The Validity of Including Turbidity Criteria For Aquatic Resource Protection in Land Development Guideline (Pacific and Yukon Region)

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THE VALIDITY OF INCLUDING TURBIDITY CRITERIA FOR AQUATIC RESOURCE PROTECTION IN LAND DEVELOPMENT GUIDELINES
(PACIFIC AND YUKON REGION)

by

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PREFACE

Land Development Guidelines were first published in 1992 by the Department of Fisheries and Oceans and the BC Ministry of Environment, Lands and Parks. The objectives of the guidelines were to assist those whose works or activities could have a harmful impact on fish habitat.

One of the chapters of the 1992 Guidelines focussed on sediment and erosion control and provided advice on mitigation strategies to address potential sediment discharges from land development sites and established standards for suspended sediment concentrations in effluent streams. There is a large amount of information pertaining to the effects of sediment on aquatic systems, and excessive sediment in waters has long been recognized as a ubiquitous issue (Waters 1995; Berry et al. 2003).

Various regulatory authorities have formulated guidelines to help protect the aquatic environment from the impacts of suspended and deposited sediment. In some jurisdictions guidelines have also been developed for turbidity; as the correlation and relationship between cloudy (turbid) water and suspended sediment is inherently strong and typically significant under many circumstances.

While suspended sediment standards were incorporated into the 1992 Land Development Guidelines turbidity was not addressed. .

The increased amount of information on turbidity (and suspended sediment) that has been generated over the last 15 years prompted this review and assessment. Specifically, the review was to ascertain the validity and desirability of including turbidity as another variable to measure and control for the protection of aquatic resources from land developments. Particular emphasis was given to protection of clear-water fish which predominate in the fresh waters of BC and the Yukon and their habitats.

This report, presented without prejudice, is provided as background material to assist those who will decide on the need for a turbidity standard and turbidity monitoring and compliance in relation to land development in the Pacific and Yukon Region of Fisheries and Oceans Canada.

ABSTRACT

Birtwell, I.K., Farrell, M., and Jonsson A. 2008. The validity of including turbidity criteria for aquatic resource protection in Land Development Guidelines (Pacific and Yukon Region). Can. Manuscr. Rep. Fish. Aquat. Sci. 2852: xiii + 72 p.

The validity and appropriateness of using turbidity criteria for the protection of aquatic organisms during land development in the Pacific and Yukon Region of Fisheries and Oceans Canada was assessed by examining published and unpublished scientific, and monitoring, information.

Effects of turbid waters at different levels of biological organization were examined in the expectation of a scientifically-defensible pattern related to different trophic levels and sensitivities. It was anticipated that a graded response to turbid waters would emerge with an associated diminishing risk from individuals to populations and to systems due to resiliency and compensatory mechanisms. This premise was refuted and the potential was revealed for even low (e.g. <10 NTU) levels of turbidity to affect various levels of biological productivity and life stages of organisms, and that increasing harm is predicted with increasing duration of exposure. Accordingly, and without prohibition of turbid water discharges, it is likely that turbid waters entering fresh waters will impose some degree of risk of harm to aquatic biota.

It was concluded that turbidity was a variable that should be monitored for compliance with stipulated levels for aquatic resource protection during developments addressed by the Land Development Guidelines (DFO/MELP 1992).

The inherent strong relationship between turbidity and the concentration of suspended solids for similar sized particles (e.g. silt and clay) in effluents from settling ponds and land development sites justifies employing criteria and monitoring both for resource protection. Both variables may limit and control organisms in different ways. Circumstances should dictate whether both or one variable should be monitored (silt and clay particles contribute to turbidity and at the same time may become trapped in stream benthic communities and substrates even under high flows, and impact primary to terminal productivity).

The suspended sediment to turbidity ratio in land development run-off waters and in effluent from settling ponds at these sites typically contrasts with that in natural flowing waters and may be ten-fold greater (e.g. ratios of 1:3 and 1:0.3, respectively). Canadian resource protection criteria for turbidity are based on the ratio for natural waters.

Stipulated criteria for turbidity in effluents from land developments are suggested which are based on published information and also reflect the current application by provincial, national and international regulators. It is important to recognize that the relatively non-biodegradable nature of inorganic sediments, which contribute to turbidity, necessitate their control at source. This is important because the mixing/dilution of effluents in

receiving waters do not eliminate cumulative depositional effects of sediments and consequential effects on aquatic organisms and their habitat.

It is suggested that effluent turbidity criteria of 25 NTU and 100 NTU be adopted for dry and wet conditions respectively. Dry conditions would equate to rainfall <25 mm, and wet conditions to rainfall >25mm the day preceding monitoring.

To determine effluent quality for compliance and monitoring, samples should be taken from the effluent stream immediately prior to its discharge to the receiving environment.

It is recognized that the stipulated effluent turbidity levels would be harmful to aquatic organisms if they were exposed to them (without mixing/dilution and settlement of suspended material). This is a compromise position to permit temporary and legitimate development of land for human needs and at the same time minimize risks to the aquatic environment. Turbidity levels of approximately 100 NTU and 25 NTU are predicted to pose a significant risk of harm to biota after hours and days of exposure, respectively; hence the need to control turbidity at source.

The respective turbidity levels for dry and wet conditions are considered to be achievable through good erosion control practices and through the use of settling ponds. Furthermore, the criteria are based on the assumption of immediate effluent mixing/dilution and that the turbidity of receiving waters will not exceed Canadian national or BC provincial guidelines. The anticipated land developments within the context of this report are over weeks to months.

The duration of exposure to turbid waters will result in increasing harm and hence increasing risk to aquatic organisms. Scenarios relating to the discharge of turbid water under dry and wet conditions have been identified based on analyses by Newcombe (2003). Risk is incorporated within this approach and, depending on the turbidity level and duration of exposure conditions, range from “ideal” to “severely impaired”.

	DRY CONDITIONS		**WET CONDITIONS**	
Effluent dilution factor	Receiving water plus effluent (25 NTU)	Approx. range in time: - increasing and significant impairment*	Receiving water plus effluent (100 NTU)	Approx. range in time: - increasing and significant impairment*
1x	25	1wk - >1 y	100	7 h - <2 wk
2x	12.5	2 wk - >1 y	50	1 d - <8 wk
3x	8	7 wk - > 1 y	33	2 d - <5 mo
5x	5	>11 mo - NA	20	1wk - >1 y
10x	2.5	NA	10	2 wk - >1 y

* Prediction of “severe impairment” with longer duration of exposure, and “slight impairment” to “ideal conditions” with lesser duration of exposure

Modification of scenarios could occur based upon predicted risks from turbid waters at the discretion of regulatory authorities, but at no time should Canadian national or BC provincial guidelines for receiving waters be exceeded. That is, a) under dry (clear-flow) conditions a maximum increase of 8 NTU for <24h, and 2 NTU for longer exposures, and b) under wet (turbid-flow) conditions a maximum increase of 8 NTU when background levels >8-<80 NTU, and ≤10% increase when background levels >80 NTU. Compliance monitoring would initially be required at 3 locations: upstream (true baseline control), the effluent discharge, and immediately downstream in receiving waters.

The primary objective of erosion and effluent control measures is to minimize the effects of turbidity to the most practical extent possible and thereby help to maintain, and not diminish, the quality of the receiving water habitat which facilitates the perpetuation of healthy biological communities.

RÉSUMÉ

Birtwell, I.K., Farrell, M., and Jonsson A. 2008. The validity of including turbidity criteria for aquatic resource protection in Land Development Guidelines (Pacific and Yukon Region). Can. Manuscr. Rep. Fish. Aquat. Sci. 2852: xiii + 72 p.

On a évalué la pertinence de l’utilisation de normes de turbidité pour la protection des organismes aquatiques durant les travaux d’aménagement de terrains dans la Région du Pacifique et du Yukon de Pêches et Océans Canada en examinant l’information, publiée ou inédite, de nature scientifique ou relative à la surveillance.

On a examiné les effets des eaux turbides à différents niveaux d’organisation biologique dans le but d’établir une caractérisation scientifiquement défendable concernant les différents niveaux trophiques et sensibilités. On s’attendait à voir se développer une réponse graduée aux eaux turbides dans laquelle il y aurait eu diminution du risque des individus aux populations et aux systèmes en raison d’une résilience et de mécanismes compensatoires. Cette hypothèse a été démentie; en effet, il est apparu que même de faibles niveaux de turbidité (p. ex. < 10 UTN) pouvaient affecter divers échelons de la productivité biologique et stades de vie des organismes, et que des dommages accrus se trouvent prédits quand la durée d’exposition augmente. Par conséquent, en l’absence d’interdiction frappant les rejets d’eaux turbides, il est probable que les eaux turbides entrant dans les eaux douces présenteraient un certain risque pour le biote aquatique.

On en a conclu que la turbidité constitue une variable qui devrait être surveillée pour veiller à ce qu’elle ne dépasse pas les niveaux ici proposés pour la protection des ressources aquatiques durant les travaux d’aménagement traités dans le document « Land Development Guidelines for the Protection of Aquatic Habitat » (DFO/MELP, 1992).

La forte relation inhérente entre la turbidité et la concentration de solides en suspension pour les particules de tailles similaires (p. ex. limon et argile) dans les effluents des bassins de décantation et des sites d’aménagement justifie l’emploi de normes et la surveillance tant de la turbidité que de la concentration de solides en suspension pour assurer la protection des ressources. Ces deux variables peuvent avoir des impacts sur les organismes de différentes façons. On devrait se fonder sur les circonstances pour décider si l’on doit surveiller les deux variables ou un seule d’entre elles (les particules de limon et d’argile contribuent à la turbidité et peuvent aussi être piégées dans les substrats et les communautés benthiques des cours d’eau même sous de forts écoulements, d’où des répercussions éventuelles sur la productivité des écosystèmes, depuis la productivité primaire jusqu’à la productivité terminale).

Le ratio entre les sédiments en suspension et la turbidité pour les eaux de ruissellement des sites d’aménagement de terrains et pour les effluents des bassins de décantation à ces sites, habituellement plus élevé que celui mesuré pour les eaux naturelles, peut être jusqu’à dix fois supérieur à ce dernier (ratios de 1:3 et de 1:0,3, respectivement). Les normes canadiennes de turbidité pour la protection des ressources sont fondées sur le ratio pour les eaux naturelles.

On propose ici des normes pour la turbidité des effluents des sites d'aménagement de terrains qui sont fondées sur de l'information publiée et qui vont dans le sens de celles actuellement appliquées par les responsables des réglementations provinciale, nationale et d'autres pays. Il est important de souligner que les sédiments inorganiques, contribuant à la turbidité, doivent être contrôlés à la source du fait qu'ils sont relativement non biodégradables. Cela est important parce que malgré le mélange et la dilution des effluents dans les eaux réceptrices, il y a dépôt cumulatif des sédiments, ce qui entraîne des effets sur les organismes aquatiques et leur habitat.

On propose d'adopter les normes de turbidité suivantes pour les effluents : 25 UTN pour les conditions de temps sec, et 100 UTN pour les conditions de temps humide. Par temps sec et temps humide, on entend que le jour précédant la surveillance, les précipitations ont été de moins de moins de 25 mm ou de plus de 25 mm, respectivement.

Pour déterminer la qualité des effluents aux fins de surveillance et d'établissement de la conformité, les échantillons devraient être prélevés dans les effluents juste avant leur entrée dans le milieu récepteur.

On sait que les niveaux de turbidité des effluents proposés ici seraient dommageables pour les organismes aquatiques s'ils y étaient exposés (sans mélange/dilution ni dépôt des matières en suspension). Ces niveaux constituent un compromis visant à permettre des travaux d'aménagement qui sont temporaires et légitimes pour répondre à des besoins humains, tout en réduisant au minimum les risques pour l'environnement aquatique. Il est prédit que des niveaux de turbidité d'environ 100 UTN et 25 UTN présentent un risque important (détérioration importante des conditions) pour le biote après une exposition se comptant en heures ou en jours, respectivement, d'où la nécessité de contrôler la turbidité à la source.

Il paraît possible de respecter les niveaux de turbidité pour les conditions de temps sec et de temps humide si on utilise de bonnes pratiques de lutte contre l'érosion ainsi que des bassins de décantation. De plus, les normes sont basées sur l'hypothèse que le mélange ou la dilution des effluents est immédiat et que la turbidité des eaux réceptrices ne dépassera pas les valeurs des recommandations nationales canadiennes ni celles des recommandations provinciales de la Colombie-Britannique. Or, les travaux d'aménagement considérés dans le cadre du présent rapport s'étendent sur des semaines ou des mois.

Plus la période d'exposition aux eaux turbides est longue, plus les dommages et donc les risques pour les organismes aquatiques sont importants. À partir des analyses de Newcombe (2003), on a établi des scénarios concernant les rejets d'eaux turbides dans les conditions de temps sec et de temps humide. Cette approche prend en compte le risque et, selon le niveau de turbidité et la durée de l'exposition, les conditions varient d'« idéales » à « gravement détériorées ».

	CONDITIONS DE TEMPS SEC		**CONDITIONS DE TEMPS HUMIDE**	
Facteur de dilution des effluents	Eaux réceptrices plus effluents (25 UTN)	Durée approximative d’exposition : détérioration importante et croissante*	Eaux réceptrices plus effluents (100 UTN)	Période approximative d’exposition : détérioration importante et croissante*
1x	25	1 sem. - >1 an	100	7 h - <2 sem.
2x	12,5	2 sem. - >1 an	50	1 j - <8 sem.
3x	8	7 sem. - > 1 an	33	2 j - <5 mois
5x	5	> 11 mois – s. o.	20	1 sem. - >1 an
10x	2,5	s. o.	10	2 sem. - >1 an

* Il est prédit une « détérioration grave » sous des durées d’exposition plus longues, et une « détérioration légère » ou des « conditions idéales » sous des durées d’exposition plus courtes.

Les autorités de réglementation pourraient modifier les scénarios sur la base de leur évaluation des risques que peuvent présenter les eaux turbides, mais en aucun cas les valeurs des recommandations nationales canadiennes ou des recommandations provinciales de la Colombie-Britannique pour les eaux réceptrices ne devraient être dépassées. Les valeurs à ne pas dépasser sont les suivantes : a) dans des conditions de temps sec (eaux claires), accroissement maximum de 8 UTN pour <24 h, et de 2 UTN pour de plus longues expositions; b) dans des conditions de temps humide (eaux turbides), accroissement maximum de 8 UTN quand les niveaux de fond sont > 8 - < 80 UTN, et accroissement ≤ 10 % quand les niveaux de fond sont > 80 UTN. La surveillance de la conformité devrait initialement être effectuée à trois endroits : en amont (valeur de référence), dans l’effluent à son point de rejet, et immédiatement en aval dans les eaux réceptrices.

