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# Effect of Suspended Sediment on Freshwater Fish and Fish Habitat

by

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## TABLE OF CONTENTS

Appendices

## LIST OF TABLES

## ABSTRACT

Robertson, M.J., Scruton, D.A., Gregory, R.S., and Clarke, K.D. 2006. Effect of suspended sediment on freshwater fish and fish habitat. Can. Tech. Rep. Fish. Aquat. Sci. 2644: v + 37 pp.

As part of the Risk Management Framework (RMF) being implemented in Fisheries and Oceans Canada's (DFO) Habitat Management Program (HMP), a series of Pathways of Effects (PoE) models have been developed. DFO Science Branch conducted literature reviews to validate key end-points (habitat impacts) resulting from development activities and this report reviews the effect of suspended sediment on fish and fish habitat. The literature review was focused on peer reviewed literature from, or of relevance to, Canada, was constrained to freshwater environments, and, owing to the nature of available literature was largely focussed on fluvial habitats. The review includes effects on fish eggs and larvae, effects on foraging and growth, physiological and behavioural effects, alterations to fish abundance and fish communities, effects on aquatic plants and invertebrates, and impacts to fish habitats. Various approaches to predicting the effects of suspended sediment on the aquatic ecosystem are discussed. Finally, the literature reviewed is summarized and evaluated in the context of application to Fisheries and Oceans' Habitat Management

## RÉSUMÉ

Robertson, M.J., Scruton, D.A., Gregory, R.S., and Clarke, K.D. 2006. Effect of suspended sediment on freshwater fish and fish habitat. Can. Tech. Rep. Fish. Aquat. Sci. 2644: v + 37 pp.

On a élaboré une série de modèles de cheminement des effets, qui feront partie du cadre de gestion du risque devant être intégré au Programme de gestion de l'habitat (PGH) de Pêches et Océans Canada. La Direction des sciences du MPO a procédé à des analyses documentaires pour valider les résultats ultimes (effets sur l'habitat) découlant des activités d'aménagement. Le rapport présenté ici passe en revue les effets des sédiments en suspension sur le poisson et sur son habitat. L'analyse documentaire a été axée sur les documents qui avaient fait l'objet d'un examen par les pairs et qui provenaient du Canada ou qui pouvaient s'appliquer au Canada; de plus, elle s'est limitée à ce qui concernait les milieux d'eau douce et, compte tenu de la nature des documents disponibles, elle s'est largement concentrée sur les habitats fluviaux. On a examiné les effets sur les oeufs et larves de poisson, ainsi que sur la quête de nourriture et la croissance, les effets physiologiques et comportementaux, les changements occasionnés dans l'abondance du poisson et les communautés de poisson, les effets sur les plantes et les invertébrés aquatiques et les effets sur les habitats du poisson. Le rapport décrit diverses approches de prévision des effets des sédiments en suspension sur les écosystèmes aquatiques. Enfin, l'analyse documentaire est résumée et évaluée dans le contexte d'une application à la gestion de l'habitat par Pêches et Océans Canada.

## BACKGROUND

Within DFO, the HMP is a key federal regulatory program with the mandate to conserve and protect fish habitat under Canada's Fisheries Act. In 2004-05, the Habitat Management Directorate implemented the Environmental Process Modernization Plan (EPMP) which is intended to provide more efficient and effective delivery of its habitat responsibilities, including improved predictability and timeliness in decision making regarding proposed developments. The EPMP is integral to the Government of Canada's "Smart Regulation" initiative by creating a more modern regulatory system that provides decisions in a more timely, efficient and effective manner. The key element in this 'plan' is the development and implementation of a science-based RMF. This framework sets out a series of principles and practices used to evaluate development projects with the potential to affect fish habitat. The RMF is intended to ensure that project proposals (referrals) are evaluated in a consistent and transparent fashion and that Program resources can be re-allocated from the review of routine, low risk activities, to the review of projects with the greatest degree of risk to fish habitat.

A major underpinning of the RMF is the development and validation of a series of PoE diagrams that describe the cause-effect linkages between a development activity and a habitat impact (see Jones et al. 1996; 'hypothesis of effects' diagrams). These diagrams are essentially a logical map (flow chart) that begin with a development activity, which leads to a series of qualitative changes in fish habitat (e.g. sediment increases, flow alterations, removal of riparian vegetation) which can be linked to changes in biological productivity (e.g. reduction in food availability, etc.- i.e. the effect). DFO's habitat biologists and proponents are to use these PoEs to assess the potential effects from any given project. These PoE diagrams would also assist the proponents develop mitigation plans to avoid the negative effects of a given activity, where possible. To date the Habitat Management program has conceptually developed 21 PoE diagrams for land based (10) and in-water (11) activities.

The HMP requested that Science Branch conduct a detailed scientific literature review to support and validate the cause-effect relationships within each PoE. In reviewing the PoE diagrams it became apparent that there was considerable overlap in the cause-effect linkages between a variety of activities and the physical environmental (habitat) change, as the end point. For example, a change in sediment concentration is an end point in 14 PoE models. It was decided that Science Branch would therefore conduct the literature review and validation on the end points common to many of the PoEs. The initial focus was on four major endpoints that comprise 70% of all the linkages in the combined set of PoE diagrams, namely: (1) change in sediment concentrations, (2) change in habitat structure and cover, (3) change in water temperature, and (4) change in dissolved oxygen concentrations.

The literature review and validation were to consider the severity, reversibility, frequency, and duration of the effect. The reviews were also to document the fish species affected, the ecotype that the effect could be characterized for, and geographic extent of the documented relationships. The effects were to be characterized over multiple spatial and temporal scales, where possible, and were to consider individual effects, population level effects and habitat 'function', effects. The focus was on peer reviewed literature relevant in the Canadian context (literature from other countries was to be included if deemed relevant to species and ecotypes within Canada).

Three working papers/reports were developed, and subsequently presented at a DFO National Workshop Meeting to determine the scientific validity of the four reviewed endpoints. The participants, including both DFO scientists and academic researchers, conducted an impartial and objective scientific peer review of the working documents. The key conclusions (scientific information/advice) from this meeting will be documented in a Canadian Science Advisory Secretariat (CSAS) Proceedings report. The working paper on change in sediment concentrations has been revised based on the feedback at this peer review meeting, and published as this report. A companion report on change in habitat structure and cover has also been published (Smokorowski et al. 2006).

## INTRODUCTION

Sediment entering aquatic habitats may become suspended in the water column (i.e. suspended sediment) or settle on the substrate (i.e. deposited sediment). In general, the size of the sediment particle separating suspended and deposited sediment is 62 µm, with suspended sediment consisting mostly of silt and clay (Waters 1995). Suspended sediment can be measured directly as the dry weight of particles suspended in a volume of water (i.e. total suspended sediment TSS: mg/L, ppm) or indirectly as the extent of light scattering reported by a turbidity meter [Nephelometric Turbidity Units (NTU), Jackson Turbidity Units (JTU), and Formazin Turbidity Units (FTU), which are approximately equivalent: Lloyd et al.1987]. The depth at which light penetrates through the water column is determined by the waters turbidity. Natural or background turbidity levels can vary greatly between adjacent rivers. Some rivers are naturally clear, whereas others are opaque. Turbidity levels within a river will also fluctuate temporally, becoming elevated when sediment enters during rain events and snowmelt.

