e.g., 24 h) are likely to cause behavioural and low sublethal effects on fish, all of which are reversible. Conditions in these systems should be rectified to prevent possible further damage of the designated water use. Small amounts of excess suspended sediment are known to cause egg mortality (40%) to rainbow trout at long durations (7 mg·L^{-1} at 48 d; 0.5–75 µm) (Slaney et al. 1977). Based on extrapolation from the SEV analysis, a long-term exposure guideline has been set at an average suspended sediment change in 5 mg·L^{-1} (e.g., for exposures lasting 30 d). According to the SEV scale this concentration-duration exposure translates to a SEV score of five (i.e., minor physiological stress, increased rates of coughing and respiration).

The guidelines have been based on a large database (Newcombe 1994a; Newcombe and Jensen 1996) that reports effects to biota, many of which are found in North America.

Guidelines for Turbidity

Although turbidity is a function of particle size per unit mass of suspended sediment, guidelines can be developed for the general case. Induced turbidity should not exceed a change of 8 NTUs for a short-term exposure (e.g., 24 h) above the background concentration in all waters during clear flows. A long-term guideline (e.g., 30 d) has been set as well, stating that mean turbidity should not exceed a change of 2 NTUs during clear flows.

During high flows and in turbid waters, the short-term guideline is adopted i.e., turbidity should not exceed 8 NTUs at any time when background turbidity is between 8 and 80 NTUs, nor should it increase more than 10% of background when background is >80 NTUs at any time (Singleton 1985; CCREM 1987).

These guidelines are extrapolated from the suspended sediment guidelines of a 25 and 5 mg·L^{-1} change from background for short-term and long-term exposures, respectively, according to the suspended sediment and the general turbidity correlation of 3 to 1. A turbidity of 8.33 NTUs has been rounded to 8 NTUs and 1.67 to 2 NTUs for practical reasons.

The turbidity guideline of an 8 NTU change from background turbidity for a short-term exposure is a recommended check in every routine field sampling program as it can be measured accurately and quickly with field nephelometers. If problem areas are found, joint measurements of turbidity and residue are recommended. The longer-term turbidity guideline of 2 NTUs, as well as the long-term guideline for nonfilterable residues, will protect against low anthropogenic suspended sediment inputs that persist over the long term. The guidelines will protect against harm to all aquatic life in freshwaters, marine, and estuarine waters.

Guidelines for Deposited Bedload Sediment

Insufficient information is currently available to develop numerical water quality guidelines for deposited bedload sediments. The effects of bedload sediment on fish and aquatic life are poorly understood, primarily due to the difficulty associated with the measurement of bedload transport in stream systems.

Streambed Substrate and Deposited Sediments

Incubation of Salmon and Trout Eggs

The results of numerous studies demonstrate that elevated levels of fine sediment in streambed substrates have the potential to compromise the survival of salmonid eggs and alevins. The survival of salmonid eggs and alevins depends on the delivery of adequate amounts of oxygen and on the removal of toxic metabolic waste products. To meet these basic requirements, streambed substrates must permit the free flow of oxygenated water to incubating embryos (Vaux 1968). Deposition of fine sediment onto and into streambed substrates tends to reduce their permeabilities and, in so doing, decreases the interchange of water between the fluvial and intragravel environments (Wickett 1958; McNeil and Ahnell 1964; Phillips 1971). Low streambed permeability can result in depressed intragravel dissolved oxygen levels, which in turn compromises the survival of incubating fish embryos (Shumway and Warren 1964; McNeil 1966). In addition, surviving sac fry tend to be smaller, weaker, and have more developmental abnormalities than alevins incubated at high levels of dissolved oxygen (Garside 1959; Silver et al. 1963). Deposited sediments can also block the emergence of fry from the gravel (Koski 1972).

While the deposition of fine sediments is generally considered to be detrimental, there are a number of mitigating factors that can reduce the severity of effects on fish. These mitigating factors can include the shape of the redds (which promotes the flow of water to the eggs), sediment removal during redd building, delivery of oxygenated water via groundwater seepage, and biological compensation for fry mortality (e.g., increase in fry-to-smolt survival due to lower fry densities) (McNeil and Ahnell 1964; Stuehrenberg 1975; Klamt 1976; Scrivener and Brownlee 1982; Sowden and Power 1985; Everest et al. 1986).

The effects of deposited sediment on the survival of eggs and alevin have been studied in a number of salmonid species that utilize freshwater habitats. Rather than determining deposition rates of fine sediments, these studies usually rely on measures of the overall textural characteristics of streambed substrates to evaluate effects on fish. The variables that are most commonly used to assess the composition of streambed substrates include percent fines (PF), geometric mean diameter (Dg), and Fredle number (FN). Significant relationships between these variables and egg-to-fry survival rates provide a basis for identifying conditions that are hazardous to salmonid fishes. While comparisons of the sensitivities of various fish species were not located in the literature, it is assumed that salmonids represent the most sensitive species to deposited sediments in freshwater ecosystems. This high sensitivity stems from the long exposure periods associated with embryo incubation and utilization of spawning habitats within the streambed matrix (Caux et al. 1997).