L’objectif premier des mesures de contrôle de l’érosion et des effluents est de réduire le plus possible les effets de la turbidité pour empêcher la détérioration de la qualité du milieu aquatique récepteur, de façon à assurer le maintien de communautés biologiques saines.

INTRODUCTION

Since the Land Development Guidelines were published (Department of Fisheries and Oceans; BC Ministry of Environment, Lands and Parks (DFO/MELP) 1992) advances have occurred in the understanding of effects of both suspended sediment and turbidity on aquatic resources. Among these advances was the identification of increasing severity of effects with increasing exposure periods (dose and time-dependent effects), and refined knowledge of the effects of turbidity and suspended sediment on, for example, the growth, survival, behaviour, biochemistry and physiology of fish. Co-incidentally there has been increasing knowledge of aquatic systems and ecology, and demonstrable successes due to the habitat provisions of the *Fisheries Act*. Collectively these changes promote the need for a revision of the Land Development Guidelines. Criteria, guidelines and standards have each been used in regulatory documents. In this document, and for simplicity, the word criteria will be used to represent each.

The specific objectives of this report were to assess the appropriateness, feasibility and practicality of establishing effluent turbidity criteria for discharges from settling ponds and other control measures associated with land development.

The basis for this assessment relied upon scientific literature and an expectation that it would be possible to justify or refute the use of turbidity criteria to protect aquatic organisms (especially clear-water fish) and their receiving water habitat. Practical considerations would then be assessed in relation to meeting the proposed criteria. With justification, these criteria would then be incorporated into revised Land Development Guidelines (DFO/MELP) for BC and the Pacific and Yukon Region of Fisheries and Oceans Canada. Thus protection of aquatic resources would be facilitated through monitoring, and compliance with the selected criteria.

METHODOLOGY

LITERATURE

The chosen approach included an assessment of literature related to effects at different levels of biological organization in the expectation of the emergence of scientifically-defensible deductions that would indicate the effects of turbid waters.

The assessed literature was from peer reviewed scientific studies, and related unpublished information pertaining to the effects of turbid water on fish and fish habitat. Monitoring data from land use developments also provided useful information.

It was expected that the effects of turbid waters on certain aquatic species would be more specific and limiting than on assemblages of organisms and ecosystems whose resiliency through compensatory mechanisms may result in the accommodation of turbid conditions to various degrees. Also it was anticipated that a graded response to turbid waters would emerge with the associated risks to individuals, to populations, and to systems.

There is an inordinate amount of scientific information on the effects of turbid conditions and related suspensions of sediment and, accordingly, it was necessary to be selective during this assessment. Reliance was placed on review articles and those directly associated with the problem of determining the advisability of using turbidity as a water quality criterion for the protection of aquatic resources (e.g. Newcombe 2003; Rosetta 2005). Relatively recent research by Fisheries and Oceans Canada on effects of turbid waters on juvenile chinook salmon (0-1270 NTU; 0-1000 $mg \cdot L^{-1}$) and coho salmon (5.8 NTU; 2.7-3.0 $mg \cdot L^{-1}$) over exposure periods from 3 to 9 weeks and 6 months respectively, also added pertinent information (refer to Birtwell et al. 2003; Birtwell and Korstrom 2002; Korstrom and Birtwell 2006; Appendix 1).

It was essential to focus at least part of the assessment on the more recent information, not only because of the increased data base which relates to the effects of turbidity, but most importantly because relatively low turbidity levels were shown to have effects on biota. Some of the earlier literature on the effects of suspended sediments and turbidity has particular value. In these studies, significantly close correlations occurred between both variables to the extent that under most circumstances neither could be considered as independent from each other despite one variable likely being of more influence than the other (e.g. McLeay et al. 1983, 1984, and 1987, - studies that included the feeding and growth of fish).

Past reviews on the effects of turbidity and suspended sediment contain much relevant information, and attention from a fish perspective has tended to address the more obvious effects that the latter variable evokes at various levels of biological organization (refer to EIFAC (European Inland Fisheries Advisory Committee) 1964; Lloyd 1985, 1987; Lloyd et al. 1987; Newcombe and MacDonald 1991; Ryan 1991; Waters 1995; Anderson et al.1996; Newcombe and Jensen 1996; Caux et al. 1997; Birtwell 1999; Henley et al. 2000; Bash et al. 2001; Berry et al. 2003; Newcombe 2003; Rosetta 2005; Robertson et al. 2006).

The opinion and discussion presented below is to provide for reasoning and understanding and assist judgments and decisions when addressing the issue of turbidity and effects on biota and habitat.

The document is not exhaustive in its review and has relied on the critical reviews of others as well as deductions from research studies and other published information.

LAND DEVELOPMENT GUIDELINES

Current requirements stipulated in the Land Development Guidelines (DFO/MELP 1992) relate to the management of suspended sediment concentrations. There are stipulated restrictions:

SITE RUNOFF WATER QUALITY REQUIREMENTS (1992)

"Runoff water from the development site should contain less than 25 mg/litre of suspended solids (or non-filterable residue, NFR) above the back-ground suspended solids levels of the receiving waters during normal dry weather operation and less than 75 mg/litre of suspended solids above background levels during design storm events. However, where spawning areas are situated in the receiving waters, the storm runoff water discharged should not, at any time, increase suspended solids levels above background suspended solids levels in the receiving waters.

Background suspended solids levels are the natural in stream suspended solids or NFR *(non-filterable residue)* levels measured upstream of the point of discharge in the watercourse" (Fisheries and Oceans Canada 1992)**.**

Compliance and recent criteria development

Compliance with the suspended sediment criteria in the Land Development Guidelines (DFO/MELP 1992) has sometimes been difficult to obtain (personal communication; M. Farrell, A. Jonsson, C. Salomi, and A. Magnan, Fisheries and Oceans Canada, Pacific and Yukon Region) especially for discharges from settling ponds which typically contain very small-sized particles which settle slowly and thereby prolong turbid conditions in receiving waters. This latter comment does not imply that all settling ponds discharge highly turbid water, but it does infer that the settling of fine material is problematic and that settling pond design and operation are critical factors in the management of turbid waters that are discharged from them.

Since the Land Development Guidelines (DFO/MELP 1992) were published there has been a greater awareness of the importance of the duration of exposure to suspended sediment and turbid conditions in the expression of effects on aquatic organisms. This awareness is based on the analyses of published information and expert opinion, and especially that which resulted in the derivation of models that predict an increasing severity of effect with increasing exposure to suspended sediment and turbid waters (e.g. Anderson et al. 1996; Newcombe and Jensen, 1996; Caux et al. 1997; CCME 2002; Newcombe 2003; Rosetta 2005; Quilty and Fleming 2005). Thus the responses of organisms to these variables were found to be dose dependent, with obvious implications to the application of criteria for resource protection; the use of a single criterion being less appropriate than the application of ranges of acceptable levels over time. While the latter approach is practically more difficult to apply, it is ecologically more meaningful, especially when related to ambient conditions (e.g. Caux et al. 1997 re BC Guidelines (BCMELP 1998); CCME (2002) re Canadian criteria; Rosetta (2005) re State of Oregon revised criteria).

Notwithstanding the desirability of managers to apply the best measures for resource protection and use precautionary principles, practical considerations often dictate the adoption of risk-based approaches, the success of which is dependent on available knowledge and the vagaries of the specific circumstances being addressed. The following components of this report attempt to address both approaches.

TURBIDITY, WATER CLARITY, AND RELATED ISSUES

TURBIDITY AND WATER CLARITY

The measurement of water clarity and turbidity has been described by, for example, Lloyd (1985, 1987), Davies-Colley and Smith (2001), Newcombe (2003), and Rosetta (2005).

Turbidity has been used to describe the cloudiness of water. It is a variable that relates to water clarity. According to Horpilla and Liljendahl-Nerminen (2005) a clay caused turbidity value of 5 NTU is visible as a slight cloudiness of water. Water clarity or changes therein, may have an effect on the ability of animals to perform certain functions such as feeding by using vision.

Turbidity is a concept that is associated with the “cloudiness’ of water, and the physical and chemical, and hence optical, characteristics of suspended matter which can vary within watersheds (Davies-Colley and Smith 2001). Rosetta (2005) provided a recent description of turbidity and inherent problems and concerns with its use for biological aquatic resource protection during the revision of Oregon State’s turbidity criteria.

Davies-Coley and Smith (2001) in their review of turbidity, water clarity and suspended sediment stated that turbidity is but a relative measure of the scattering of light (vs. arbitrary criteria) that has no intrinsic environmental relevance until calibrated to a “proper” scientific quantity. Davies-Colley et al. (1992) and Davies-Colley and Smith (2001) question the use of turbidity as an accurate measure of water clarity, and their preference is for the use of visual clarity determinations through the employment of such methods as Secchi or black disc visibility. They considered this approach to be more precise than the use of determinations of turbidity.

Davies-Colley and Smith (2001) considered that much of the impact of suspended sediment is related to its light attenuation which reduces visual range in water and light availability for photosynthesis. “Thus measurement of the optical attributes of suspended matter in many instances is more relevant than measurement of its mass concentration.” Lloyd (1985, 1987) stated that at the lower levels of turbidity the very close correlation and relationship with suspended matter promotes the former as an appropriate measurement to use in aquatic resource management.

These comments and opinions notwithstanding, the validation of the use of an optical measure of water clarity is emphasized because one of the most ecologically significant impacts of suspended sediment in water is an optical one, that is, reduced light transmission. Reduced visual range of “sighted animals” and reduced penetration of light for photosynthesis being the primary effects. This opinion is reinforced by the recent studies on the impacts of the smaller and slower-settling particles on fish feeding and behaviour. One cannot ignore however, that such small-sized particles, which may be deposited within water courses and under different flow end energy conditions, have the capacity to significantly and negatively impact upon fish habitat (Graham 1990; Quinn et al. 1992).

TURBIDITY AND SUSPENDED SEDIMENT

A number of studies have used turbidity as a measured variable when assessing the effects of suspended material in waters on aquatic organisms and systems, but more studies have used suspended sediment concentrations (total suspended sediment - TSS), and also addressed the ancillary effects of the deposition of sediment. Suspended solids not only alter water clarity but also change the aquatic environment especially as particles settle, thus the potential impact is on all trophic levels and habitat.

Turbidity determinations should be calibrated against other measures such as mass determination (TSS) or optical measures, depending on the area of interest, to be of most value to an assessment of effects and for monitoring. Within waters where there is a limited range of particle sizes there tends to be a close and significant correlation between the TSS and turbidity (e.g. Lloyd 1985; Lloyd et al. 1987). Under such circumstances measurement of turbidity is appropriate, and a relative index of water cloudiness and clarity can be ascertained.

Henley et al. (2000) in their “concise review” of the effects of sediment and turbidity on lotic food webs concluded that the use of NTU as a surrogate measurement of suspended sediment to predict biotic effects within watersheds is dubious. They do, however, qualify this statement and accept that turbidity could be used if correlations are obtained under different flow characteristics (thus agreeing with the comments of Lloyd (1985) and Lloyd et al. (1987) mentioned above).

Henley et al. (2000) stated that there are direct effects of sediment and turbidity at each trophic level - “mortality, reduced physiological function, and avoidance; however decreases in available food at trophic levels also result in depressed rates of growth, reproduction, and recruitment. Impacts of turbidity to aquatic organisms often seem inconsistent among watersheds and experiments, but this apparent difference is actually due to the lack of correlation between suspended sediment concentration (mg/L) and units of measure (Nephelometric Turbidity Units, NTU)”. This latter comment does not seem appropriate in light of some of the published information (e.g. Lloyd 1987) where very close correlations have been found, especially for certain size classes of sediment. However, their comments do have validity regarding macro-scale generalizations, but even here significant relationships have been determined between measures of turbidity and suspended sediment concentrations (see Lloyd 1985, 1987; Lloyd et al. 1987; Packman et al. 1999). These relationships must, for practical reasons especially, relate to the solids in suspension and accordingly only provide an approximate indication or inference of sediment movement and deposition.

Fine (small-sized particles) sediment

There are light attenuating constituents of water besides suspended particles of inorganic sediment such as the water itself and its content of humic substances (Davies-Colley and Smith 2001). However, and of necessity, those particles that are in suspension are typically small and slow-settling and of low density compared with water.

Disc shaped clay particles settle at only half that of spheres of the same volume (Davies-Colley and Smith 2001). Larger particles such as those in the sand range are brought into suspension during high energy events such as during floods but particles greater than silt size are seldom important in contributing to light attenuation in natural waters (Davies-Colley and Smith 2001). These authors also report that colloidal clay particles that are smaller than the wavelength of light and remain in suspension contribute little to the overall light attenuation in natural waters. These considerations are important when using turbidity determinations of water to imply adverse effects. While the larger size particles are well known to contribute to effects on aquatic organisms and their habitat, the impact of low concentrations of the smaller fractions and turbid conditions has received more attention over the last 20 years.

TURBIDITY AS AN INDEPENDENT VARIABLE FOR AQUATIC RESOURCE PROTECTION

The appropriateness of using turbidity as a water quality criterion (vs. suspended sediment or other measures) may be questioned because of the seeming lack of independence of turbidity from suspended solids determinations (Packman et al. 1999); with few exceptions, they are both dependent variables. However, both factors may have different effects on aquatic organisms. For example, low levels of suspended sediment *per se* may not directly affect the feeding of fish but the corresponding levels of turbidity would. There are effects that can be separated as those attributable to each factor within certain studies, and particularly so for certain size classes of suspended material that induce turbid conditions (the size and nature of the particles discharged will have a bearing on turbidity and the associated effects (refer to Servizi and Martens 1987,1991,1992; Lake and Hinch 1999). This is so for the individual organism, as well as at the ecosystem level.

Turbidity is primarily associated with particles suspended in waters. It is therefore important to recognize this association, and the effects of both which may be separate or combined.