The characteristics of fine sediment in streams can be highly variable throughout Canada reflecting variations in geology and geomorphology, climate and precipitation, erosion and delivery mechanisms (Wood and Armitage 1997). The two mains sources of sediment in fluvial systems are channel sources, derived from the river bed and banks, and non-channel (off-channel) sources, derived from sources within the catchment such as exposed soils. Channel sources are strongly linked to river hydrology and the stability of the streambed and banks. Principle sources include: (i) stream banks subject to erosion, (ii) mid-channel and point bars comprised of fine materials, (iii) fines stored in interstices, (iv) backwaters where sediments accumulate, and (v) fines associated with aquatic plants that undergo seasonal growth and decline. In some instances biological particles, e.g. phytoplankton and zooplankton, are considered components of fine sediment. The main non-channel sources of fine sediment include: (i) soils subject to erosion and delivered to the stream by runoff, (ii) mass failures such as landslides, (iii) urban runoff, (iv) anthropogenic activities (e.g. land use activities), (v) litterfall from vegetation in the riparian areas, and (vi) atmospheric deposition including dust storms.

use activities), (v) litterfall from vegetation in the riparian areas, and (vi) atmospheric deposition including dust storms.

Organisms living in aquatic environments have adapted to natural fluctuations in turbidity which are highly variable throughout Canada making it difficult to generalize sensitivity and potential impacts across species. Many anthropogenic activities such as forestry, mining, hydroelectric development and agricultural operations can increase suspended sediment levels in aquatic environments leading to increases in turbidity. Given the potential negative effects of increased suspended sediment levels on aquatic organisms, a considerable amount of scientific research investigating these effects has been published, reviews include: Bruton 1985; Everest et al. 1987; Lloyd et al. 1987; Newcombe 1994; Waters 1995; Anderson et al. 1996; Wood and Armitage 1997; Harvey and Lisle 1998; Henley et al. 2000; Bash et al. 2001; and Wilber and Clarke 2001).

## LITERATURE REVIEW

High suspended sediment levels can affect fish in a variety of ways including: (i) adversely affecting their swimming, reducing growth, reducing disease tolerance, or causing death (normally caused by clogging gill filaments) (Bruton 1985); (ii) reduction in habitat quality (suitability), particularly spawning habitats affecting eggs and developing larvae (e.g. Chapman 1988); (iii) forcing the modification of migration patterns (Alabaster and Lloyd 1980); (iv) reduction of food availability (primary production, plants, and benthic invertebrates) (Bruton 1985); and (v) altering predatory efficiency, particularly for sight feeders (Bruton 1985; Gregory and Northcote 1993 and others). These various effects are discussed in more detail in the ensuing sections.

The objective of this paper was 1) to review scientific literature that pertains to the effect of suspended sediment on freshwater fish or fish habitat and 2) to summarise and evaluate this literature for fish habitat management purposes. Sediment from potentially toxic origins (e.g. mining and ore processing, agriculture, water treatment facilities) and volcanic sediments have been excluded from this review. This review has focused on freshwaters only (marine and estuarine literature has not been reviewed) and owing to the nature of the literature, most of the review emphasizes fluvial systems.

### EFFECTS ON FISH EGGS AND LARVA (TABLE 1)

Numerous laboratory and field studies have demonstrated that fish embryo survival to emergence declines as the percentage of fine sediment (≤ 6 mm) within redds increases above 5-10 % (Wickett 1958; Shelton and Pollock 1966; Phillips et al. 1975; Hausle and Coble 1976; Peterson and Metcalfe 1981; Morgan et al. 1983; Tappel and Bjornn 1983; Witzel and MacCrimmon 1983; Fudge and Bodaly 1984; Marty et al. 1986; review Chapman 1988; Reiser and White 1988; O'Conner and Andrew 1998; Argent and Flebbe 1999; Bernier-Bourgault and Magnan 2002; Curry and MacNeill 2004). These studies suggest that fine sediment within spawning gravels kill eggs by inhibiting both gas exchange and the removal of toxic metabolites from the redd (review Chapman 1988; Argent and Flebbe 1999).

Quantifying the amount of fine sediment that will settle within spawning gravels, and the duration that it will remain there before being potentially resuspended, is extremely difficult as it relates to numerous stream properties (e.g. hydrology, geology, geography) which affect flow rate and the ability to retain sediments in suspension (Fudge and Bodaly 1984; Everest et al. 1987; Lisle and Lewis 1992; Schälchi 1992; Sear 1993). Therefore, the effect sediment has on fish embryo development and survival will vary widely between streams (Lisle and Lewis 1992). If the effects of sedimentation are severe, extreme decreases in egg-to-larva survival may cause population declines (Marschall and Crowder 1996).

## PHYSIOLOGICAL EFFECTS ON FISH (TABLE 2)

Juvenile and adult fish can potentially move to avoid increases in suspended sediment (see Behavioural Effects), but for fish remaining in affected areas, exposure to sediment may have negative impacts on fish health. Fish can generally tolerate high concentrations of suspended sediment, with direct mortality occurring only when concentrations are extremely high and beyond those generally recorded in rivers (96h LC50 >10 000-100 000 mg/L: Servizi and Martens 1987, 1991; Lake and Hinch 1999). However, tolerance to suspended sediment appears to be related to fish size (Servizi and Martens 1987; 1991) and newly emerged fish have been reported to die at much lower concentrations (>100-1500 mg/L; Sigler et al. 1984; McLeay et al. 1987). Tolerance to suspended sediment may also be affected by temperature (McLeay et al. 1987; Servizi and Martens 1991). Underyearling coho salmon (Oncorhynchus kisutch) survived higher concentrations of suspended sediment at 7°C (22 700 mg/L) compared to 1°C (10 669 mg/L) and 18°C (7491 mg/L; Servizi and Martens 1991). Mortalities (10-20%) of Arctic grayling occurred at 5°C but not at 15°C after a 4-day exposure to sediment concentrations ≥20 gL-1 (McLeay et al. 1987).

The potential effects of increased suspended sediment on fish health, at those levels generally recorded in rivers, are expected to be sublethal (Servizi and Martens 1987, 1992). Sublethal responses to short-term exposure (i.e. hours-weeks) to suspended sediment have been shown to occur at approximately 10-20 NTU under laboratory conditions. The shape of the sediment particles may also be important, as 'angular' sediments have been shown to elicit a stress response in fish at lower concentrations than 'round' sediments (Lake and Hinch 1999).

Sublethal responses to suspended sediment include:

1) elevated blood sugar, plasma glucose or plasma cortisol levels (i.e. stress response, >500 mg/L: Sigler et al. 1984; Servizi and Martens 1987, 1992; Redding et al. 1987; Lake and Hinch 1999)

2) increased cardiac output (10 NTU or approx. 3300 mg/L: Bunt et al. 2004)

3) increased ventilation rates (i.e. reduced respiratory function, >6000 mg/L or >20 NTU: Horkel and Pearson 1976; Berg and Northcote 1985; Servizi and Martens 1987)

4) gill damage (>3000 mg/L: Sigler et al. 1984; Servizi and Martens 1987; Bergstedt and Bergersen 1997; Lake and Hinch 1999)

5) reduced resistance to disease (270 mg/L: Herbert and Merkens 1961; Redding et al. 1987).