The term "percent fines", is often used to describe the portion of a streambed substrate sample that is thought to be harmful to fish. Various particle size classes have been used to define the quantity of fine sediment in streambed substrates. From these, 1 mm, 2 mm, 3 mm, 6.35 mm, and 9.52 mm represent the upper limits of the particle size classes that have been used most commonly in studies on the effects of fine sediments on salmonid incubation success (Caux et al. 1997).

The results of a number of studies indicate that elevated levels of fine sediment in streambed substrates can be deleterious to fish. For example, introduction of greater than 10% fines <0.75 mm in diameter substantially reduced the survival of brown trout eggs and alevin incubated in artificial stream channels (Olsson and Persson 1986). In addition, a high proportion of the brown trout alevin emerged prematurely, underweight and underdeveloped. Phillips et al. (1975) reported delays in emergence timing, reductions in the size of emergent fry, and decreases in the survival of coho salmon embryos incubated in substrates containing more than 10% fines (1.0–3.0 mm in diameter). In chinook salmon and steelhead trout, reduced incubation success was observed when streambed substrates contained more than 12% fines <1.7 mm in diameter or 30% fines <6.35 mm in diameter (Tappel and Bjornn 1983). Similar results were obtained for coho salmon, kokanee, cutthroat trout, and rainbow trout embryos incubated under controlled laboratory conditions (Hall and Lantz 1964; Irving and Bjornn 1984).

The results of two laboratory studies suggest that the eggs of bull trout and cutthroat are more sensitive than other species to the effects of deposited sediment. In this investigation, substantially reduced egg-to-fry survival rates were observed when percent fines exceeded 4 and 10% in the <2.00 and <6.35 mm size classes, respectively (Weaver and White 1985; Weaver and Fraley 1993). Differences in the egg diameter of these species failed to account for their higher apparent sensitivity. The authors indicated that the use of eyed eggs might have increased mortality due to crushing as the eggs were buried in the gravel matrix. Limited data from a study conducted in artificial spawning channels suggest that Atlantic salmon may be somewhat less sensitive to the effects of deposited sediments than other salmonid species (Marty et al. 1986).

Numerical relationships between egg-to-fry survival rates and the prevalence of two particle size classes of fine sediment (% <2.00 mm and % <6.35 mm) have been reported in the literature. Pooled data from a number of studies concluded that the emergence success of coho salmon, steelhead trout, cutthroat trout, and brook trout was strongly influenced by the amount of fine sediment, <2.00 mm in diameter, in the incubation medium (Cederholm and Salo 1979). The relationship between percent fines (<2.00 mm) and survival to emergence was described by the following equation:

$$\text{Survival (\%)} = 104 - 2.42 \cdot (PF_{<2.00})$$

where

$$PF_{<2.00} = \text{percent fines } (<2.00 \text{ mm})$$

Similarly, the survival of bull trout embryos in artificial redds is related to the percent fines <6.35 mm in diameter (Weaver and White 1985). The following equation describes the relationship:

$$\text{Survival (\%)} = 225.2 - 5.13 \cdot (PF_{<6.35})$$

where

$$PF_{<6.35} = \text{percent fines } (<6.35 \text{ mm})$$

Both of these relationships provide a basis for predicting the survival of salmonid embryos during the incubation period.

Natural spawning substrates contain a wide variety of particle sizes, including cobble, gravel, sand, silt, and clay. Therefore, permeability to water flow is not only dependent on the quantity of fine sediments in the substrate, but also on the presence of larger sized particles, such as gravel and cobble (Shirazi and Seim 1979). Platts et al. (1979) proposed geometric mean diameter (Dg) as an alternative measure of streambed substrate composition because it incorporates more information on the overall textural characteristics of the gravel. For any sediment sample, Dg is calculated as follows:

$$Dg = (d_{84} \cdot d_{16})^{0.5}$$

In this equation, d_{84} is the 84th percentile particle size and d_{16} is the 16th percentile particle size. Both of these parameters can be estimated from log-probability plots of the particle size distribution.