Is it necessary to guard against elevated turbidity for the benefit of protecting the aquatic environment? The simple answer is yes, but as many responses of fish, for example, to increasing turbidity are non-linear and typically exponential or power functions especially at lower turbidity values, simple derivations of threshold levels may be difficult to obtain. Even small changes in turbidity have been shown to have very dramatic effects on the feeding of clear-water fishes, and impact stream and lake productivity similarly (e.g. Lloyd 1985).

Figure 1 (from Birtwell et al. 2005) depicts the pathway whereby turbid waters resulting from land development may affect fish production. It provides the linkage between components of systems that may be affected. As such it identifies system components that should be managed to ensure protection from turbid events and conditions.

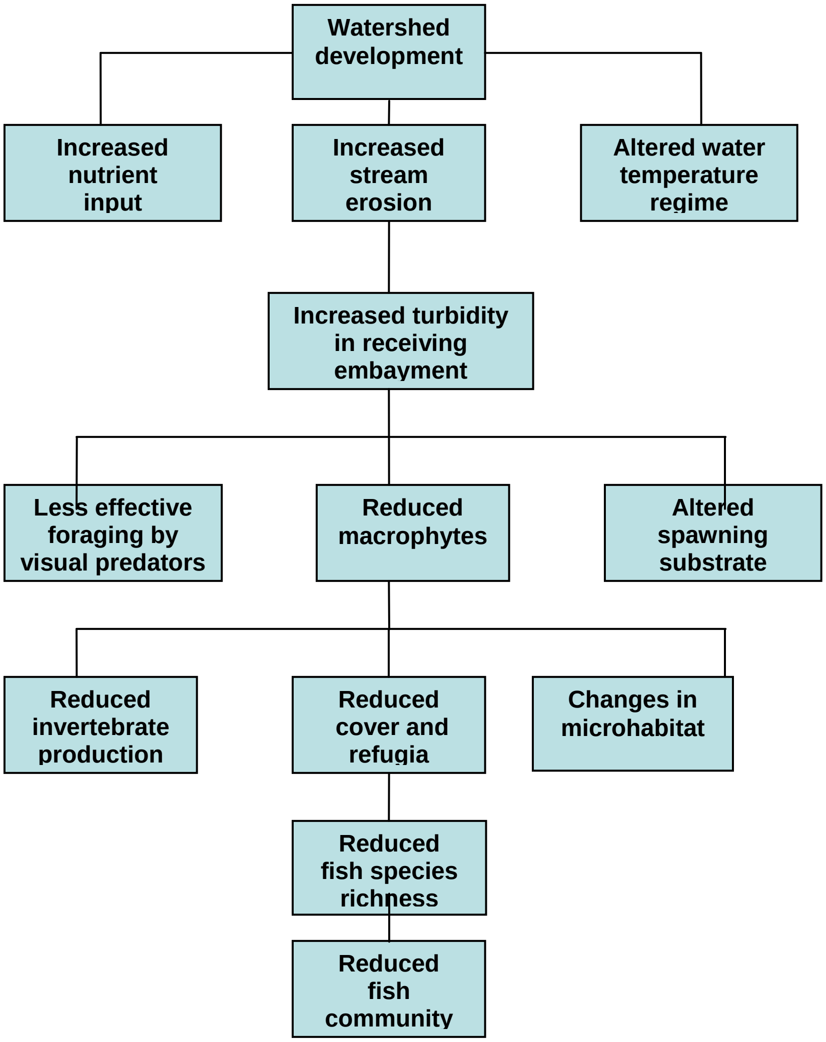

Figure 1. An example of cause-effect pathways from watershed development to fish production (adapted from Jones et al. 1996)

STUDIES RELATED TO TURBIDITY (AND SUSPENDED SEDIMENT)

SUSPENDED SEDIMENT - TURBIDITY EFFECTS

Studies that have addressed the effects of suspended material on, for example, the feeding and behaviour of fish (e.g. Gregory 1993; Gregory and Northcote 1993; McLeay et al. 1987; Liber 1992; Birtwell and Korstrom 2002) are, in reality, studies primarily pertaining to the effects of changes in water clarity (turbidity). Typically these authors have expressed much of their research findings on feeding in relation to suspended sediment concentrations and/or turbidity. It is apparent however, that as the predominant particle sizes of sediment used in these experiments were silt and clay and that there was a close correlation and relationship with turbidity; the studies in reality, and coincidentally, addressed the effects of turbidity at the lower suspended sediment levels (e.g. McLeay et al. 1987; Liber 1992; Birtwell and Korstrom 2002; Birtwell et al. 2003). Hitherto the results of these studies have not been overtly considered as those which reveal the effects of turbidity *per se*. These studies add to the increasing voluminous literature on the effects of turbidity and suspended sediment on aquatic organisms.

TURBIDITY AND THE SETTLING OF SMALL PARTICLE SIZES OF SEDIMENT

That the coarser particles of sediment may be transported within streams and settle under appropriate energy conditions is well known. Physical abrasion of stream beds has, according to Davies-Colley and Smith (2001) been suggested by some authors as an impact of suspended sediments. However, they state that such would not be expected from silt and clay-sized fractions whose impact would be “much gentler” than that of the coarser grades of material. The latter, of course, are more likely to impact the benthos through smothering, reduction in microhabitats for invertebrates, and also reduce the food quality therein, potentially resulting in an avoidance of the silted epilithon or the use of poorer quality habitat (refer to Quinn et al. 1992; Davies-Colley and Smith 2001).

Graham (1990) commented that “The observation that deposits of fine sediment are found on stream beds only in areas of slower water velocity promotes a common misunderstanding of the depositional behaviour of fine suspensoids in flowing water and a disregard for the potential for siltation effects on the biota on the surface of stones in fast flowing water”. Calculated depositional rates for clay-sized mineral particles at low suspended sediment concentration (2-5 $mg \cdot L^{-1}$) accounted for accumulation in epilithic periphyton, and accounted for up to 50% of its dry weight (a reduction of 78% in organic content compared with 48% in a reference stream where the concentration of suspended mineral particles was <1 $mg \cdot L^{-1}$ during non-freshet flows). Graham (1990) deduced that the proportional reduction in organic content would affect the food value of the periphyton thereby impacting invertebrate consumers. Furthermore, Davies-Colley and Smith (2001) suggested the suppression of primary production was probably the more important environmental effect in the New Zealand nutrient-poor streams they studied, despite them being “food-limited”: Quinn et al. (1992) found that clay-sized inorganic “suspensoids” created highly turbid conditions and that to prevent substantial impacts on invertebrate communities turbidity increases should be <5 NTU. Rosetta (2005) reviewed the results of field studies by Davies-Colley et al. (1992) and determined that periphyton productivity was correlated with turbidity, and that the 50% and 25% response level was 2.6 NTU and 1.6 NTU respectively (chronic exposure).

Contrasting, in part, with the opinions of Davies-Colley and Smith (2001), but supportive of the findings of Graham (1990) and Quinn et al. (1992), are the results from laboratory stream experiments that have used silt and clay suspensions to examine their effects on fish. In the experiments of Sigler et al. (1984), McLeay et al. (1987), Liber (1992), Birtwell and Korstrom (2002), Shaw and Richardson (2001), and Korstrom and Birtwell (2006), sediment was deposited within the stream environment by constantly adjusting stock solutions to ensure the correct turbid conditions and sediment concentrations in the experimental flow-through streams. Very small silt and clay sized fractions of inorganic sediment will settle under appropriate water velocity conditions (refer to Graham 1990), hence the embeddedness of certain streams receiving long-term discharges of turbid waters. The result is reduced invertebrate taxa (Seakem Group Ltd. 1992). The main impact of clay on invertebrates was considered to be mainly on their food supply.

TURBIDITY AND ITS EFFECTS ON AQUATIC ORGANISMS

The world-wide scientific literature that documents the effects of exposing aquatic organisms to sediment is large, however, much of the information is related to short-term studies (days) using relatively high levels of thousands to tens of thousands $mg \cdot L^{-1}$ suspended sediment and turbidity levels (refer to EIFAC 1964; Hollis et al. 1964; Lloyd et al. 1987; Newcombe and MacDonald 1991; Waters 1995; Anderson et al. 1996; Caux et al. 1997; Birtwell 1999; Henley et al. 2000; Bash et al. 2001; Newcombe 2003; Rosetta 2005; Robertson et al. 2006). There is less information, however, on the specific effects of turbidity and suspended sediment at relatively low levels (0 to tens of NTU or $mg \cdot L^{-1}$ respectively) and especially over longer periods of time (weeks and months) (e.g. McLeay et al. 1987; Sigler et al. 1984; Sigler 1990; Liber 1992; Birtwell and Korstrom 2002; Birtwell et al. 2003).

The most comprehensive reviews of the topics of turbidity and suspended sediment contain much relevant information, and attention from a fish perspective has tended to address the more obvious effects that the latter variable evokes at various levels of biological organization (refer to EIFAC (European Inland Fisheries Advisory Committee) 1964; Lloyd 1985, 1987; Lloyd et al. 1987; Newcombe and MacDonald, 1991; Ryan 1991; Waters 1995; Anderson et al.1996; Newcombe and Jensen 1996; Caux et al. 1997; Birtwell 1999; Newcombe 2003; Henley et al. 2000; Bash et al. 2001; Berry et al. 2003; Rosetta 2005; Robertson et al. 2006). The document by Rosetta (2005) is the most comprehensive current review regarding the environmental effects of turbidity and augments the previous significant reviews of Lloyd (1985, 1987).

Recent focus

Recently, sediment-related studies have been focused on the effects of turbid waters on the feeding behaviour and success of fish (e.g. Vinyard and Yuan 1996; Abrahams and Kattenfeld 1997; Rowe and Dean 1998; Reid et al. 1999; Vogel and Beauchamp 1999; Sweka and Hartman 2001; De Robertis et al. 2003); their migration and avoidance (Boubée et al. 1997; Quigley 2000); growth and physiology (Quigley 2000; Shaw and Richardson 2001; Suttle et al. 2004; Sutherland and Meyer 2007); communities (Richardson and Jowett 2002), and the effects of discharges of fine particulate matter on benthos (Davies-Colley et al. 1992; Quinn et al. 1992; Shaw and Richardson 2001).

Modelling effects of turbidity on fish

Newcombe (2003) used information from numerous recent studies, together with opinions from researchers internationally, to devise models that relate the level of "water cloudiness" to effects on fish and habitat while recognizing that duration of exposure to "cloudy water" is an important consideration.

Vulnerability of aquatic organisms to turbidity

The effects of increases in turbidity may be transient or prolonged resulting in different levels of exposure to aquatic organisms and, accordingly, potentially different levels of responses. In this context it is important to recognize that apart from obligate resident species, certain life cycle stages of free swimming salmonids may be particularly susceptible.

The effect of elevated levels of turbidity on fish is related to the life stage and its tolerance and resistance to the exposure conditions. As stated by Sutherland and Meyer (2007) survival of sensitive early life stages of fish is one of the most important determinants of inter-annual population dynamics.

Juvenile salmonids that reside in the stream environment for protracted periods before other phases in their life will likely be impacted to a greater degree than those organisms that do not have such fidelity to their habitat (an example of such fidelity for a salmonid (Arctic grayling) has been documented over many years by Buzby and Deegan (2000)). Suttle et al. (2004) stated that steelhead trout remain in natal streams for up to two years longer than do other anadromous salmonids, and are accordingly more susceptible to the effects of changes in suspended sediment levels. Similarly, one would expect that other salmonid species that reside in fresh water would be vulnerable (such as juvenile coho salmon that occupy small streams for periods of one year or more before migrating to the ocean). In more northern latitudes such life history patterns are also observed for chinook salmon juveniles that reside for up to two years or more in fresh water before migrating to sea.

Quigley (2000) observed through *in-situ* experimentation that "ecological motivation, due to the high value of tributaries, likely caused juvenile chinook to temporarily override adaptive avoidance responses and endure sub-lethally stressful conditions" to turbid waters. Also, rates of coughing observed in the exposed fish were at substantially lower levels of turbidity and suspended sediment than those that have been determined in other studies.

Thus, when determining the effects of turbidity on aquatic organisms it is important to understand that responses may change depending on life history stage and fidelity to particular habitats. It is therefore necessary to focus upon those effects that affect the more sensitive stages, and their habitat, if full protection is to be assured.

Individual and population responses and importance

Behavioural responses in relation to increases in turbidity have been reported in the review documents by, for example, Newcombe and MacDonald (1991), Anderson et al. (1996), Newcombe and Jensen (1996), Bash et al. (2001), Newcombe (2003), Rosetta (2005), and Robertson et al. (2006). Certain behaviours are no doubt adaptive and promote the survival of fish in the face of a variety of circumstances in the wild. Turbid water can elicit changes in fish behaviour. Such responses may be downstream displacement, avoidance, disruption of territoriality, seeking or avoidance of cover, lethargy, altered food seeking (visual mechanisms to chemosensory/lateral line) etc. That these behaviour modifications can occur in turbid waters may be considered transient and reversible and hence of little significance. However, this could be an erroneous deduction for in the wild fish can survive exposure to a range of circumstances, but may be physiologically and behaviourally compromised as a consequence. Without knowledge of the potential consequences of such compromises to the survival of these fish when faced with the additional rigors associated with life in the wild, it would be easy to overlook indirect mortality or “ecological death” (Kruzynski and Birtwell 1994).

The environment in which fish live is dynamic and fraught with challenges that, if met, will facilitate their survival. While the maintenance of fish health and performance are critical to the meeting of such challenges, the inherent behaviour of fish is intimately associated with these factors and their survival. Innate behaviour has ensured the survival of individual fish, and hence populations over time, and is, presumably, adaptive. In the face of anthropogenic change to the aquatic environment and the associated creation of stressful conditions for fish, behaviours that previously have ensured their survival may become maladaptive and detrimental (Birtwell and Kruzynski 1989; Schreck et al. 1997). Not only do fish have to detect anthropogenic change of consequence to their well being, but subsequent actions must be balanced in the face of other ambient stimuli, and it is the adaptive response to the latter or the lack of detection of stressful factors that may compromise their survival and well being. Examinations of the behavioural responses of fish provide data relevant to an assessment of such factors. This opinion is reinforced by Schreck et al. (1997) who state that behavioural measures may be readily interpreted within an ecological context, thereby increasing the efficacy of extrapolating laboratory results to the field. However, it is the integration of behavioural responses by fish to the multiple cues in their dynamic environment that requires resolution, if a meaningful understanding of their adaptive capacity and response(s) to various environmental conditions is to be attained.