## EFFECTS ON FISH FORAGING AND GROWTH (TABLE 3)

Suspended sediment in streams increases turbidity and thus reduces the visual ability of fish to detect prey and predators. As turbidity increases above 10 NTU, the maximum distance at which predator-prey interactions occur (i.e. reactive distance) decreases (Vinyard and O'Brien 1976; Berg and Northcote 1985; Crowl 1989; Gregory 1990; Barrett et al. 1992; Gregory and Northcote 1993; Miner and Stein 1996; Vogel and Beauchamp 1999; Sweka and Hartman 2001a). A reduction in the ability to detect prey in turbid water has been shown to reduce foraging rates (i.e. consumption) in some species (>30-100 NTU: Gardner 1981; Berg and Northcote 1985; Boehlert and Morgan 1985; McLeay et al. 1987; Redding et al. 1987; Breitburg 1988; Vandenbyllaardt et al. 1991; Borgström et al. 1992; Reid et al. 1999). However, the affect turbidity has on fish foraging rates may be influenced by light conditions (Miner and Stein 1993), fish size (Gregory 1994) or the perceived risk of predation (Gregory 1990; 1994; Gregory and Northcote 1993). Increases in turbidity (range 10-40 NTU) reduced the foraging rates of larval bluegill (Lepomis macrochirus) under low-light conditions (<450 lx) but increased foraging under high-light conditions (>450 lx). At higher light levels, prey may have been more visible against a turbid background (i.e. contrast enhancement, Miner and Stein 1993). Foraging rates have also been shown to increase at moderate turbidities (18-150 NTU and 50-200 mg/L) in larger underyearling coho salmon (Oncorhynchus kisutch: 57-69 mm) and chinook salmon (O. tshawytscha: 60-70 mm: Gregory 1990, 1994; Gregory and Northcote 1993). Predation rates and anti-predator behaviours have been shown to be lower in turbid water compared to clear water (Table 4: Ginetz and Larkin 1976; Gradall and Swenson 1982; Gregory 1993; Miner and Stein 1996; Abrahams and Kattenfeld 1997; Gregory and Levings 1998). Therefore, some fish may increase feeding activity in turbid water as it provides cover (i.e. visual isolation) from predators (Gregory and Northcote 1993).

Growth rates may also be reduced in turbid water (>10-25 NTU, exposure duration 5 days to 1 year: Crouse et al. 1981; Sigler et al. 1984; McLeay et al. 1987; Borgström et al. 1992; Bergstedt and Bergersen 1997; Shaw and Richardson 2001; Sweka and Hartman 2001b). However, a reduction in growth rate cannot always be attributed to a reduction in foraging rate (Sweka and Hartman 2001b). Growth in turbid water may be limited by other factors such as increased energy expended to capture prey (i.e. active foraging tactic vs. drift feeding: Sweka and Hartman 2001a, 2001b) or a reduction in prey availability (i.e. aquatic invertebrates: See Effects on Aquatic Plants and Invertebrates). Factors reducing growth rates of small juveniles may result in population declines (Borgström et al. 1992; Marschall and Crowder 1996).

Some studies have found no affect of turbidity on foraging and/or growth rates (Swenson and Matson 1976; Speir and Heidinger 2002; Rowe et al. 2003; Granqvist and Mattila 2004). In these studies, factors such as increased activity, increased prey encounter, reduced anti-predator behaviour of prey and/or altered contrast of prey may have compensated for reduced visual ability (Granqvist and Mattila 2004). Some fish species may also use other senses such at the lateral line system to detect prey (Speir and Heidinger 2002; Rowe et al. 2003).

## EFFECTS ON PRIMARY PRODUCERS AND AQUATIC PLANTS

Even small increases in suspended sediment (e.g. 5-10 NTU) will reduce the production of aquatic plants (i.e. primary production: Hansmann and Phinney 1973; Barko and Smart 1986; Brookes 1986; Lloyd et al. 1987). Fine sediment suspension and deposition affects primary producers by: (i) reducing light penetration thereby reducing photosynthesis and primary production, (ii) reducing the organic content of periphyton at the cellular level, (iii) damaging macrophyte stems and leaves through abrasion, (iv) by preventing the attachment of periphyton to substrates, and (v) smothering and eliminating periphyton and macrophyte beds (Wood and Armitage 1997).

Macrophyte growth is seasonal and can affect stream hydraulics and channel roughness. Macrophyte stands actually act to slow water velocity and thereby enhance the deposition and accumulation of sediment in suspension and these fines can then be released when the macrophytes die off and discharge increases (Carpenter and Lodge 1986).

## EFFECTS ON INVERTEBRATES

Benthic communities are normally able to withstand short-term increases in suspended sediment and even communities disturbed over a short duration are able to rapidly recover (Wood and Armitage 1997). However, even small increases in suspended sediment over longer or continuous durations can affect the quantity and composition (i.e. species richness) of aquatic invertebrates (Barton 1977; Rosenberg and Snow 1975; Rosenberg and Meins 1978; McCabe and O'Brien 1983; Culp et al. 1986; Zettler and Carter 1986; Lloyd et al. 1987; Borgström et al. 1992; Shaw and Richardson 2001).

Fine sediment deposition can affect benthic invertebrates by: (i) altering the substrate composition making the substrate unsuitable for some taxa (or more preferred for others) (e.g. Erman and Ligon 1988); (ii) increasing drift due to substrate instability (Culp et al. 1986); (iii) affecting respiration by silt deposition on respiratory structures or as a result of low oxygen concentrations often associated with sediment deposition (Lemly 1982); and (iv) reducing feeding by altering effectiveness of filter feeders (Alderidge et al. 1987), reducing food value of periphyton (Graham 1990), and reduction in density of prey (Peckarsky 1984).

Aquatic invertebrates affected by short-term increases in suspended sediment (i.e. during highway culvert installations) have been shown to recover in quantity within a period of days to a year (Barton 1977). However, the drifting invertebrates recolonising the area may differ in species composition (Barton 1977).

## BEHAVIOURAL EFFECTS ON FISH (TABLE 4)

The most common behaviour noted in laboratory studies examining the effect of turbidity on fish is an avoidance response. This behaviour is usually recorded as an 'alarm reaction' and is characterized by erratic swimming and an apparent attempt to avoid the turbid water (>40 NTU: Bisson and Bilby 1982; Berg and Northcote 1985; Servizi and Martens 1992; Chiasson 1993). Research also suggests that substantial emigration may result when increases in suspended sediment occur soon after fish emergence (Sigler et al. 1984; Curry and MacNeill 2004). If suitable habitat is not available downstream, fish production within the stream may decline. Other behaviours such as the breakdown of dominance hierarchies and reduced territorial behaviour (i.e. aggression) have been noted at moderate turbidities (30 and 60 NTU) but these behaviours were re-established when turbidities returned to lower levels (<20 NTU; Berg and Northcote 1985).

Low concentrations of turbidity may be beneficial to some young fish by reducing risk from predators (Ginetz and Larkin 1976). Predation rates and anti-predator behaviours have been shown to be lower in turbid water compared to clear water (Ginetz and Larkin 1976; Gradall and Swenson 1982; Gregory 1993; Miner and Stein 1996; Abrahams and Kattenfeld 1997; Gregory and Levings 1998). As with its adverse effect on feeding rates, turbidity reduces the encounter rate between predators and prey (Gregory and Levings 1996, 1998).

## EFFECTS ON FISH HABITAT

### *Spawning Habitat*

Salmonids require clean gravel for spawning (see 1. Effects on Eggs and Larva). Fine sediment is usually removed from the gravel during redd excavation (Chapman 1988). However, if the amount of fine sediment is excessive, suitable habitat for spawning will be reduced (Platts et al. 1989; Sear 1993; Wu 2000; Kondolf 2000). Studies have shown that salmonids select redd sites with low proportions of fine sediment (Witzel and MacCrimmon 1983; Crisp and Carling 1989; Bernier-Bourgault and Magnan 2002) and traditional spawning habitats have been abandoned due to sedimentation (Hamilton 1961).