Information from various sources indicates that egg-to-fry survival rates are compromised when the overall particle size distribution of streambed substrates is reduced. The survival of brown trout embryos decreased substantially when Dg fell below 9.6 mm (Olsson and Persson 1986). Similarly, egg-to-fry survival rates for coho salmon were reduced at Dgs of roughly 15 mm or less (Koski 1966; Phillips et al. 1975; Tagart 1976). While similar results were obtained for steelhead trout in another study (Cederholm and Lestelle 1974), Tappel and Bjorn (1983) reported that the survival of steelhead trout and chinook salmon embryos was not adversely affected until Dgs fell below 10 mm. The differences between these studies likely reflect the use of eyed eggs in the Tappel and Bjorn (1983) investigation, which reduced the period of exposure to the adverse environmental conditions. Consequently, the chinook salmon and steelhead trout tested in this study appeared to be less sensitive to deposited sediments. The highest concentration of fine sediment tested in this study also caused premature emergence and reduced size of chinook and steelhead fry.

Significant variability is evident in the relationship between Dg and embryo survival rates. A stronger correlation between substrate composition and embryo survival was obtained when Dg was divided by the mean egg diameter (De) for the species tested (i.e., to account for differences in egg sizes between different fish species; Shirazi and Seim 1979). Among the species tested, substantially reduced embryo survival was generally observed when Dg/De fell below 3.0.

The Fredle number (FN) provides a better overall indication of the composition of streambed substrates than do percent fines or geometric mean diameter because it integrates more information on the overall particle size distribution. The FN is calculated by dividing the geometric mean diameter of a sediment sample by the sorting coefficient (So; where So = $[d_{75} \div d_{25}]^{0.5}$) (Lotspeich and Everest 1981) and can be used as a measure of the pore size of the streambed substrate. These data show that the survival rate of salmonid embryos during incubation drops rapidly when the FN falls below 5.

Rearing of Young Salmon and Trout

Deposited sediment can affect the rearing habitats utilized by juvenile salmonids after emergence, by increasing the embeddedness of streambed substrates. For species that are closely associated with the streambed, sediment deposition decreases the available rearing habitat. The production of fish-food organisms can also be reduced in areas with high embeddedness. These factors can combine to reduce the carrying capacity of the stream and, thereby, lead to decreased recruitment rates when fry densities are higher than can be accommodated by the available rearing habitat (Pratt 1985).

Invertebrates

Information from a number of studies indicates that the deposition of fine inorganic sediment in stream ecosystems can be detrimental to aquatic invertebrates. Tebo (1955) reported significant reductions in the densities of macroinvertebrates in a small stream due to smothering by sediment from logging operations. Similarly, substantial decreases in macroinvertebrate production were reported after fine sediments were deposited into a small stream from a rock quarry (Gammon 1970). Benthic macroinvertebrate biomass was also substantially reduced in stream reaches, which had high levels of sediment deposition, primarily as a result of logging activities. It is likely that short-term changes in population densities result from increased rates of invertebrate drift (Culp et al. 1985).

In addition to reducing densities, longer-term exposure to deposited sediments can also influence the structure of benthic macroinvertebrate communities (Williams and Mundie 1978). Importantly, many of the organisms (e.g., mayflies, caddisflies, and stoneflies) that are favoured as food items by stream-dwelling fish species prefer relatively coarse streambed substrates and are harmed by intrusions of fine sediment (Everest et al. 1986). Other groups of invertebrates that are used less preferentially as fish-food organisms (e.g., midges) are more tolerant of fine sediment intrusions into gravel beds (Nuttall 1972). While differences in preferences for coarse and fine sediments accounts for some of the changes in community composition associated with the deposition of fine sediments, alteration of predator–prey relationships may be an important secondary factor. For example, predacious stoneflies consistently reduced both the density and colonization rates of prey species under control conditions (Peckarsky 1985). The effects of predation on stream insect prey densities and colonization rates, however, were eliminated during periods of sediment transport and silt deposition in the stream systems investigated.

Periphyton

The deposition of fine sediment onto streambed substrates can smother periphyton and cover the stable substrates to which algae attach. Accumulations of fine sediment can also render portions of the streambed too mobile to support periphyton communities, thereby eliminating much of the primary productivity (Nuttall 1972). Primary production, however, is usually eliminated by turbidity and scouring well before this condition occurs (Langer 1980).

Guideline for Streambed Substrate

The quantity of fine sediment in streambed substrates (i.e., percent fines) should not exceed 10% <2.00 mm, 19% <3.00 mm, and 25% <6.35 mm at potential salmonid spawning sites. The geometric mean diameter and Fredle number of streambed substrates should not be less than 12 and 5 mm, respectively. The guideline for intragravel dissolved oxygen is 6.5. These guidelines for percent fines, geometric mean diameter, and Fredle number apply to actual and potential spawning sites in streams, and were derived based on the analysis of the available data and extrapolating the value that would produce a survival rate of 80% for egg-to-fry life stages (Caux et al. 1997). The intergravel dissolved oxygen guideline is based on the 1999 CCME guideline for dissolved oxygen (freshwater). Please consult the dissolved oxygen fact sheet for more information.

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Excerpt from Publication No. 1299; ISBN 1-896997-34-1

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