The foregoing comments merely serve to highlight the importance of what could be perceived as trivial responses because they are potentially reversible and sub-lethal in nature. Fish survival in the wild is challenging and those which are conspicuous and/or behave abnormally typically suffer higher mortality than those with normal behavioural repertoires (refer to Mesa et al. 1994; Birtwell et al. 2001).

Fish live in a competitive environment in which their survival is related to the maintenance of health and performance. Predators tend to attack those prey that are in sub-standard condition or those that are conspicuous, hence the effect of aquatic variables, such as turbidity, that render fish more conspicuous (e.g. by a change in behaviour), or debilitate them so that they become easier to catch, are an obvious cause for concern. Reinforcing these opinions Bash et al. (2001) commented, in relation to turbid conditions, that such "changes may lead to immediate death or population decline or mortality over time". Conversely the studies of De Robertis et al. (2003) are supportive of the benefits accorded to e.g. planktivorous fish (e.g. chum salmon in sea water) whereby turbidity confers cover and thereby diminishes the risk of predation, while at the same time allowing the planktivorous fish to capture their food (e.g. refer to Gregory 1993; Gregory and Levings 1996). Coincidentally, and by comparison, the feeding success of piscivorous fish was compromised at 5-10 NTU. The often ancillary effects of turbid conditions negatively diminishing the food supply for fish under natural conditions may further confound such findings.

Gregory and Levings (1998) found that predation of juvenile chinook salmon by fish (including cutthroat trout, rainbow trout, chinook and coho salmon), was significantly less in the Fraser River, BC (turbidity 27 to 108 NTU), than predation in the clear-water Harrison River tributary (<1 NTU), and a low turbidity site (1-6 NTU). Predation by salmonids in the Fraser River remained consistently low when turbidity was approximately 27 NTU, but northern squawfish were more successful in capturing fish in the turbid waters (considered to be related to its use of other senses besides vision to locate its prey). However, despite the seeming advantages to juvenile chinook prey of occupation of proximal and contiguous turbid water conditions and reduced predation risk, 75% of the 35,000 fish captured during the study came from the clear water site where predation was 3 times greater based on predator stomach analyses. Thus the clear waters of the Harrison River were utilized more so that the Fraser River, despite any advantage the latter may provide through reduced risks of predation by piscivorous fish. While these authors deduced that naturally elevated turbidity in the Fraser River would protect underyearling salmon from excessive predation, a moderate protection here represents a moderate impact for the predatory species (Newcombe 2003). Furthermore, these results imply that despite the higher risk of predation in high clarity conditions, the clear water site provided better habitat and feeding opportunities for both predatory species and their juvenile salmon prey. One may also deduce that despite an apparent advantage of cover, the more turbid Fraser River waters provided relatively poorer quality habitat for these fish.

Avoidance, cover and territoriality:

It is important for juvenile salmonids not to move from or be evicted from preferred habitat in streams, as may occur due to the discharge of turbid waters. Their territoriality limits their ability to crowd into shrinking areas of good habitat (Suttle et al. 2004).

Rainbow trout:

Shaw and Richardson (2001) recorded behavioural changes in rainbow trout exposed to pulses of turbid water (23 NTU) in experimental streams. The fish were "moving between cover objects and feeding areas more frequently and were exposed to potential predators for a longer duration than control fish". Barrett et al. (1992) reported a lack of avoidance responses (indicative of stress) in rainbow trout in waters with a turbidity of 30 NTU.

Arctic grayling:

Arctic grayling were displayed downstream in turbid water >120 FTU, in laboratory streams (McLeay et al. 1987) and avoided turbid waters in streams receiving placer mine effluents (Birtwell et al. 1984).

Coho salmon:

Sigler et al. (1984) found downstream displacement of steelhead trout and coho salmon fry in artificial streams receiving suspensions of clay with turbidity values as low as 25 NTU. No fish were found in waters with turbidity of 167 NTU or higher, but were found at 57-77 NTU.

Servizi and Martens (1992) estimated the avoidance threshold of juvenile coho salmon to turbid waters was 37 NTU.

Berg (1982) determined that the movement of juvenile coho salmon occurred during pulses of turbid waters at 60 NTU but the fish returned at 20 NTU. The concomitant loss of territory was considered to potentially decrease growth and feeding rates and mortality in nature (Berg and Northcote 1985).

Bisson and Bilby (1982) concluded that juvenile coho salmon did not prefer water with turbidity of 10-20 NTU over clearer water conditions (even if they had been acclimated to 2-15 NTU waters).

The response of juvenile coho salmon to seek cover at the Capilano Salmon Hatchery during a 6.5 month exposure to waters with a mean turbidity of almost 6 NTU was sequentially assessed during this time (Birtwell et al. 2003). In contrast to the results with sediment/turbidity-stressed fish (Korstrom and Birtwell 2006), there was no indication of an impairment of cover-seeking behaviour that could be attributable to prior exposure to highly stressful conditions. In all trials the fish generally, and consistently, moved rapidly to cover (< 3 s).

Chinook salmon:

Juvenile chinook salmon were displaced and distributed in downstream sections of artificial streams receiving suspended sediment levels >38 NTU (76 $mg \cdot L^{-1}$; Liber 1992).

Quigley (2000) carried out experiments in the field and examined a number of responses of juvenile chinook salmon to turbid conditions. At 5-min pulses:5-min recovery periods over 1.5 h and suspended sediment concentrations of 368 $mg \cdot L^{-1}$ (equivalent turbidity 122 NTU), he recorded avoidance responses and movements up to 8 fold different than normal. Also coughing occurred at sediment/turbidity levels much lower than previously documented. Quigley (2000) deduced that ecological factors temporarily overrode adaptive avoidance responses and the fish endured sub-lethally stressful conditions with increased vulnerability.

Previously unexposed fish showed a distinct (80%) preference for clear water (<4 NTU), generally avoiding all waters with a turbidity >8 NTU (Liber 1992). There was no avoidance to waters at <340 NTU by test fish previously exposed for 6 weeks to turbid waters (Liber 1992).

Experiments carried out by Fisheries and Oceans Canada (e.g. Korstrom and Birtwell 2006) assessed the effects of exposure to highly turbid conditions (clay/silt; 48h, 50,000 NTU) on the behaviour and performance of juvenile chinook salmon by using a response to cover test. The responses of fish to seek cover, and especially once frightened, is an adaptive behaviour that caters to their survival (Sigismondi and Weber 1988). The rapidity of the response is decreased if the fish is performing sub-optimally and, therefore, may be used as a measure of performance (fish that behave abnormally or are conspicuous tend to be consumed in preference to those behaving "normally" (Coutant et al. 1979)).

The results of the research by Birtwell and Korstrom (Fisheries and Oceans Canada, Science Branch) are summarized in Appendix 1. They reveal that more of the turbid water-treated fish behaved abnormally. Not only did they take longer to find cover overall, but 17% more than those in the control group never went to cover. Similarly, the number of fish that did not move at all once challenged to seek cover was 16% greater than fish that behaved similarly in the control groups. It was concluded that the turbid water/suspended sediment treatment was acutely stressful to the fish and resulted in performance deficits and abnormal behaviour which would jeopardize survival in the wild. However, such effects would not necessarily be expected upon exposure to much lower turbidity, but could occur with prolonged exposure as predicted by Newcombe and Jensen (1996) and Newcombe (2003).

Recently reported studies by Young and Woodey (2007) revealed the adaptive behaviour of spawning sockeye salmon to use glacially-turbid waters (mean turbidity 7.8 NTU at the time of spawning, and continuing to decline thereafter) coincident with seasonally decreasing suspended sediment and turbidity levels.

Baker (2003) determined that avoidance threshold and responses (by banded kokopu, New Zealand) can be affected by pheromones such that turbid waters avoided at 25 NTU were not avoided until 50 NTU when the pheromones were present.

Feeding and growth:

It is to be expected that changes to an organism's ability to feed successfully (that is, to feed without undue stress or significantly elevated energy expenditure) would have ramifications to their growth which, in turn, would affect their chances of survival by rendering them more susceptible to predation (e.g. Gardner 1981). While these general comments appear valid, they are not specifically attributable to all species of fish. In this regard Sutherland and Meyer (2007) documented significant reductions (up to 15-fold) in the growth of juvenile minnows at concentrations of suspended silts and clays (100 to 500 mg·L^{-1}; turbidity 87 to 410 NTU) over 3 weeks. The authors related their findings to gill damage and respiratory impairment. This research emphasizes the importance of exposure to fine sediment at low concentrations and effects at levels much lower and over shorter exposure periods than those studies that have documented similar effects on juvenile salmonids.

As stated by Sutherland and Meyer (2007) survival of sensitive early life stages of fish is one of the most important determinants of inter-annual population dynamics. Furthermore, age and size play critical roles in survivorship with the mortality of young of the year fish being inversely proportional to size. Furthermore, Suttle et al. (2004) stated that differences in growth and survival imposed by fine sediment (all aspects thereof) could have important population level effects, and that by even modestly protecting such juveniles effective conservation may be achieved. Exposure to excessive turbidity and suspended sediment can have effects on these important survival issues. Juveniles of some species however, may derive a benefit from the occupancy of turbid waters. They gain an advantage through a reduced risk of predation by visual predators while, for example, feeding. But, at higher levels of turbidity both the fish prey and the predators are affected, aside from any effects on the food of the prey fish. The impairment of feeding and reduced growth of fish are considered to lower the chances of survival. Suttle et al. (2004) stated that declines in growth rates lower survival of salmonids and other fishes (citing Werner and Gilliam, 1984; Walters and Korman 1999). They stated that larger body size confers a higher survival of over wintering (Quinn and Peterson 1996) and smolting juvenile salmonids (Ward and Slaney 1988; Yamamoto et al. 1999).

Turbid waters have been recognized for many years for their adverse effect on the feeding of clear-water fish, but in recent years attention has been focused on the effects at the lower turbidity levels. This research has usually been carried out under laboratory conditions and only a few experiments have occurred in the field.

Rosetta (2005) provided examples of the reduction in reactive distance of fish encountering turbid conditions. For example, Asaeda et al. (2002) reported a marked reduction in the reactive distance of a planktivorous cyprinid (60% reduction from 0-15 NTU), and Barrett et al. (1992) recorded a reduction of 20% and 55% for rainbow trout in waters with turbidity between 15 and 30 NTU respectively, compared to fish in water of 4 to 6 NTU. Turbidity had a “consistent and negative effect on reactive distance but did not affect pursuit speed” (Barrett et al. 1992).

Brook trout:

Sweka and Hartman (2001) examined feeding in brook trout. They provided evidence of the link between the extra energy required to capture prey in turbid conditions and consequential reduced growth.

At 10 NTU, the lowest turbidity tested, the reactive distance of brook trout was significantly reduced (approximately 50%). As turbidity increased, and decreased the reactive distance to the prey, the brook trout were forced to expend more energy in searching for prey. Accounting for invertebrate prey drift due to turbid conditions the authors concluded that a 16-fold increase would be required at 20 NTU to compensate for the diminished feeding behaviour and opportunities. Interestingly, turbidity did not influence the probability of capture once the prey item was attacked. This result contrasts with the impairment in capture success by other salmonids as reported by Berg and Northcote (1985), McLeay et al. (1987), and Birtwell and Korstrom (2002; Appendix 1).

Sweka and Hartman (2001) noted the negative effect that active feeding has on fish growth through a reduction in net energy expenditure due to active searching for food. They deduced that there was a 62% decrease in growth rates of brook trout at 40 NTU when compared with growth in clear water: a result of the transition from drift- to active-fishing. Rosetta (2005) calculated a 50% response level for these findings to be 25 NTU.

Lake trout:

Vogel and Beauchamp (1999) determined that the reactive distance of lake trout preying on rainbow and cutthroat trout was diminished at turbidity levels <7.4 NTU).

Rainbow trout:

Shaw and Richardson (2001) recorded behavioural changes in rainbow trout exposed to pulses of turbid water (23 NTU) and suggested that foraging was not as successful or efficient as that of control fish. The growth of rainbow trout in experimental streams was negatively influenced by the duration of pulses of turbid water and the results support the model of Newcombe and Jensen (1996) and Newcombe (2003) regarding increased severity of effects with increasing duration of exposure to turbid conditions.

Between 15 and 30 NTU rainbow trout reactive distance was reduced 20% and 55% respectively (Barrett et al. 1992).

Lake char, and rainbow and cutthroat trout:

Mazur and Beauchamp (2003) examined the effects of light and low turbidity on prey detection in piscivorous salmonids. They concluded that there was a lack of effect on reactive distance between 0.08 and 0.55 NTU, but a measurable decline from 0.55 to 1.5 NTU revealing a turbidity threshold between those levels.

Arctic grayling:

Previous research (e.g. McLeay et al. 1987) showed that while Arctic grayling can survive short-term exposure to high levels of clay/silt and turbidity (thousands of NTU), at ≥120 FTU; 90 $mg \cdot L^{-1}$ (the lowest level tested above control waters at 1.1 FTU), a number of significant adaptive behaviours and functions were impaired. In particular, there was a reduction in feeding success and efficiency with increasingly turbid conditions and these, over a 6-week period, positively correlated with reduced growth.

Other studies, by Scannell (1988), revealed the importance of water clarity (turbidity) in the feeding of Arctic grayling. At 10 NTU (63 $mg \cdot L^{-1}$) it was calculated that only 10% of the Arctic grayling's food supply would be available; at 25 NTU only 3% would be available. These deductions were based on the effect that turbidity (suspended sediment) has on reducing macroinvertebrate prey density and, at the same time, decreasing the "reactive volume" of water immediately in front of the fish and in which it feeds.

Chum salmon:

The feeding of planktivorous chum salmon was not impaired at 5-10 NTU in experiments in sea water, whereas the feeding of their predators (sablefish) was (De Robertis et al. 2003).

Coho salmon:

Reid (1998), cited by Bash et al. (2001), reported that the feeding efficiency of coho salmon decreased by 45% at a turbidity of 100 NTU, but prey acquisition increased as turbidity decreased from 60 to 20 NTU. These results are comparable to those of Berg (1982), and Berg and Northcote (1985), for at 60 NTU only 35% of prey were consumed, and even at 10 NTU miss-strikes at prey occurred. Ingestion rates decreased to below 50% between 30 and 60 NTU.