### *Overwintering Habitat*

Small fish use the spaces between gravel and cobble substrate in winter to avoid predators, minimize energy expenditure, and avoid harsh environmental conditions (Lauzier and Levings 1986; Gregory and Griffith 1993; Cunjak et al. 1998; Valdimarsson and Metcalfe 1998). Studies have found that winter fish densities decrease as the proportion of fine sediment within the substrate increases (Bjornn et al. 1977; Hillman et al. 1987). The availability of suitable winter habitat in North America is considered the critical factor limiting the abundance of salmonids in streams (Chapman 1966; Bustard and Narver 1975). Therefore, reductions in suitable winter habitat through sedimentation may further limit the productive capacity of streams.

## EFFECTS ON FISH ABUNDANCE AND COMMUNITY STRUCTURE

Sediment accumulation in steams has been correlated with reduced fish abundance (Herbert and Merkens 1961; Saunders and Smith 1965; Alexander and Hansen 1983; Berkman and Rabeni 1987; Lloyd et al. 1987; Houston 1996). This reduction may be attributed to many factors including physiological impacts, changes in foraging success and prey availability, emigration and/or habitat alteration.

Fish community structure is also affected by sedimentation. Fish that eat invertebrates and require clean gravel for spawning (e.g. salmonids) may decline in habitats affected by sediment (Berkman and Rabeni 1987; Bergstedt and Bergersen 1997). However, these species may be replaced by species with more general feeding and spawning requirements (e.g. carp and suckers: Bergstedt and Bergersen 1997).

## PREDICTING THE EFFECTS OF SUSPENDED SEDIMENT ON AQUATIC ECOSYSTEMS

Using the results from previous scientific literature, Newcombe and MacDonald (1991) developed a stress-index model as a convenient tool for predicting the effects of suspended sediment on aquatic ecosystems. This model highlighted the importance of considering not only the concentration of sediment but also exposure duration (i.e. dose-response) when determining the severity of effects. This model was an improvement over the previous concentration-response model that assumed concentration alone would provide adequate information for protecting aquatic environments from sediment pollution. However, the stress-index model was criticized for being unrealistically simplistic and having low predictive power, which may lead managers to suggest inappropriate policies for protecting aquatic environments (Gregory et al. 1993). The dose-response model was refined by Newcombe and Jensen (1996) who developed meta-analysis dose-response models that consider fish species, life stage of species, and particle size of suspended sediment when assessing the effects of suspended sediments on fishes. Newcombe and Jensen (1996) describe the severity of ill effects ranging from no effects to lethal effects (Appendix 1). Given the variable results from previous studies, the thresholds between the different levels of severity occur over a wide range of concentrations and durations. However, for the same exposure duration, adverse effects are predicted to increase as concentration increases. Validation and refinement of these dose-response models will require new directed research that provides the information necessary for the models and more precise determinations of the thresholds between sublethal and lethal effects (Newcombe and Jensen 1996).

## SUMMARY AND EVALUATION OF THE LITERATURE FOR FISH HABITAT MANAGEMENT

General summary statements regarding the scientific literature investigating the effect of suspended sediment on freshwater fish and fish habitat:

1) The vast majority of studies have been conducted on salmonids.

2) Most studies reported adverse effects, including studies on non-salmonid fishes.

3) The magnitude of adverse effects will be related to exposure frequency, duration, concentration, fish species and fish life stage, particle size and type, % fines, water temperature (or season), and background turbidity levels.

4) Fish species that eat invertebrates and require clean gravel for spawning (e.g. salmonids) are most vulnerable to suspended and deposited sediments.

5) The greatest impact of sedimentation is on incubating eggs and larval fish, as high mortality rates of these life stages may result in reduced fish production.

In general, short-term (i.e. hours, days) and infrequent exposure to small increases in suspended sediment may result in sublethal effects (physiological and behavioural) on individual fish. These effects are usually temporary and are reversed when turbidities return to background levels. Fish populations can be negatively affected by short-term increases in suspended sediment if sedimentation is severe, resulting in the destruction of suitable spawning habitat or extreme decreases in egg-to-larva survival. Sediment settling within rearing habitats may also impact fish populations by reducing prey availability and thus the growth potential of small juvenile fish.

Long-term (i.e. months, years) or frequent exposure (i.e. chronic exposure) to elevated levels of suspended sediment will result in fish population declines and changes in fish community structure. Fish species that eat invertebrates and require clean gravel for spawning (e.g. salmonids) will decline in sedimented areas and be replaced by more tolerant species (e.g. carp and suckers). Chronic releases of sediment usually occur as a result of increased erosion potential from various anthropogenic activities.

## WATER QUALITY GUIDELINES

The province of British Columbia's Ambient Water Quality Guidelines (Criteria) for Turbidity, Suspended and Benthic sediments (developed from Canadian Environmental Quality Guidelines CEQG; Appendix 2) provide guidelines to protect aquatic life under both clear and turbid flow periods. These guidelines were based on scientific background information and, with the exclusion the guidelines for Streambed Substrate Composition (section 2.3), are supported by the findings of the present review.

The percentages selected and sediment diameter transitions suggested in the guidelines for Streambed Substrate Composition are not supported by the findings of the current review and will result in reduced egg and alevin survival. B.C.'s guidelines differentiate between sediments having a 2mm and 3 mm diameter; however, these sediment sizes appear to have similar adverse effects on developing eggs. Substrates with 10% fines (<2 mm) have also been shown to reduce alevin survival by 28% in Atlantic salmon (O'Conner and Andrew 1998). Guidelines reflecting the current literature would improve the protection of developing eggs if they were changed to ".should not exceed 5% having a diameter less than 3 mm..." Small amounts of fines can be removed from the substrate during redd excavation. Therefore, sediment inputs during egg development will have the greatest adverse effects. Thin layers of sediment (<2 mm diameter) deposited on developing eggs resulted in 100% mortality of white perch eggs (1.2 mm deep: Morgan et al. 1983) and reduced survival of lake whitefish eggs (1-4 mm deep: Fudge and Bodaly 1984).

As stated in the guidelines, the recommended transition value (25 mg/L or 8 NTU) between clear and turbid flows was selected by examining streams in British Colombia. This transition value may not be appropriate for all provinces or aquatic habitats. Resource managers need background information regarding turbidity levels and temporal fluctuations in these levels in order to predict, with some confidence, the impact of sediment pollution on an aquatic ecosystem. However, appropriate values are not expected to deviate substantially from these levels.

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Table 1. Effects of suspended sediment on fish larvae and eggs.

| | Common name | Scientific name | Field/ Lab | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|
| 1 | Coho salmon | *Oncorhynchus kisutch* | Field | | | Survival of reduced as % of fine particles (<3.3 mm) in redd increased. | Oregon, USA | Koski 1966 (cf Chapman 1988) |
| 2 | Coho salmon | *Oncorhynchus kisutch* | Field | >20% fines in gravel | | Survival to emergence reduced 14% compared to redd with <20% fines. | Washington, USA | Tagart 1976 (cf Chapman 1988) |
| 3 | Coho salmon | *Oncorhynchus kisutch* | Field/ Lab | Lab: 10% fines in redd<br>Field: 15% fines in redd<br>Lab: 13% fines in redd<br>Field: 25% fines in redd | | 30% survival to emergence<br>30% survival to emergence<br>15% survival to emergence<br>15% survival to emergence<br>Survival to emergence decreased as % of fine particles (<0.85 mm) in both artificial and natural redds increased. | Washington USA | Cederholm et al. 1981 (cf Chapman 1988) |
| 4 | Coho salmon and Steelhead trout | *Oncorhynchus kisutch*<br>*Oncorhynchus mykiss* | Lab | 0, 10, 20, 30, 40, 50 60, 70% sand (<3.3 mm) in gravel | | Survival to emergence decreased as % of sand increased (0% sand = 96% survival and 70% sand = 8% survival). | Oregon, USA | Phillips et al. 1975 |
| 5 | Steelhead trout and Chinook salmon | *Oncorhynchus mykiss* and *Oncorhynchus tschawytscha* | Lab | 50% fines (<0.84 mm)<br>Mixture fine and coarse sediment (0.84-4.6 mm) | | 100% egg mortality.<br>In general egg survival decreased s % sediment increased and % egg survival increased as intragravel velocities increased (range 36-1550 cm/hr). | Idaho, USA | Reiser and White 1988 |

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Table 1. (Cont'd.)

|  | Common name | Scientific name | Field/ Lab | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|
| 6 | Steelhead trout and<br>Chinook salmon | *Oncorhynchus mykiss*<br>*Oncorhynchus tschawytscha* | Lab | various gravel mixtures mixtures (mean, 4.0-21.5 mm) |  | Survival to emergence decreased as % of fine particles increased (i.e. lower mean size). | Idaho, USA | Tappel and Bjorn 1983 |
| 7 | Chinook salmon | *Oncorhynchus tschawytscha* | Field/ Exp | 13-30% sediment (< 4 mm) |  | Up to 85% egg mortality. | Oregon, USA | Shelton and Pollock 1966 |
| 8 | Brook trout | *Salvelinus fontinalis* | Field/ Exp |  |  | Lower % fines (<1 mm) in selected over non-selected substrates and selected substrates had higher hatching and emergence success than non-selected substrates. | Quebec, CA | Bernier-Bourgault and Magnan 2002 |
| 9 | Brook trout | *Salvelinus fontinalis* | Lab | 0, 5, 10, 15, 20, 25% sand (<2 mm) |  | Survival to emergence decreased as % of sand increased. | Wisconsin, USA | Hausle and Coble 1976 |
| 10 | Brook trout | *Salvelinus fontinalis* | Lab | 0, 5, 10, 15, 20, 25% fines (<0.85 mm) |  | Survival to emergence decreased as % of fines increased, survival 50% less at 25% sediment compared to 0% sediment. | Pennsylvania, USA | Argent and Flebble 1999 |

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Table 1. (Cont'd.)

| | Common name | Scientific name | Field/ Lab | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|
| 11 | Brook trout | *Salvelinus fontinalis* | Field | rivers of differing sediment loads | | Survival to emergence was reduced (50%) in redds in which fines accumulated, effect reduced by groundwater. | New Brunswick Canada | Curry and MacNeil 2004 |
| 12 | Brook trout | *Salvelinus fontinalis* | Lab | | | | Ontario, Canada<br>1983 | Witzel and MacCrimmon |
| | and<br>Brown trout | *Salmo trutta* | | 100% gravel (9.2 mm) or ≤20% sand (mean, 5.1 mm) in gravel | 112 d<br>60-96%. | Survival to emergence | | |
| | | | | 100% fines (≤6.2 mm) or ≥ 60% sand (mean, 5.1 mm) in gravel | | Survival to emergence 0-20%, therefore survival reduced 40-96% in smaller fines and gravel mixture. | | |
| 13 | Atlantic salmon | *Salmo salar* | Lab | 10% fines 0.063-1 mm) in redd. | 126 d | Alevin survival reduced 28% vs control. | Ireland | O'Conner and Andrew 1998 |
| | | | | 15% fines in redd | 126 d | Alevin survival reduced 35% vs control. | | |
| | | | | 20% fines in redd | 126 d | Alevin survival reduced 37% vs control. | | |
| | | | | 25% fines in redd | 126 d | 100% egg mortality. | | |
| 14 | Atlantic salmon | *Salmo salar* | Field/ Lab | various mixtures of fine sand (0.06-0.05 mm) and coarse sand (0.5-22 mm) added to gravel | | Survival to emergence decreased as % of sand increased and fine sand has more negative effect than coarse sand. | New Brunswick, Canada | Peterson and Metcalfe 1981 |

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Table 1. (Cont'd.)

| Common name | Scientific name | Field/ Lab | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|
| 15 Atlantic salmon | *Salmo salar* | Field/Exp | | | Survival to emergence reduced as volume of fines, particularly those <10 mm and <0.2 mm, in gravel, increased. | France | Marty et al. 1986 |
| 16 Lake whitefish | *Coregonus clupeaformis* | Field/ Exp | layer of clay and silt 1-4 mm deep naturally deposited on substrate | | Egg survival was significantly higher for eggs protected by cages Compared to exposed eggs. | Manitoba Canada | Fudge and Bodaly 1984 |
| 17 White perch | *Morone americanus* | Lab | ≤1500 mg/L suspended sediment (0.003-2 mm) | | Developmental rates significantly reduced. | Maryland, USA | Morgan et al. 1983 |
| | | | 1626-5280 mg/L | 1 d | 15-19 % morality | | |
| and | | | | 2 d | 23-49% mortality | | |
| | | | layer 1.2 mm on top of egg | | 100% mortality | | |
| Striped bass | *Monroe saxatilis* | Lab | ≤ 1300 mg/L | | Developmental rates significantly reduced. | | |
| | | | 1557-5210 mg/L | 1 d<br>2 d | 20-31% mortality<br>25-57% mortality | | |

Table 2. Physiological effects of suspended sediment on fish.

| | Common name | Scientific name | Field/ Lab | Fish size | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Coho salmon | *Oncorhynchus kisutch* | Lab | 80-111 mm | 96h LC50 = 164 500 mg/L for 'round' sediment <150 µm | 96hLC50 | Mortalities at >100 000 mg/L, gill damages and stress response at >40 000 mg/L. | British Columbia, Canada | Lake and Hinch 1999 |
| | | | | | 96h LC50 = 164 500 mg/L for 'extremely angular' sediment <150 µm | 96hLC50 | Mortalities at >100 000 mg/L, gill damages and stress response at >41 000 mg/L. | | |
| 2 | Coho salmon | *Oncorhynchus kisutch* | Lab | 0.52-0.73 g | 96h LC50 = 22 700 mg/L for sediment <240 µm at 7°C | 96hLC50 | | British Columbia, Canada | Servizi and Martens 1991 |
| | | | | | 96h LC50 affected by temperature: 53% less at 1°C (10 669 mg/L) 77% less at 18°C (7491 mg/L) | | | | |
| 3 | Coho salmon | *Oncorhynchus kisutch* | Lab | mean, 1.7 g and 5.2 mm | 0, 20, 30 and 60 NTU; sediment (0.02-0.06 mm) | 1 h and 2 d | Increase in ventilation rates at >20 NTU. | British Columbia, Canada | Berg and Northcote 1985 |
| 4 | Coho salmon | *Oncorhynchus kisutch* | Lab | mean, 20 g and 120 mm | 0, 20, 240, 2460, and 6780 mg/L (0, 3, 30, 260, and 666 NTU), sublethal as determined by previous studies | 96 h | Cough frequency at 240 mg/L 8 times that of controls, increased blood sugar with increased sediment concentration. | British Columbia, Canada | Servizi and Martens 1992 |
| 5 | Coho salmon and | *Oncorhynchus kisutch* | Lab | mean, 121 mm | High, 2000-3000 mg/L of topsoil kaolin clay | 7-8 d | Temporary (48 h) increase plasma cortisol when exposed to all three sediment types at both high and low concentrations. | Oregon, USA | Redding et al. 1987 |