Berg and Northcote (1985) noted that prey capture success by coho salmon was reduced at 20 NTU the lowest turbidity tested. This coincided with a 50% reduction in reactive distance.

Long-term exposure to turbid waters:

A reduction or cessation of feeding of juvenile coho salmon after natural exposure to elevated concentrations of suspended sediment and turbidity (21 and 26 $mg \cdot L^{-1}$; 18.2 and 23.9 NTU, on February 8 and 25 1999 respectively), were considered to have adversely affected their growth at the Capilano Salmon Hatchery North Vancouver, BC (refer to Birtwell et al. 2003). An attempt to validate such concerns over a 6.5-month period was undertaken by Birtwell et al. (2003).

It was deduced that a mean turbidity of 5.8 NTU (suspended sediment concentrations of 2.7 and 3.0 $mg \cdot L^{-1}$) from November 2001 until May 2002 did not have any measurable effect on the growth of juvenile coho salmon at the hatchery.

Over the study period the cumulative effect of exposure duration was evident, and calculated Severity of Ill Effect (SIE) values (Newcombe and Jensen 1996) encompassed levels close to 2 and <9 including 95% confidence intervals. Such a widespread range of SIE values could be manifest in behavioural (≤3), and sub-lethal (>3 - <9) responses, but not lethal effects (>9).

There was no evidence of adverse effects on the growth of fish during the 6.5 month exposure period that could be attributed to exposure of the coho salmon to suspended sediment and/or turbidity.

These results are consistent with the predictions of Newcombe and Jensen (1996), and Newcombe (2003). But, one should not place too much confidence in the use of the models in this circumstance because the measured suspended sediment concentrations and levels of turbidity were, overall, lower and outside of the data boundaries used to construct the SIE models.

C. Newcombe (personal communication; British Columbia Provincial Government, Victoria, BC) commented that any effects of the elevation in suspended sediment and turbidity on the coho salmon that may have occurred would have been minimized or mitigated by low water temperature and by the very small particle size of material in suspension. Newcombe's comments are also applicable to the other potential effects of suspended sediment and turbidity that could have occurred.

Data on the sub-lethal and behavioural effects of suspended sediment and turbidity on juvenile salmonids were typically higher than those to which the fish at the Capilano Salmon Hatchery were exposed in the winter of 2001-2002 (refer to, for example, Anderson et al. 1996; Newcombe and Jensen 1996; Caux et al. 1997; Birtwell 1999; Newcombe 2003; Robertson et al. 2006).

To our knowledge there are no strictly comparable data with respect to the exposure of juvenile salmonids to suspended sediments and turbidity with which to compare the results that were obtained at the Capilano Salmon Hatchery.

The turbidity levels that the fish were exposed to were low compared to those that have been determined to affect the feeding and growth of coho salmon and elicit other negative effects. For example, Noggle (1978) cited by Newcombe and Jensen (1996), determined that the feeding of juvenile coho salmon decreased when exposed to 25 $mg \cdot L^{-1}$ suspended sediment. At 100 $mg \cdot L^{-1}$ suspended sediment feeding on caddisfly larvae was reduced by 45%, and ceased at 300 $mg \cdot L^{-1}$. Turbidity values for silt/clay suspensions of 30, 100 and 300 $mg \cdot L^{-1}$ would result in turbidity values of 33, 130, and 390 NTU respectively, (based on McLeay et al. 1984).

Sigler et al. (1984) provided the most relevant research to that carried out at the Capilano Salmon Hatchery. They exposed juvenile coho salmon (and steelhead trout) to different levels of suspended sediment/turbidity through additions of clay to artificial channels and raceways. They determined that juvenile coho salmon had a reduced growth rate when exposed for 336 h to a turbidity level as low as 25 NTU ($NTU = 10.0 + 0.178\ mg \cdot L^{-1}$ suspended material in the water). These results are similar to those obtained by Shaw and Richardson (2001) for rainbow trout exposed to pulses of turbid water (23 NTU).

Overall, however, at the Capilano Salmon Hatchery, *where food was provided and was not limiting,* in addition to metabolic demands being low during winter conditions, elevations in turbidity were transient and mean values (< 6 NTU) were substantially lower than those that Sigler et al. (1984) determined to have an adverse effect of the growth of juvenile coho salmon (Birtwell et al. 2003). In all studies on the effects of turbid waters on salmonids growth and feeding, the effects were at levels higher than the mean value recorded in these studies.

Chinook salmon:

The reactive distance of juvenile chinook salmon was reduced in turbid waters (<18 NTU) by 50% relative to waters of <0.5 NTU (Gregory and Northcote 1993).

Between 35-150 NTU juvenile chinook salmon had the greatest foraging rates despite having a greater capture rate in the clearer waters (above 150 NTU the “visual ability of juvenile chinook becomes substantially impaired and foraging ability is reduced regardless of any concurrent gains” (Gregory and Northcote 1993). This result is considered to relate to the benefits of turbid cover (in the absence of object cover) that decreased risks of predation (avian). The premise is valid for predators that rely on sight to locate prey, but would likely be untenable for those predators that locate their prey by other means and may be adapted to, or adapt to, feeding in turbid environments (Vandenbyllaardt et al. 1991; Gregory and Levings 1996).

Fisheries and Oceans Canada initiated research relating to concerns over the effects of discharges of turbid and sediment laden waters into salmonid habitats in the Yukon. These studies included those by Liber (1992) who determined that juvenile chinook salmon grew in similarly turbid waters (4-2868 NTU) and yet their ability to feed during trials was compromised with increasing turbidity (especially so for turbid water-naïve fish). Although feeding activity was impaired in waters with turbidity values >50 NTU in trials using live prey, there was no concomitant reduction in growth over 28 d (the fish were fed a standard commercial diet and exposed to turbid water up to 2868 NTU and suspended sediment concentrations up to 3,400 $mg \cdot L^{-1}$). The reasons for the absence of reduced growth (despite an impairment of feeding) may relate to the different feeding strategies of this fish species relative to those of drift and surface-feeding Arctic grayling (see McLeay et al.1987), and the experimental protocols employed in the respective studies.

Research by Birtwell and Korstrom (refer to Appendix 1; Fisheries and Oceans Canada, West Vancouver Laboratory, West Vancouver BC) was designed to help resolve this seeming discrepancy and unexpected results of Liber (1992), and to compare with results obtained from similar studies by McLeay et al. (1987) with Arctic grayling.

The particle sizes of sediment for this research were the same as that which is discharged from a well operated settling pond (silts and clays). Furthermore, these size fractions of sediment have been recorded from active and abandoned mine sites (Pentz and Kostaschuk 1999). Here, the authors’ reported that the sediment is mainly fine-grained and likely transported primarily in suspension.

Growth of juvenile chinook salmon over 3 weeks was adversely affected by turbidity and sediment concentrations to which they were exposed (132, 455, 1270 NTU; 100, 300, and 1000 $mg \cdot L^{-1}$ respectively). Relative to control fish, those exposed to 1270 NTU grew 21% less, and those exposed to 455 and 132 NTU grew 8.1% and 1.9% less, respectively.

Feeding of juvenile chinook on surface prey was impaired in all sediment concentrations to which the fish were exposed, relative to controls in clear water. Time to capture prey was increased, and capture success and efficiency diminished substantially. These effects were greater after 9-weeks exposure than after 3-weeks exposure.

After 3-weeks exposure to 132 NTU the fish were 2.5 times less efficient in capturing prey (60.4% decrease relative to controls); in turbid waters at 1270 NTU the feeding efficiency was reduced (95.6% decrease relative to controls) by a factor of 22.8.

After 9-weeks exposure to turbid conditions at 132 NTU the fish were 8 times less efficient in capturing prey (87.5% decrease relative to controls), and those in waters with a turbidity of 1270 NTU were 60 times less efficient. Thus, relative to controls there was an 87.5%, 94.2%, and 98.3% decrease in feeding efficiency in waters with respective turbidity levels of 132 NTU, 455 NTU, and 1270 NTU.

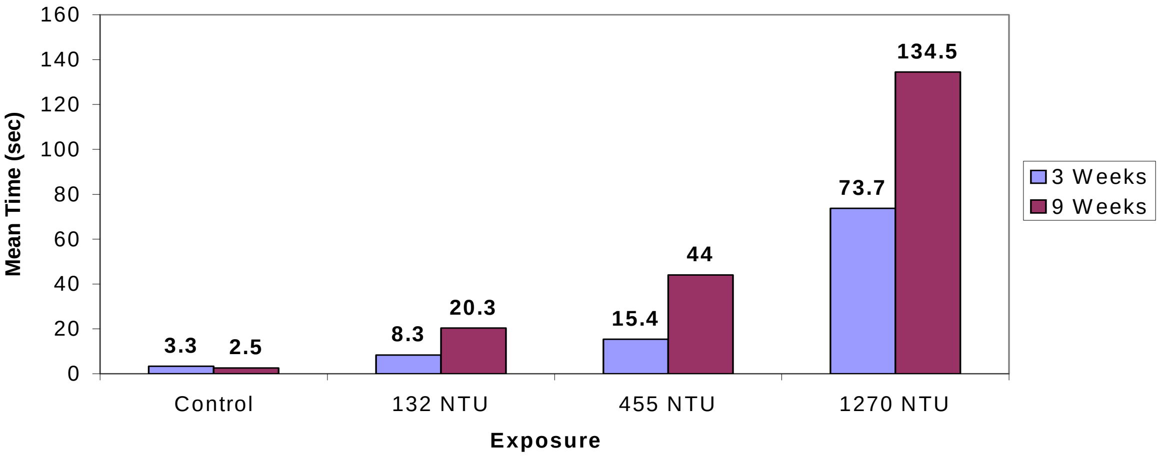

Figure 2. Mean time for 19 juvenile Chinook salmon to consume one prey item (krill) at the water surface after 3 and 9 weeks exposure, n = 90.

Feeding success on surface prey did not change significantly over a 10-day period following initial exposure of juvenile chinook to waters with a turbidity of 1270 NTU; there was no obvious accommodation by the fish to the conditions imposed, and impairment of feeding occurred (time for consumption of prey was 14.9-27 times longer than that of controls).

These studies were not carried out to research the nature of, or the threshold of, impairment of feeding responses. However, it is apparent that after 3 weeks and 9 weeks exposure to turbid conditions of 132 NTU, chinook feeding efficiency relative to controls was reduced 60.4% and 87.4% respectively. Clearly, any threshold for significant effects lay at a much lower level of turbidity.

It appears that the impairment of the feeding response may well be an exponential or a power function. There was obviously no accommodation to the turbid conditions between 3 and 9-weeks exposure. The results are consistent with an anticipated reduction in growth rate of the chinook salmon over the exposure period and in relation to sediment concentration and turbidity, and also fit the prediction of reduced feeding success and rate relative to duration of exposure (Newcombe and Jensen 1996; Newcombe 2003).

Significance of findings in relation to food limitation: That juvenile chinook salmon are able to grow in sediment laden waters is probably related to their adaptive feeding behaviours for they will feed upon benthic organisms and also forage in mid- and surface-waters. Juvenile chinook salmon are opportunistic and facultative predators, however food availability will affect growth. It is implied by the research of Birtwell and Korstrom (2002) that chinook salmon may feed and grow in turbid waters (albeit slower than controls in clear water) where food rations are not limited and also within a protected and predator-free environment.

However, the imposition of turbid waters and elevated suspended matter in streams typically results in increased drift and a reduction of benthic invertebrates (especially those favoured as prey by juvenile salmonids (refer to Waters 1995)). Hence it is likely that these prey would be scarce or limited, even over the short-term. In conditions where food is limited a reduction in the growth rate of juvenile chinook salmon (and other fish) would be expected which, in turn, would have implications to their survival.

Suttle et al. (2004) noted that decreases in steelhead growth and survival were associated with lower prey availability, aggression, and risk of injury in turbid conditions. While Shaw and Richardson (2001) noted a decrease in rainbow trout growth due to exposure to waters with a turbidity of 23 NTU. They considered the effect due to impairment of prey capture and/or increased metabolic demands during feeding as the causative factors rather than increased invertebrate drift and decreases in invertebrate family richness (similar to the deductions of Sweka and Hartman (2001) for brook trout).

The above examples of effects of turbid waters on individuals at the sub-lethal level imply potential problems for survival of smaller individuals. This is a complex issue that is discussed more fully by Birtwell et al. (2003). They report that there is a great deal of information in the literature that indicates that smaller fish are often more vulnerable to predation than larger fish, but that optimum foraging theory would predict that the predators would consume prey from which they derive the maximum energetic benefit (e.g. Martin and Olver 1980; refer to Birtwell et al. 2005).

Survival:

Juvenile salmonids may survive short-term exposure to turbid waters (NTU levels of tens to hundreds of thousands) containing very small-sized particles (e.g. McLeay et al. 1987; Servizi and Martens 1987, 1991, 1992; Liber 1992; Birtwell and Korstrom 2002; Korstrom and Birtwell 2006). But, the above-mentioned sub-lethal effects singly or in combination also threaten chances of survival.

Elevated levels of suspended sediment that directly kill fish (Arctic grayling sac-fry - see Anderson et al. 1996; Berry et al. 2003) can be as low as 25 $mg{\cdot}L^{-1}$ (the corresponding turbidity level was not recorded).

From a management perspective it is imperative to ensure that turbid waters are not acutely or chronically harmful to fish and their habitat. Because an array of responses to turbid waters may be evoked at the sub-lethal level, it is necessary to understand the ramifications in relation to risks to survival.

While growth has been used as a metabolic integrator and indicator of the effects of “stressors” on fish, behavioural considerations also participate as variables that relate to survival. Aside from fate and fortune, the maintenance of fitness and performance enhance survival opportunities in the wild.

Exposure to turbid conditions can both enhance and adversely affect some of the life stages of fish and their habitat. Rosetta (2005) provided information on the effects of turbid water from both perspectives. Suttle et al. (2004) considered that any augmentation of fine sediment will further impair the population-limiting life stage of steelhead trout. This statement is also applicable to many other salmonid species. Clearly, knowledge of all potential effects is desirable for sound and responsible management, but the paucity of information heightens levels of risk in decision making.