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Table 2. (Cont'd.)

| | Common name | Scientific name | Field/ Lab | Fish size | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | Steelhead trout | *Oncorhynchus mykiss* | Lab | mean, 137 mm clay | low, 500 mg/L of topsoil and kaolin | 7-8 d | | | |
| | | | | mean, 96 mm | 2500 mg/L suspended topsoil | 2 d | Reduced resistence to disease (bacterial pathogen *Vibrio anguillarum*). | | |
| 6 | Steelhead trout and Chinook salmon | *Oncorhynchus* mykiss<br>*Oncorhynchus tschawytscha* | Lab | 30-65 mm | 500-1500 mg/L (100-300 NTU) | | Mortality of newly emerge fish. | Idaho, USA | Sigler et al. 1984 |
| 7 | Chinook salmon | *Oncorhynchus tschawytscha* | Lab | 1.0-7.0 g | 96h LC50 = 17 600 mg/L for sediment at 7°C | 96hLC50 | | British Columbia, Canada | Servizi and Gordon 1990 (c.f. Servizi and Martens 1991) |
| 8 | Rainbow trout | *Oncorhynchus mykiss* | Lab | | 270 mg/L diatomaceous earth | 121 d | More susceptible to finrot. | Great Britain | Herbert and Merkens 1961 (c.f. Anerson et al. 1996) |
| 9 | Sockeye salmon | *Oncorhynchus nerka* | Lab | 0.8-1.5 g smolt and adult | 96h LC50 = 31 000 mg/L for sediment <780 µm at 7.8-8.3°C. | 96hLC50 | Y-O-Y gill damage at 3148 mg/L, smolt slight impairment respiration after 96h at 14 407 mg/L. | British Columbia, Canada | Servizi and Martens 1987 |
| | | | | | | | Adult stress response (increase plasma glucose) at 500 and 1500 mg/L -less impact on older life stages (i.e. larger fish). | | |

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Table 2. (Cont'd.)

| | Common name | Scientific name | Field/ Lab | Fish size | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 10 | Mountain whitefish | *Prosopium williamsoni* | Field | | 1800 mg/L (1200 times mean concentration during low-flow conditions) | 5-18 h (25-32 times per year) | Dam sluiced by opening gates: fish downstream from dam had abnormal gills and pseudobranchs, and fin damage. | Wyoming, USA | Bergstedt and Bergersen 1997 |
| 11 | Green sunfish | *Lepomis cyanellus* | Lab | 4.9-15.8 g | 3333, 6667, 13333, 17778, 26667 mg/L at 5, 15, and 25°C | 3 d | 50-70% increase in ventilation rates at > 6667 mg/L (15 and 25°C) vs controls. | Texas, USA | Horkel and Pearson 1976 |
| 12 | Rock bass (Riverine) | *Ambloplites rupestris* | Lab | mean, 90 g and 170 mm | 0-6726 mg/L (0-800 NTU) bentonite clay (2.5-4 µm). | 140 m | Increased cardiac output at low concentrations (10 NTU, approx. 3300 mg/L) for both fish, however riverine fish acclimated wiithin 60 m. | Ontario, Canada | Bunt et al. 2004 |
| | and | | | | | | | | |
| | Rock bass (Lacustrine) | *Ambloplites rupestris* | | | | | Lacustrine fish were less tolerant to increased sediment. | | |
| 13 | Arctric grayling | *Thymallus arcticus* | Lab | 0.03-1.0 g | inorganic sediment ≥20 g/L | 4 d | mortalities (10-20%) at 5°C but no mortalities at 15°C. | British Columbia, Canada | McLeay et al. 1967 |

96h LC50 is the concentration of a substance I air or water that kills 50% of test organisms in 96h.

Table 3. Effects of suspended sediment on fish foraging and growth.

| | Common name | Scientific name | Field/ Lab | Fish size | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Chinook salmon | *Oncorhynchus tshawytscha* | Lab | 57-69 mm | <1,18,35,70,150,370, 810 NTU, sediment (<0.4 mm) | 1, 5, and 10 m | Feeding rates highest at 18-150 NTU. | British Columbia, Canada | Gregory 1994 |
| | | | | 49-55 mm | <1,18,35,70,150,370, 810 NTU, sediment (<0.4 mm) | 1, 5, and 10 m | Feeding rates highest at <1 NTU. | | |
| 2 | Coho salmon | *Oncorhynchus kisutch* | Lab | mean, 52 mm and 1.5 g | 0, 20, 40, 60, 80 and 100% of sediment substrate. | 6 mths | Production (g/m2) decreased as % sediment increased. | Oregon, USA | Crouse et al. 1981. |
| 3 | Coho salmon | *Oncorhynchus kisutch* | Lab | mean, 17 g and 5.2 mm | 0, 20, 30, and 60 NTU; sediment (0.02-0.06 mm) | 2 d | Reactive distance reduced in turbid water (20-60 NTU), prey capture success reduced 50% at 30 and 60 NTU compared to 0 NTU. | British Columbia, Canada | Berg and Northcote 1985 |
| 4 | Coho salmon<br>and | *Oncorhynchus kisutch* | Lab | Mean, 121 mm | High 2000-3000 mg/L and low, 500 mg/L of topsoil, kaolin clay and volcanic ash | 7-8 d | feeding rates for both species were reduced at high concentrations (2000-3000 mg/L). | Oregon, USA | Redding et al. 1987. |
| | Steelhead trout | *Oncorhynchus mykiss* | | mean, 137 mm | | | | | |
| 5 | Coho salmon | *Oncorhynchus kisutch* | Lab | 30-65 mm | | | | | |
| | and Steelhead trout | *Oncorhynchus mykiss* | | 30-65 mm | 25-50 NTU | 14 d | Reduced growth at 25-25 NTU compared to clear water. | Idaho, USA | Sigler et al. 1964. |
| 6 | Rainbow trout | *Oncorhynchus mykiss* | Field/ Exp | mean, 46 mm and 1 g | 700 mg/L (23 NTU) sediment sand-silt (425 µm) | 19 d | Duration of sediment pulse ranged from 0.6 hrs, growth decreased with increased pulse duration. | British Columbia, Canada | Shaw and Richardson 2001 |

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Table 3. (Cont'd.)

| | Common name | Scientific name | Field/ Lab | Fish size | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 7 | Rainbow trout | *Oncorhynchus mykiss* | Lab | 87-185 mm | Control 4-6 NTU, low turbidity 14-16 NTU and high 29-31 NTU. | 3 h | 20% and 55% reduction in reactive distances at low and high turbidity compared to control. | Georgia, USA | Barrett et al. 1992 |
| 8 | Rainbow trout | *Oncorhynchus mykiss* | Lab | mean, 46 mm | 0, 10, 20, 40, 80 and 160 NTU | 30 M | Turbidities up to 160 NTU had no effect on feeding rates but smaller prey were selected. | New Zealand | Rowe et al. 2003 |
| 9 | Mountain whitefish, Brown trout and Rainbow trout | *Prosopium Williamsoni*, *Salmo trutta*<br>*Oncorhynchus mykiss* | Field | | 1800 mg/L (1200 times mean concentration recorded during normal low-flow conditions) | 5-18 h (25-32 times per year) | Dam sluiced by opening gates fish downstream from dam had lower fat index levels and lower condition factors than fish upstream from dam. | Wyoming, USA | Bergstedt and Bergersen 1997 |
| 10 | Chinook salmon | *Oncorhynchus tshawytscha* | Lab | 65-70 mm | 0, 25, 50, 100, 200, 400 and 800 mg/L | 5 m | Feeding rates highest at intermediate turbidity levels (50-200 mg/L), reduced at >200 mg/L and very low in clear and very turbid water (800 mg/L). Reaction distance and perceived risk to predation decreased with increasing turbidity. | British Columbia, Canada | Gregory 1990 |
| 11 | Chinook salmon | *Oncorhynchus tshawytscha* | Lab | 60-70 mm | <1,18,35,70,150, 370,810 NTU, sediment (<0.4 mm); 370 NTU = 400 mg/L | 1.5 and 10 m | Feeding rates highest at intermediate turbidity levels (35-150 NTU), reduced at 370 and 810 NTU: reaction distance decreased with increasing turbidity. | British Columbia, Canada | Gregory and Northcote 1993 |

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Table 3. (Cont'd.)

| | Common name | Scientific name | Field/ Lab | Fish size | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 12 | Brook trout | *Salvelinus fontinalis* | Lab | mean, 136 mm and 25 g | 0, 10, 15, 20, 25, 30 35 and 40 NTU | | Reactive distance decreased with increasing turbidity (light 49 lx), turbidity did not effect capture success once prey detected. | West Virginia, USA | Sweka and Hartman 2001a |
| 13 | Brook trout | *Salvelinus fontinalis* | Lab | mean, 126 mm and 22 g | various levels ranging from clear (<3 NTU) to very turbid (>40 NTU) | minimium 5 d | Turbidity had no effect on consumption rates but growth decreased with increasing turbidity. | West Virginia, USA | Sweka and Harman 2001b |
| 14 | Lake trout | *Salvelinus namaycush* | Lab | 330-456 mm | 0.09, 3.18 and 7.4 NTU, bentonite clay | 4 h | Reactive distance to salmonid prey (rainbow trout and cutthroat trout) decreased with increasing turbidity. | Utah, USA | Vogel and Beauchamp 1999 |
| 15 | Brown trout | *Salmo trutta* L. | Field | population | increased erosion from exposed bottom reservoir upon lowering the water level | approx. 1 yr | Reduced fish feeding rates in post-siltation period, resulted in reduced growth and reproductive potential and increased mortality of mature fish. | Norway | Borgström et al. 1992 |
| 16 | Largemouth bass | *Morone salmoides* | Lab/ Field | Lab: 83-130mm<br>Field: 192-245 mm | Lab: 1, 18, 37 and 70 NTU, bentonite clay<br>Field: 2.3 and 20 NTU | Lab: 1 hr | Lab: feeding rates on fathead minnows reduced at highest turbidity 70 NTU<br>Field: feeding rates on redbelly dace (*Phoxinus eos*) similar at 2.3 and 20 NTU. | Ontario, Canada | Reid et al. 1999 |
| 17 | Largemouth bass | *Morone salmoides* | Lab | 280-300 mm | clear 1-3 JTU (Jackson Turbidity Units), moderately turbid 17-19 JTU | | Reduced prey recognition in turbid water (light 200 lx). | Oklahoma, USA | Crowl 1989 |

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Table 3. (Cont'd.)

|  | Common name | Scientific name | Field/ Lab | Fish size | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 18 | Striped bass | *Morone saxatilis* | Lab | larvae | 0, 75, 200 and 500 mg/L | 25 m | 40% reduction in consumption at 200 and 500 mg/L compared to that at 0 and 75 mg/L (low light 5 lx). | Maryland, USA | Breitburg 1988 |
| 19 | Bluegill | *Lepomis macrochirus* | Field/ Exp | mean, 12.5 mm | high 30-40 NTU and low 10 and 20 NTU, bottom sediment | 3.5-5.5 h | Low-light (<450 lx) consumption decreased with increasing turbidity high-light (>450 lx): consumption increased with increasing turbidity. | Ohio, USA | Mines and Stein 1993 |
| 20 | Bluegill | *Lepomis macrochirus* | Lab | mean, 75 mm | 60, 120 and 190 NTU, bentonite clay | 3 m | Feeding rates decreased with increasing turbidity (light 150 lx). | Washington, USA | Gardner 1981 |
| 21 | Bluegill | *Lepomis macrochirus* | Lab | mean, 65 mm | range 1-30 JTU | 3 m | Reactive distance decreased with increasing turbidity (light 35 lx) | Kansas, USA | Vinyard and O'Brien 1976 |
| 22 | Black crappie and White crappie | *Pomoxis nigromaculatus*<br>*Pomoxis annularis* | Lab | mean, 4 mm and 0.001 g | 7-174 FTU (Formazin turbidity units) | 25 weeks | Growth not affected by turbidity. | Illinois, USA | Spier and Heidinger 2002 |
| 23 | Perch | *Perca fluviatilis L.* | Lab | 0+ mean, 48 mm, 1 g: 1+ mean, 67 mm 2.4 g | 1, 10, 20 and 30 NTU | 3 h | No reduction in consumption with increased turbidity at 3 light levels (daylight, twilight and night). | Finland | Granqvist and Mattila 2004 |
| 24 | Walleye | *Stizostedion vitreum* | Lab |  |  |  | Feeding rates reduced at 100 NTU. |  | Vandenbyllaardt et al. 1991 |

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Table 3. (Cont'd.)

| | Common name | Scientific name | Field/ Lab | Fish size | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 25. | Lake herring | *Coregonus artedii* | Lab | larval, 3 days old | range 0-48 FTU (1-28 ppm), red clay | 62 d | Growth not affected by turbidity. | Wisconsin, USA | Swenson and Matson 1976 |
| 26 | Arctic grayling | *Thymallus arcticus* | Lab | 0.03-1.0 g | >100 mg/L | 6 week | Impaired feeding activity and reduced growth rates. | British Columbia, Canada | McLeay et al. 1987 |
| 27 | Pacific herring | *Clupea harengus pallasi* | | | 2000 mg/L | <1 d | Reduced feeding rate. | | Boehlert and Morgan 1985 |

Table 4. Effects of Suspended Sediment on Fish Behaviour.

|  | Common name | Scientific name | Field/ Lab | Fish size | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Coho salmon | *Oncorhynchus kisutch* | Lab | mean 1 g | 0, 20, 240, 2460, and 6780 mg/L (0, 3, 30, 260, and 666 NTU), sublethal as determined by previous studies. | 96 h | Avoidance (i.e. alarm reaction) <5 % up to 2550 mg/L (37 NTU) and 25% at 7000 mg/L | British Columbia, Canada | Servizi and Martens 1992 |
| 2 | Coho salmon | *Oncorhynchus kisutch* | Lab | 0.7-2 g | 10-195 NTU | 30 m | Avoid turbidities > 70 NTU (acclimated in clear water 0.3 NTU); 2 choice test, and alarm reaction in some fish at >42 NTU. | Washington, USA, | Bisson and Bilby 1982 |
| 3 | Coho salmon | *Oncorhynchus kisutch* | Lab | mean, 1.7 g, 5.2 mm | 0, 20, 30 and 60 NTU sediment (0.02-0.06 mm) | 1 hr and 2 d | Alarm reaction when exposed to sudden increase to 60 NTU, and dominance hierarchies broke down and territories not defended at a gradual increase ≥30 NTU. | British Columbia, Canada | Berg and Northcote 1985 |
| 4 | Brook trout | *Salvelinus fontinalis* | Field | YOY | 60-80 mg/L |  | Sediment affected areas appeared unable to support all YOY produced. | New Brunswick, Canada | Curry and MacNeill 2004 |
| 5 | Steelhead trout and Chinook salmon | *Oncorhynchus mykiss*<br>*Oncorhynchus tschawytscha* | Lab | 30-65 mm | 11-265 NTU |  | Emigration of newly emerged fish increased with increasing turbidity. | Idaho, USA | Sigler et al. 1984 |
| 6 | Chinook salmon | *Oncorhynchus tschawytscha* | Field/ Exp. |  | 2 rivers; <1 NTU and 27-108 NTU |  | Predation rates higher in the clear river compared with the turbid one; therefore predation risk reduced in turbid water. | British Columbia, Canada | Gregory and Levings 1998 |