Integrated effects in ecosystems:

The effects of turbid waters (and other constraints) on ecosystems can only be effectively managed through the application of cause-effect information. Typically this process is more complex the larger the system being managed as depicted in Figure 3 in regards to the basic foundation of knowledge required for sound decision making in relation to ecological complexity, risk, and uncertainty.

The information presented in Figure 3 is also applicable to assessments of the effects of turbid conditions on watersheds, lakes, and streams; a topic which has received some analytical assessment (e.g. in reports by Lloyd 1985, 1987); Lloyd et al. (1987)).

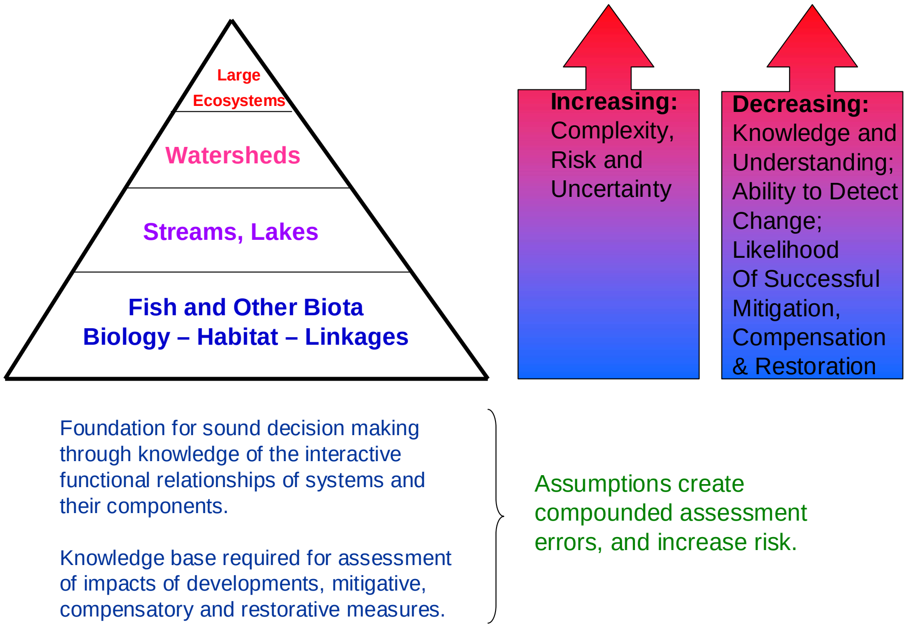

Figure 3. The difficulties associated with decision making relative to ecological complexity and available knowledge (from Birtwell et al. 2005)

Primary production - plants:

Lloyd (1985) and Lloyd et al. (1987) provided information on the effects of turbidity on primary production in streams and lakes in Alaska.

Lloyd et al. (1987) showed that the productivity of aquatic systems could be reduced by turbid conditions. Increases in turbidity reduced light penetration in lakes and streams (Lloyd 1987; Lloyd et al. 1987), which led to decreased plant biomass and hence reduced primary production, decreased abundance of fish food organisms (secondary production) and decreased production and abundance of fish. They also determined that compensation depth showed a strong inverse relationship with turbidity in 14 Alaskan lakes, and these results were comparable with those for other lakes referenced in their document. The compensation depth is sensitive to small changes in turbidity, and is directly related to primary production. This is the depth of an aquatic system at which light intensity is just sufficient to promote that level of photosynthesis equalling the respiratory, or metabolic, requirements of the phytoplankton population. It is usually considered to be the depth at which 1% of available surface light penetrates into a body of water. Net production of plant material occurs above this depth. A 5 NTU increase in turbidity was associated with an 80% reduction in euphotic volume (the volume of water above the compensation depth; surface area multiplied by the compensation depth).

In streams, as for lakes, there appears to be a close correspondence between turbidity and reduced light penetration (Van Nieuwenhuyse and LaPerriere 1986). Van Nieuwenhuyse (1983) found that light extinction was related to increased mining-induced turbidity. Based on these studies it was calculated that a turbidity of 5 NTU could decrease the primary productivity of shallow clear-water streams by about 3% to 13%, and that an increase of 25 NTU (75 mg·L^{-1} to 100 mg·L^{-1}) may decrease primary production by 13% to 50%. LaPerriere and Reynolds (1997) documented that in Birch Creek there was no measurable productivity at a turbidity of 749 NTU.

Rosetta (2005) reviewed the results of field studies by Davies-Colley et al. (1992) and determined that periphyton productivity was correlated with turbidity, and that the 50% and 25% response level for chronic exposure was 2.6 NTU and 1.6 NTU respectively.

Despite the foregoing examples wherein primary production was found to be negatively affected by turbidity, Parkhill and Gulliver (2002) concluded that photosynthetic production was not significantly different at 35 NTU when compared with that at 5-10 NTU. The reasons, it was thought, pertain to greater photosynthetic efficiency at the higher turbidity level. However, the research confirmed that small amounts sediment did indeed decrease biological activity in the streams. Similarly, in the studies of VanNieuwenhuyse and LaPerriere (1986), and Davies-Colley et al. (1992), the photosynthetic efficiencies of the epilithic algae were enhanced but not enough to keep the total community productivity from being reduced (Parkhill and Gulliver 2002). Parkhill and Gulliver (2002) considered that, contrary to much reported information that "primary producers are among the most resistant members of the lotic ecosystem to sediment deposition and increased turbidity".

Lloyd (1987) suggested that a moderate level of protection for lakes and streams would be approximately 5 NTU and 25 NTU respectively, and a higher protection level ≤5 NTU above ambient for both.

Secondary production - benthic organisms (prey for fish):

Information on the effects of turbidity on food organisms for fish is much less than that which describes the effects of suspended and deposited sediment on these organisms.

In shallow (0.2-0.4m depth) streams Quinn et al. (1992) determined significant reductions in invertebrate densities and species richness at turbidity values >7 NTU when compared with waters wherein turbidity was 0.9-4 NTU. These authors suggested that lower epilithon biomass and productivity and poor food quality was likely the reason why the invertebrate densities were reduced. Rosetta (2005) estimated a 50% response level for the reduction in invertebrate densities to be 3.7 NTU, and that 25% of species disappeared at 3 NTU and 50% at 25 NTU.

Based upon studies on a number of streams in the Yukon Territory, it was deduced that taxonomic diversity, density, and biomass of benthic macroinvertebrates was reduced in those waters subject to turbid water resulting from placer gold mining (Seakem Group Ltd., 1992). Densities of benthic invertebrates were reduced by factors of up to 118 to 204 times at sites where mean concentrations of suspended sediment exceeded a threshold (in the range of 50-175 mg·L^{-1}) relative to less impacted streams. Unfortunately there are no turbidity values to directly relate to the numbers, however, based upon the relationships provided by Lloyd et al. (1987) for Alaskan streams, these values of suspended sediment could equate to turbidity levels of about 12-73 NTU (or 40-170 NTU depending on relationships chosen for different streams - the latter encompassing natural and mined streams, whereas the former was for state-wide analyses, or using the information from the monitoring of placer mined streams in New Zealand (Davies–Colley et al. 1992), 30-105 NTU). These derived turbidity values serve to illustrate the need for deriving turbidity - suspended sediment relationships if both variables are to be used to relate to their effects on biota.

Seakem Group Ltd., (1992) concluded that in areas with high suspended sediment concentrations, the suspended sediment threshold for major effects appeared to be in the range of 25 to 100 $mg{\cdot}L^{-1}$ (estimated to be between a minimum of 6 and maximum of 106 NTU). Reduced taxonomic diversity was also documented in the heavily-sedimented locations. This result supports the findings of other researchers who have examined the effects of elevated levels of sediment and turbid waters due to land disturbance through placer mining operations on aquatic organisms (Mathers et al. 1981; LaPerriere et al. 1983; Soroka and McKenzie-Grieve 1984; Wagener and LaPerriere 1985; Weber 1986).

Poor (biologically impaired) conditions occurred for invertebrates in small streams in Oregon at turbidity levels of 10 NTU (Rosetta 2005).

Lloyd (1985), and Lloyd et al. (1987), assessed the effects of turbid conditions on lake productivity and showed that turbid lakes (approximately >5 NTU) had zooplankton densities that were 5% of those in clear water lakes. In addition, they found that zooplankton density diminished with decreasing compensation depth. Of eight glacially turbid lakes they examined, none had populations of *Cladocera*, a group of highly favoured food organisms of juvenile salmonids.

Fish:

Lloyd et al. (1987) assessed the production of fish from different lakes and determined that the yield of juvenile sockeye salmon was related to the magnitude of change in the euphotic volume, caused in some cases by increased turbidity, and the resultant decrease in primary and secondary production. Other references, cited by these authors, substantiate the relationship between turbidity and biological productivity.

Seakem Group Ltd. (1992), provided information in relation to Yukon waterways and Bash et al. (2001) and Rosetta (2005) provide an analysis of the information on turbidity and macro-scale effects. Integrative effects studies reveal the effects of not only turbid conditions on aquatic organisms but also of suspended and deposited sediment. The research of Sigler et al. (1984) and Suttle et al. (2004) provide examples in relation to the effects on fish.

Fish population and biomass studies in Yukon streams provided evidence of the limiting effect that suspended sediments and turbid conditions may have on the capacity of Arctic grayling and juvenile chinook salmon rearing habitat to support these fish.

Non-placer mined streams (Moose, Stoney, and Flat creeks) with turbidity values ranging from 22-23 NTU supported a standing stock of fish that was 40 times greater than placer-affected Clear Creek (440-465 NTU (approximately equivalent to 500 $mg \cdot L^{-1}$). The differences appear attributable to variables affected by placer mining (turbidity/sediment load, presence/absence of pools and cover). Substrate composition, water depth and velocity, and stream size were generally comparable at all sites. Those waters that had seasonal suspended sediment concentrations in excess of 50 $mg \cdot L^{-1}$ did not support "significant" numbers of under-yearling Arctic grayling or juvenile chinook salmon. In Clear Creek, the clay load alone provided an average turbidity of approximately 250 NTU (suspended sediment concentration of 285 $mg \cdot L^{-1}$) over the placer mining sluicing season (Seakem Group Ltd. 1992).

From the results of their field studies, Seakem Group Ltd., (1992) concluded the threshold for direct and indirect effects of sediment from placer mining on juvenile Arctic grayling and juvenile chinook salmon was "<75 mg/L to 130 mg/L" (estimated to range between <38-65 NTU based on Liber (1992), and <100-170 NTU based on McLeay et al. 1984).

Large glacial rivers with substantial flows of groundwater are essential to fish year round (Reynolds 1997), and while these rivers tend to be of higher turbidity in June and July (> 30 NTU) the clarity of water improves through the fall and winter; levels about10 NTU have been recorded in October (Reynolds 1997). Declining turbidity and suspended sediment levels are associated with increased fish use and sockeye salmon have been found to spawn in the rivers. This is, seemingly, an adaptive response to seasonal turbidity cycles "reducing the exposure of developing embryos to the adverse effects of fine sediments (Chapman 1988)" (Young and Woodey 2007).

Spawning sockeye salmon occurred in turbid waters in Alaska at the time of decreasing temperature, suspended sediment and turbidity levels (Young and Woodey 2007). These researchers radio-tagged salmon and found that 66% of fish spawned in waters with a turbidity level <14.2 NTU (median 2.1 NTU and a minimum of 0.3NTU in clear waters; median 7.8 NTU and a maximum of 14.2 NTU in turbid habitats, at the time of spawning). Young and Woodey (2007) suggested that this spawning behaviour was likely an adaptive response to seasonal turbidity cycles. Fish spawning later in the turbid waters would be "reducing the exposure of developing embryos to the adverse effects of fine sediments" and increasing "fitness". These authors also reported on the use of up-welling groundwater springs by spawning salmon in cold glacial systems, the flows being sufficient to remove fine sediments from spawning substrates and also produce a relatively warm incubation environment in winter.

Duration of exposure to turbid conditions

Information in Table 1 shows the relationship between duration of exposure to turbid waters and the predicted effects. The modelled adverse turbidity level effects on clear-water fish with respect to duration of exposure were calculated from the data of Newcombe (2003), and presented by Rosetta (2005). The use of turbidity values ≤5 NTU in such a model is questionable, depending on application, based on the results of studies by Birtwell et al.

(2003) who examined juvenile coho salmon in a protected hatchery environment over winter and in similarly turbid waters.

Table 1. Turbidity levels (NTU) at or above which adverse effects are estimated to occur (Rosetta 2005).

Duration	**Slight impairment** [behavioural effects]	**Significant effects** [growth and habitat]	**Severe impairment** [habitat alienation]
1 h	38	160	
2 h	28	120	
3 h	23	100	
8 h	15	65	710
1 d	10	39	440
5 d	5	19	215
3 wk	3	10	115
>10 mo		3	35

Rosetta (2005) commented that there is good qualitative agreement between the model results of Newcombe (2003) and the "threshold" between severely impaired and poor water quality conditions for fish at 25 NTU (declines starting around 10 NTU for some Oregon streams). This result, relative to the model, is also supported by the research of Sweka and Hartman (2001), Shaw and Richardson (2001), and Birtwell and Korstrom (2002), for brook trout, rainbow trout and juvenile chinook salmon, respectively.

Rosetta's (2005) review revealed that even low levels of turbidity will harm aquatic life, and particularly so over time (refer to Table 2).

Table 2. Turbidity levels at and above which significant turbidity effects are estimated to take place for aquatic life relative to duration of exposure (based on Newcombe's (2003) Impact Assessment Model for Clear Water Fish).

Turbidity (NTU)	**Duration**
3	10.5 months (long duration)
10	3 weeks
120	2 hours (short duration)

Ranges in turbidity that impact aquatic organisms

The data presented in Tables 3 and 4 indicate the ranges in turbidity that have been determined to impact aquatic organisms.

Table 3. Overview of turbidity levels (NTU) and responses that may lead to adverse effects to aquatic life in flowing waters (adapted from Rosetta 2005).

Turbidity (NTU)	**Selected organism response**
<3 – 25	Primary productivity: dependent on water depth/color/nutrients. (for 0.5 m water depth; shallower water: less effect; deeper water: more effect)
<4	Invertebrate densities, dependent on primary production /allochthonous inputs
≤10	Fish reactive distance (visible range is decreased by approximately one-half, with potential change to active feeding strategy)
10 – 20	Fish foraging/feeding strategy (brook trout)
<22	Coho salmon growth rate (significant decrease at 22 NTU, the lowest level tested above the control (0 NTU)
<38	Steelhead trout growth rate (significant decrease at 38 NTU, the lowest level tested above the control (0 NTU)
70-100	Coho salmon avoidance (significant avoidance at 70 and 100 NTU compared to controls ~0 NTU, and for similar test fish acclimated to <0.3 and 2-15 NTU, respectively)

Table 4. Overview of turbidity levels (NTU) and responses that may lead to adverse effects to aquatic life in lakes (adapted from Rosetta 2005).