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Table 4. Effects of Suspended Sediment on Fish Behaviour.

| | Common name | Scientific name | Field/ Lab | Fish size | Concentration | Duration | Effect/Result | Location of study | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 7 | Chinook salmon | *Oncorhynchus tschawytscha* | Lab | mean approx. 80 mm | clear <1 NTU, turbid approx. 23 NTU, natural sediment (<2-25 μm) | 12 d | Fish associated with bottom clear water but randomly distributed in turbid water: therefore perceived predation risk reduced in turbid water | British Columbia, Canada | Gregory 1993 |
| 8 | Sockeye salmon | *Oncorhynchus nerka* | Lab | Fry | Turbidity simulated with Bismarch brown Y, secchi depth 20-30 cm | 2 d | Predation rate (rainbow trout 25-35 cm) reduced in turbid water. | British Columbia, Canada | Ginetz and Larkin 1976 |
| 9 | Ninespine stickleback and Golden shiner | *Pungitius pungitius*<br>*Notemigonus crysoleucas* | Lab | mean 50 mm, 0.7 g<br>mean, 72 mm, 5.4 g | 0, 15, 75 and 150 JTU | 15-20 m | Exposed at 5 and 20°C: fleeing response (i.e. alarm reaction) noted for golden shiner at ≥15 JTU at 20°C. | New Brunswick, Canada | Chiasson 1993 |
| 10 | Bluegill | *Lepomis macrochirus* | Lab | 35-40 mm | 0.3, 5, 10, 20, 52 and 91 NTU | | Reactive distance to predataor (largemouth bass) decreased with increasing turbidity (light 135 lx); perceived predation risk reduced in turbid water. | Ohio, USA | Mines and Stein 1996 |
| 11 | Creek chubs | *Semotilus atromaculatus* | Lab | 53 mm | Gradiet in tank 6.4 to 59 FTU; clay (<2 μm) | | Creek chubs preferred highly turbid (56.6 FTU) over moderately turbid water (5.8 FTU); provides visual isolation from brook trout. | Wisconsin, USA | Gradall and Swenson 1982 |
| 12 | Fathead minnows | *Pimephales promelas* | Lab | Mean approx. 40-45 mm, 1 g | control and turbid (13 NTU) | 2 d | Increased use of dangerous habits in turbid water (reduced antipredator) behaviour), therefore perceived predation risk reduced in turbid water. | Manitoba, Canada | Abrahams and Kattenfeld 1997 |

Appendix 1: Severity of Effects Table for Sediment Impacts (from Newcombe, C.P. and J.O.T. Jensen. 1996).

| Severity | Description |
|---|---|
| 0 | No behavioural effect |
| 1 | Alarm reaction |
| 2 | Abandonment of cover |
| 3 | Avoidance response |
| 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 or success; poor condition |
| 9 | Reduced growth rate; delayed hatching; reduced fish density |
| 10 | 0-20% mortality; increased predation; moderate to severe habitat degradation |
| 11 | 20-40% mortality |
| 12 | 40-60% mortality |
| 13 | 60-80% mortality |
| 14 | 80-100% mortality |

1-3: Behavioural effects

4-8: Sublethal effects

9-14: Lethal and paralethal effects

Appendix 2: British Colombia's Ambient WaterQuality Guidelines (Criteria) for Turbidity, Suspended and Benthic Sediments

## Overview Report

Prepared pursuant to Section 2(e) of the *Environment Management Act*, 1981

H. Singleton B.Sc. RPBio.

Water Management Branch
Environment and Resource Division
Ministry of Environment and Parks (now called Ministry of Water, Land and Air Protection)

Original signed by Don Fast
Assistant Deputy Minister
Environment and Lands (now called Ministry of Water, Land and Air Protection)
December 31, 1988

Updated August 7, 2001

## AQUATIC LIFE

The guidelines set here are designed to protect aquatic life in fresh, estuarine and coastal marine waters from excessive suspended sediments originating from anthropogenic sources. They are established according to the amount of suspended sediments and the turbidity of the aquatic system. Guidelines for substrate composition and for bedload transport have also been developed, which are specific to salmonid spawning and mariculture areas. As the biotic, physical and chemical conditions describing aquatic ecosystems are diverse, the recommended guidelines will need to be compared to natural background levels.

Distinct water quality guidelines for suspended sediments and turbidity are required for the protection of aquatic life during clear flow and turbid flow periods. The terms clear flow period and turbid flow period are used to describe the portion of the hydrograph when suspended sediment concentrations are low (i.e. less than 25 mg/L or less than 8 NTU) and relatively elevated (i.e., greater than or equal to 25 mg/L or greater than or equal to 8 NTU), respectively.

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. The recommended transition value (25 mg/L or 8 NTU) was selected by examining the hydrographs for a number of streams in British Columbia and is intended to provide an operational definition of clear flow conditions that can be applied consistently in the province.

## Suspended Sediments

### Clear Flow Periods

***Induced suspended sediment concentrations should not exceed background levels by more than 25 mg/L during any 24-hour period (hourly sampling preferred). For sediment inputs that last between 24 hours and 30 days (daily sampling preferred), the average suspended sediment concentration should not exceed background by more than 5 mg/L.***

The statistical reliability of the data set is improved with increased monitoring frequency. Ideally, 24 samples in 24 hours and/or 30 samples in 30 days are preferred.

### Turbid Flow Periods

***Induced suspended sediment concentrations should not exceed background levels by more than 25 mg/L at any time when background levels are between 25 and 250 mg/L. When background exceeds 250 mg/L, suspended sediments should not be increased by more than 10% of the measured background level at any one time.***

## Turbidity

### Clear Flow Periods

***Induced turbidity should not exceed background levels by more than 8 NTU during any 24-hour period (hourly sampling preferred). For sediment inputs that last between 24 hours and 30 days (daily sampling preferred) the mean turbidity should not exceed background by more than 2 NTU.***

The statistical reliability of the data set is improved with increased monitoring frequency. Ideally, 24 samples in 24 hours and/or 30 samples in 30 days are preferred.

### Turbid Flow Periods

***Induced turbidity should not exceed background levels by more than 8 NTU at any time when background turbidity is between 8 and 80 NTU. When background exceeds 80 NTU, turbidity should not be increased by more than 10% of the measured background level at any one time.***

### Streambed Substrate Composition

***The composition of fine sediment in streambed substrates (i.e., percent fines) should not exceed 10% having a diameter of less than 2.00 mm, 19% having a diameter of less than 3.00 mm, and 25% having a diameter of less than 6.35 mm at potential salmonid spawning sites. The geometric mean diameter and Fredle number of streambed substrates should not be less than 12.0 mm and 5.0, respectively. The minimum and 30-day average guideline for intra-gravel dissolved oxygen levels are 6.0 and 8.0 mg/L, respectively. These guidelines apply to actual and potential spawning sites in streams throughout the province.***