Turbidity (NTU)	**Aquatic life**
<5	Primary productivity
<5	Zooplankton densities
≤10	Fish reactive distance
10 - 20	Fish foraging
<5	Smolt production

General conclusions regarding the effects of turbid water

The initial expectation that the resiliency of ecosystems would perhaps mediate the responses of aquatic organisms to turbid conditions is not immediately obvious from the results of research studies examined. The foregoing comments related to a diversity of studies and synopses reveal that turbid waters affect all trophic levels comprising aquatic communities. The effects may be transient and reversible and/or debilitating and potentially lethal and, on the macro-scale, reduce overall biological productivity.

The effects of turbid conditions at low (e.g. <10 NTU) levels have been documented to negatively affect all levels of biological productivity; a result related to the concomitant effects of suspended and deposited material. The literature does contain information in relation to fishes that are adapted to life in turbid conditions, but with few exceptions they are not abundant in the Pacific and Yukon Region of Fisheries and Oceans Canada.

Confounding the negative aspects of exposure to turbid conditions are the seeming benefits that accrue for the prey of piscivorous visual predatory fish. By the occupation of turbid “cover” (in the absence of object cover) the prey are able to forage with diminished risk of predation, but the predators of such fish are correspondingly and negatively affected. However, because elevated turbidity is usually associated (at least over time) with diminished food for fish, the benefit of cover afforded by turbidity may be transient. Furthermore, the overall negative effects of increased turbidity on the productivity of aquatic system emphasize that decisions to protect particular organisms may be better considered through protection their habitat, for if habitat complexity and function were compromised the effect would likely cascade through trophic levels and result in diminished productivity.

Site specificity could be a significant factor to consider when attempting to apply criteria for the protection of specific life stages of aquatic resources. For example, if one were to solely protect rearing juvenile chinook salmon because of reduced risk of predation alone (and where adequate food supplies existed), it may be concluded that moderate levels of turbidity confer a survival advantage. But, if juvenile coho salmon and rainbow trout were in the same system, research results would imply the need for lower levels of turbidity for them to be protected (refer to the results of Sigler et al. 1984; Shaw and Richardson 2003). Despite any need to protect certain species from increased turbidity, the protection of the fundamental elements of the food chain and the habitat that supports aquatic life is a prerequisite. It is apparent that criteria to protect aquatic organisms should protect the habitat base which supports all trophic levels. In this regard it is turbidity determinations that are especially useful because of their impact on primary productivity.

The challenge for those who manage and protect aquatic resources is to decide upon the turbidity level(s) that do or do not cause harm to organisms and systems and the risk associated with the available options and choices. This specific topic has received much attention by Lloyd (1985, 1987), Lloyd et al. (1987), Berry et al. (2003), and Rosetta (2005). Within these and other review documents (e.g. Newcombe and Jensen 1996;

Anderson et al. 1996; Caux et al. 1997; Bash et al. 2001) are tables that relate the effects of different levels of turbidity to aquatic organisms and different trophic levels and assemblages. While Lloyd (1985, 1987), and Rosetta (2005), have used much of the specific information relating to the effects of turbidity *per se* when deducing turbidity criteria, Caux et al. (1997) relied upon information on the effects of both suspended sediment and turbidity (and especially the relationship between the two) in deriving levels of turbidity for use in water quality criteria for British Columbia (British Columbia Ministry of Environment, Lands and Parks (BCMELP) 1998; revision by Singleton 2001).

The following sections relate particularly to these assessments and also the analyses of Newcombe (2003) regarding the effects of turbid water and the setting of criteria for the protection of aquatic organisms.

TURBIDITY CRITERIA AND RELATED CONCERNS

To fully protect aquatic habitats turbidity values should prevent loss of aquatic productivity, as mentioned above, and at the same time cause no lethal, or chronic sub-lethal effects (Lloyd 1985).

An important consideration, and one that inevitably leads to confusion in the setting of criteria, is the difficulty in establishing whether a factor is limiting and/or controlling, for example, with respect to fish ecology. Because of the close correlation between turbidity and suspended sediment both variables may be considered as controlling and limiting factors depending upon levels and circumstances within the receiving waters. Different levels of turbidity will control photosynthetic activity and this may become a limiting factor considering trophic linkages and fish production. On the other hand, levels of suspended sediment and their deposition have a capacity to limit fish production through changes in fish habitat as well as through direct effects on the fish. Hence both turbidity and suspended sediment have the potential to be limiting factors regarding fish production. As such, and depending upon the relationship between the two and the specific circumstances being considered, monitoring either may suffice for compliance purposes. But, this assumes that the relationship between the variables and the risks from exposure to each are known and threshold effects levels have been determined.

A precautionary approach suggests that because of the inherent link between turbidity and suspended solids that both should be used for resource protection. The complexities of doing this in a general manner make this a difficult task. Both turbidity and suspended sediment should be monitored for compliance purposes, and that the one likely to have the most biological impact in specific receiving waters should receive the greatest attention and restriction. It would be especially acceptable to utilize turbidity values for those discharges in which the particle sizes of sediment are relatively close in dimensions.

Because turbidity has been intimately associated with elevations in suspended material in water and that both can adversely affect aquatic organisms, it would be only prudent to utilise criteria that are based on different levels of biological organization (trophic levels), and to rely on sensitive indicators.

It would be inappropriate to consider that one organism's response would be applicable to the protection of all stream biota and their habitat, however, depending upon the information available and the resources at risk in the receiving waters it may be possible to select sensitive organisms and response thresholds that will confer appropriate levels of protection upon the ecosystem as a whole

DEVELOPMENT OF CRITERIA

There is no standard formula for the setting of criteria nor are there definitive studies that reveal what appropriate thresholds are with respect to risk to the environment. Risk has been addressed with respect to levels of suspended sediment and EIFAC (1964), provided such following a review of the pertinent information over 40 years ago. Rosetta (2005) compiled much of the relevant information on the effects of turbid conditions and suspended sediments on the aquatic environment and this review has relevance to the stated objectives of this report. The creation of criteria is thus a relatively subjective process that is mediated through the availability of information and ecosystem complexities.

To provide maximum protection *without prohibition of the substance considered*, the material should have no detrimental effect at the point of discharge. The practicality of such has been challenged particularly as mixing/dilution will occur following discharge and, thereby, presumably lessen the impact of substances in the water column that are not bio-accumulated and that are degraded in the environment. It is imperative that effects in receiving waters be minimized to the greatest extent possible for maintaining ambient conditions of receiving waters is a desirable objective for biological resource protection and their perpetuation.

The following topics address issues regarding the use of criteria and choices regarding risk of harm with reference to both sources of turbid waters, and receiving waters whose resources are the subject of protection.

CRITERIA

The use of criteria for both turbidity and sediment variables will have the greatest value for resource protection. In relation to the Land Development Guidelines (DFO/MELP 1992) such is possible if applied to the effluents from settling ponds (because they generally discharge small-sized fractions of sediment (of silt and clay)), and run-off waters from land development sites.

Turbidity-suspended sediment relationships and ratios

If the relationship between suspended sediment concentrations and turbidity is known for a particular area (watershed, stream, reach etc.), then either variable may be used as an approximate surrogate for the other and criteria applied. The wide variation in these relationships indicates that the setting of criteria to protect aquatic resources from the combined effects of turbidity and suspended solids in large natural differing systems are likely very approximate. Lloyd (1985, 1987) supported this application from the perspective of low levels of turbidity that can adversely affect "coldwater salmonids".

Table 5**.** Turbidity (NTU) values predicted for a range of suspended sediment concentrations (mg·L-1) by the use of relationships between these variables within different watercourses (adapted from Rosetta 2005).

LOCATION	**A**	**B**	**C**	**D**	**E**
Suspended sediment ($mg \cdot L^{-1}$)	Turbidity (NTU)	Turbidity (NTU)	Turbidity (NTU)	Turbidity (NTU)	Turbidity (NTU)
1	2.1	0.2	0.2	1.1	0.5
10	11	1.7	1.8	10	3.2
25	17	3.1	3.7	20	5.8
50	32	7.3	9.2	49	13
80	44	11	15	77	19
400	140	49	73	360	75

A - Lower Willamette River and Tributaries (Portland, OR); NTU = 2.1172 $(mg \cdot L^{-1})^{0.6945}$; $R^2 = 0.8407$; Oregon State Department of Environmental Quality data compilation.
B - Fraser R. (British Columbia); NTU = 113 $(g \cdot L^{-1})^{0.916}$; $R^2 = 0.952$; Servizi and Martens (1992).
C - Susitna River (Alaska; glacially turbid); NTU = 0.185 $(mg \cdot L^{-1})^{0.998}$; $R^2 = 0.92$; equation from Peratrovich et al. (1982).
D - Interior Alaska streams; NTU = 1.103 $(mg \cdot L^{-1})^{0.968}$; $R^2 = 0.92$; Lloyd et al. (1987).
E – State-wide Alaska streams; NTU = 0.44 $(mg \cdot L^{-1})^{0.858}$; $R^2 = 0.83$; Lloyd et al. (1987).

The information in Table 5 illustrates the difficulty of using either suspended sediment or turbidity as respective surrogates in different natural rivers and creeks because of the variation in their relationship that occurs within disparate waters. This table was constructed from the review by Rosetta (2005).

Adding to this list of suspended sediment turbidity relationships, Packman et al. (1999) analyzed the relationship between turbidity and suspended solids and concluded that turbidity was a viable surrogate for suspended solids determinations. The regression model was l_n(total suspended solids) = 1.32 $\log_n$(NTU) + 0.15 for the majority of creeks examined.

Other relationships describe the relationships between the two variables, some being linear others logarithmic.

McLeay et al. (1987), as well as Birtwell and Korstrom (2002), used silt and clay fractions to create turbid conditions in laboratory experiments. Relationships between the variables revealed that for a given mass of sediment the equivalent turbidity was numerically close. Others have recorded similar results when using such materials (e.g. Baker 2003; laboratory study: TSS = 0.82 NTU – 0.12; 1 mg·L^{-1} = 1.4 NTU).

To convert from suspended solids concentrations to turbidity for natural river systems one would employ a factor of 0.25-0.3. An approximate conservative estimate of turbidity in effluent from well-functioning settling ponds (presented below) would be to use a factor of 1.5-2 applied to suspended sediment values (mg·L^{-1}). Thus for a given suspended solids concentration the equivalent turbidity would be much higher for a given mass of sediment from settling ponds than that which would usually be obtained from natural river systems.

Settling ponds and erosion control measures

With respect to the inherent association between turbidity and suspended material, the latter is expected to exert a variety of effects on biota depending upon such factors as stream flow, and stream energy that will keep material in suspension and/or permit its deposition. Degradation of inorganic fine material (e.g. clays and silts) will not occur rapidly hence it is important to remove as much of this material as is practical prior to its discharge in order to minimize *in-situ* effects in receiving waters.

Settling ponds, as well as erosion control measures, provide a practical means to reduce the impacts of suspended sediment on receiving waters and at the same time potentially reduce the impact of turbidity. Unfortunately the finer fractions of sediment contribute significantly to turbidity and at the same time have been shown to create an array of effects at various levels of biological organization. *Colloidal* clay particles, much smaller than the wavelength of light, remain suspended almost indefinitely and contribute little to light attenuation in natural waters according to Davies-Colley and Smith (2001).

The following comments exemplify some efforts undertaken to control sediment and turbid water discharges and the results of control measures in relation to different land developments and disturbances.

Placer mining - large scale industrial settling ponds

Settling pond function in the Yukon Placer industry (Yukon Placer Implementation Steering Committee and Yukon Placer Working Committee 2005) has been examined and it was stated that " A well-designed facility operated under optimal conditions can reduce effluent discharges to the 0.2 ml/L range" (192 mg·L^{-1}) under average performance for normal conditions (excluding non-compliance events)". In 2003 and 2004 such values were 0.3 ml/L and 0.5 ml/L (334 mg·L^{-1}) based on Yukon-wide averages for the correlation between settleable solids (ml/L) and TSS (mg·L^{-1}). Despite the correlation (albeit a poor one) that exists between settleable solids and suspended solids, these data suggest that equivalent turbidity values would be approximately 288-384 NTU for the "well-designed facility". In 2004 these values would have been approximately 501-668 NTU.

These predicted turbidity values are approximate and based on suspended sediment/turbidity ratios for materials discharged from settling ponds during land development in the Fraser Valley, BC (presented below). The data from the Yukon do serve, however, as indicators of large-scale settling pond performance under a variety of harsh environmental conditions (and contrast with those not performing optimally).

Land development sites, erosion control, and settling ponds:

In order to understand the efficacy and potential for source control at land development sites to reduce suspended sediment and turbidity, monitoring data from urban development sites in the BC lower mainland were examined.

Sites with little or no control (2004, 2006):

Table 6. An example of monitoring results for suspended sediment and turbidity from housing development sites (Surrey, BC, 2004) with no erosion/source control. Receiving waters were influenced by historic urban development (20 years ago).

SITE	**1**	**2**	**3**
Effluent			
Suspended sediment ($mg \cdot L^{-1}$)	1360	476	748
Turbidity (NTU)	2950	725	1380
Ratio ($mg \cdot L^{-1}$: NTU)	1:2.2	1:1.5	1:1.8
Receiving waters			
Suspended sediment ($mg \cdot L^{-1}$)	33	5	9
Turbidity (NTU)	13.8	5.6	10.7
Ratio ($mg \cdot L^{-1}$: NTU)	1:0.4	1:1.1	1:1.2

Site 1 - sloping 30-lot subdivision, undersized settling pond: no source control.
Site 2 - large condominium development: no source control.
Site 3 - sloping 100-lot subdivision: little source control.

The data in Table 6 (unpublished data; A. Jonsson, Lower Fraser Area, Oceans Habitat and Enhancement Branch, Pacific and Yukon Region, Fisheries and Oceans Canada) reveal the elevation in turbidity that can occur from developments which do not have adequate erosion source controls and adequate effluent management. These monitoring results also reveal the disparity that typically exists between suspended material in natural systems and that in discharges from settling ponds. In the latter circumstance effluents typically contain small grain size materials which contribute more to elevate turbidity than do large particles (the mean equivalent turbidity would be approximately 1.9 times the suspended sediment concentration at these locations).

These examples emphasize the requirement for erosion control measures at development sites. The sediment concentrations greatly exceeded the levels stipulated in the Land Development Guidelines (DFO/MELP 1992), and the associated high turbidity values would also be harmful to the aquatic environment. The elevated levels of both variables would be expected to have significant impacts on the receiving waters based on effects information presented earlier in this document.

At Finlay Creek, Vancouver Island, in wet weather conditions in December 2005, suspended sediment concentrations in settling ponds ranged from 30 to 100 mg·L^{-1}, with corresponding turbidity values between 64 and 187 (NTU). The mean suspended sediment to turbidity ratios ranged from 1:1.9 to 1: 2.7 with a mean value of 1: 2.1 (n = 4; unpublished data Fisheries and Oceans Canada, Campbell River, BC: K. Bond monitoring results).

The above examples illustrate a range of sediment and turbidity controls. Over time the discharges from these developments would be harmful to aquatic life at the point of discharge.

Sites with a range of control measures, Surrey BC (winter 2006):

Table 7. The assessment rating of erosion and sediment control measures used during land development in Surrey, BC, 2006.

Facilities		**pass**		**fail**	
	number	number	%	number	%
Non-existent	10	2	4.5	8	18
Poor	5			5	11
Fair-good/ excellent	26	16	36	10	23
Excellent	3	3	7		
Total	44	21	48	23	52

Land development sites were monitored in winter 2006 to determine the scope of measures to prevent turbid waters entering creeks and the values of turbidity and suspended solids in run-off waters (unpublished data from the City of Surrey, courtesy of A. Jonsson, Lower Fraser Area, Oceans Habitat and Enhancement Branch, Pacific and Yukon Region, Fisheries and Oceans Canada). An arbitrary pass or fail assessment (presented in Table 7) was assigned regarding the meeting of certain criteria namely: turbidity <25 NTU or <100 NTU if rainfall had been < or > 25 mm respectively in the preceding 24 h. Background winter "benchmark" values (n = 4) averaged 12.7 NTU (range 4-17 NTU).

This information illustrates the broad range of sediment containment and the judged success (%) of these efforts relative to the erosion control facilities. Although the data are relatively sparse they provide an indication of what may be achieved in controlling discharges of turbid water during the winter period in this city, as shown in Table 8 (unpublished data supplied by A. Jonsson, Lower Fraser Area, Oceans Habitat and Enhancement Branch, Pacific and Yukon Region, Fisheries and Oceans Canada).

Table 8. The range and mean value for turbidity determinations related to different erosion control measures during land development in Surrey BC, winter 2006.

Facility category	**Number of determinations**	**Turbidity: range (NTU)**	**Turbidity: mean (NTU)**
non-existent	7	5.2-1350	431
poor	2	148-185	166
fair	1	49	49
good	18	12-168	58
good-excellent	2	67-190	128
excellent	3	13-34	26

Overall the mean turbidity was 143 NTU, but 66% were ≤58 NTU and 73% ≤128 NTU. The ratio of suspended sediment to turbidity could be calculated for some of the data from the development sites referred to above (n= 15), and this resulted in the equivalency of 1 $mg \cdot L^{-1}$ = 0.8 NTU (these data include a variety of discharges, and not just from settling ponds).

Because of the transport of non-natal material to some development sites (A. Jonsson, Lower Fraser Area, Oceans Habitat and Enhancement Branch, Pacific and Yukon Region, Fisheries and Oceans Canada), there is variation in the suspended sediment : turbidity ratio from that which may be expected from *in-situ* natural soils. However, the ratio still infers the discharge of relatively small suspended particles rather than the more typical particle-size range of natural systems (see above).

Site with controls, Victoria, BC (winter 2006):

The data presented in Table 9 were collected at Bear Mountain, a large golf course development west of Victoria, BC. The developer's environmental consultant devised a sampling scheme to measure water quality at a series of locations in the watershed (see Figure 1, Appendix 2).

The golf course project was built around Osborne Creek, which is a tributary of the Millstream River, that has been "severely altered" by this development. Extensive assessment work has occurred in this tributary, and no fish were captured, however, there are resident cutthroat trout in the Millstream River (unpublished data courtesy of P. Law, Government of British Columbia). The data in Table 9 were abstracted from comprehensive water quality monitoring data collected during the winter 2006.

Rainfall had a bearing on the monitoring results. There is a significant relationship between, for example, turbidity data for site H10 and rainfall.

Table 9. Results of suspended sediment concentrations (SSC) and turbidity in water samples collected at 4 sampling sites, November 2006 to February 2007, from upstream and downstream locations, and in settling pond effluent at the Bear Mountain golf course development, Victoria, BC. Rainfall (mm) is for the day before and on the day of monitoring.

	SITE								
	H21		**H9**		**H10**		**H12**		**Rainfall**
	SSC	Turbidity	SSC	Turbidity	SSC	Turbidity	SSC	Turbidity	
Date	($mg \cdot L^{-1}$)	(NTU)	($mg \cdot L^{-1}$)	(NTU)	($mg \cdot L^{-1}$)	(NTU)	($mg \cdot L^{-1}$)	(NTU)	(mm)
Nov-07	14	2.5	<4	3.9	24	45.3	13	32.1	145
14	<4	0.9	<4	1.1	5	9.7	<4	2.5	32
21	18*****	1.1	5	1.1	17	32	<4	6.7	12
Dec-05	<4******	0.4	4	0.1	10	6.7	<4	0.1	0
12	<4	1	<4	1	12	29.4	3.2	0.1	48
21	<4	0.9	<4	0.6	<4	5.9	<4	1.7	15
27	<4	0.5	<4	0.8	<4	4.5	<4	1.1	2
Jan-02	5	1.7	98	49	75	49.5	14	12.9	70
9	<4	2.1	<4	1.1	5	7.6	<4	2.2	16
23	<4	0.7	<4	0.8	9	17.7	<4	3.1	27
30	24	10.1	<4	0.5	<4	3.8	<4	0.9	0
Feb-01	<4	1.1	<4	1.3	<4	4.1	<4	1.3	0
6	4	3.5	<4	0.8	<4	2.7	7	1.1	3
Mean	7.4	2.0	11.3	4.7	13.6	16.8	5.6	5.0	52.8

* a questionable data point relative to turbidity (not eliminated during calculations).
**values determined as <4 were incorporated as 4 in the calculations of averages.

H 9 - Millstream Creek above the confluence with Osborne Creek.

H10 - outlet of the settling pond.

H12 - Millstream Creek below the discharge of the Osborne Creek system.

H21 - Millstream Creek, above any influence of the Bear Mountain development.

Suspended sediment to turbidity ratio for waters from the settling pond (H10) was 1: >1.2, for H21 it was 1: >0.2; for H9 it was 1: >0.4, and for H12, 1: >0.9. The ratio at site H10 reflecting the typical discharge of small-sized particles.

Land Development Guidelines and predicted turbidity levels

The stipulated minimum suspended solids concentration in waters from land development is 25 mg·L^{-1} above the back-ground suspended solids levels of the receiving waters under dry weather conditions (DFO/MELP 1992). This concentration in *natural river waters* would be expected to result in turbidity values of about 6-8 NTU (refer to Lloyd 1985; Caux et al. 1997; CCME 2002; Rosetta 2005): levels at which effects on the lower trophic levels would have commenced, and especially so with prolonged exposures. Similarly, the stipulated upper suspended sediment level of 75 mg·L^{-1} above back-ground suspended solids levels of the receiving waters under wet weather conditions, would equate to turbidity values approximating 18-25 NTU *in natural river waters*.

Turbidity levels determined through monitoring of settling pond effluents from land developments (Table 10) have yielded greater turbidity values than those predicted for the same concentration of suspended sediment in natural river waters.

Table 10. Approximate equivalent turbidity levels for suspended sediment concentrations based upon data for natural systems and discharges from land developments and settling ponds using the ratio of suspended sediment to turbidity**.**

Location and data source	**City of Surrey[1] 2006**	**City of Surrey 2004**	**Finlay Creek**	**Bear Mountain**	***Combined Data[2]***	***"Natural systems"[3]***
Suspended sediment (mg·L^{-1})	Turbidity (NTU) n=15	Turbidity (NTU) n=3	Turbidity (NTU) n=4	Turbidity (NTU) n=13	*Turbidity (NTU)*	*Turbidity (NTU)*
25	20	49	52	30	***37.5***	***6-8***
75	60	146	160	90	***112.5***	***18-25***

1. - Includes effluents from settling pond and other sediment control measures.

2. - Combined data from land development in Surrey, Finlay Creek and Bear Mountain.

3. - Data in Caux et al. (1997), Lloyd (1985), CCME (2002), and Rosetta (2005).

Accordingly, in effluents from disturbed land, turbidity levels of approximately 37.5 NTU, and 112.5 NTU would be expected in waters with suspended sediment concentrations of 25 $mg{\cdot}L^{-1}$ and 75 $mg{\cdot}L^{-1}$ respectively. (1 $mg{\cdot}L^{-1}$ suspended sediment equating to 1.5 NTU - combined data constituting Table 10). Waters with these turbidity values would be detrimental to certain aquatic organisms, and, as revealed above, the effects would be expected to be exacerbated with increasing exposure periods.

It would, therefore, be a prudent step to utilize more appropriate lower levels of turbidity and suspended sediment concentrations when setting criteria for effluent discharges from land developments.

Criteria selection and examples

The setting of criteria for a particular discharge is possible based on knowledge of effects and especially so if the discharge contains non-toxic and no bio-accumulative substances.

It is possible to recommend values for, for example, turbidity, knowing that there will be different consequences depending on the receiving environment and exposed organisms. As stated by Suttle et al. (2004) in relation to the effects of fine sediment on juvenile rainbow trout, there is no threshold below which exacerbation of fine-sediment delivery and storage in gravel bedded rivers will be harmless. Implicit in this statement is the identification of increasing harm due to increasing levels of input; an issue addressed by Newcombe and MacDonald (1991) Newcombe and Jensen (1996), and Newcombe (2003), in relation to suspended sediment and to changes in water clarity and turbidity.

The discharge of fine suspended sediment and turbid waters ***will*** result in deposition within natural water bodies. This as been documented for natural streams in the Yukon and New Zealand (e.g. Seakem Group Ltd., 1992; Davies-Colley et al. 1992; Quinn et al. 1992) as well as experimental streams used to examine the effects of turbidity and suspended sediment on aquatic organisms such as fish (Sigler et al. 1984; McLeay et al. 1987; Liber 1992; Shaw and Richardson 2001; Birtwell et al. 2003; Birtwell and Korstrom 2005).

The foregoing information, including that from historical and recent studies has not resulted in a revised thinking about the overall negative effects of turbid conditions on aquatic productivity. Recent studies have refined our knowledge of the effects of lower levels of turbidity on fish and invertebrates in particular, with the result that it has been possible to better define acceptable levels for resource management. Some examples presented below reveal that reliance upon suspended sediment alone for resource protection may be inadvisable in light of recent information on the associated effects of turbidity. The examples emphasize the need to control turbid water discharges.

Use of tiered turbidity response levels and risk:

European Inland Fisheries Advisory Commission (EIFAC) and Yukon Placer mining:

The protection of aquatic resources from solids in watercourses was identified by EIFAC (1964) in relation to the effects of suspended material (and ancillary effects). This commission produced a general scale of suspended sediment which would likely be associated with certain fish assemblages. The results of this review were based on the literature available over 40 years ago; this included European data from already degraded streams and fisheries. Accordingly, the levels stipulated above would not likely be acceptable for the pristine waters of North America. This approach was further refined for the Yukon Placer Mining Authorization (Government of Canada 1993) so that various levels of risk were stipulated depending upon the concentration of suspended sediment.

Because much of the information at lower levels of suspended material also relate to the effects of turbidity *per se* it is probable that the above-mentioned risk relationship would have validity regarding the latter variable, and especially so for discharges of relatively small ranges of fine sediment (that is silts and clays).

Utilizing the basic understanding of the effects of suspended solids provided by EIFAC (1964) and the recognition of associated risks to fish presented within the Yukon Placer Authorization (YPA) (Government of Canada 1993) equivalent turbidity values have been calculated. These data are presented in Table 11 together with a revision of risk based upon the information on effects due to turbidity, and using data from land development sites and discharges from settling ponds (Table 10).

Table 11. Levels of risk to aquatic resources from exposure to suspended sediment and predicted levels of turbidity. Calculations are based upon relationships between suspended sediment and turbidity for natural waters and for land development effluents and settling pond discharges.

Suspended sediment ($mg \cdot L^{-1}$)	**Suspended sediment risk to fish and their habitat[1]**	**Equivalent turbidity[2] (NTU)**	**Revised turbidity risk to fish and their habitat**
0	No risk	0	No risk
<25	Very low	<37.5	Low-Moderate
25 - 100	Low	>37.5-150	Significant
100 - 200	Moderate	>150-300	Unacceptable
200 - 400	High	>300-600	Unacceptable
>400	Unacceptable	>600	Unacceptable

1. – Yukon Placer Authorization (YPA) (Government of Canada 1993) scenario.
2. – Based on data presented in Table 10.

The effects of turbidity applied to this scenario results in a heightened requirement for the protection of aquatic resources based on current knowledge, such that even at the lowest level of 25 $mg{\cdot}L^{-1}$ suspended sediment concentration adverse effects would be expected, especially with chronic exposure. EIFAC (1964), deduced that at <25 $mg{\cdot}L^{-1}$ of suspended solids - no evidence of harmful effects on fish and fisheries; 25-80 $mg{\cdot}L^{-1}$ - it should be possible to maintain good to moderate fisheries, however the yield would be somewhat diminished relative to waters with <25 $mg{\cdot}L^{-1}$ suspended solids; 80-400 $mg{\cdot}L^{-1}$- these waters are unlikely to support good freshwater fisheries; and >400 $mg{\cdot}L^{-1}$ suspended solids - at best, only poor fisheries are likely to be found. Ryan (1991) commented that what constitutes a good fishery in Europe may be entirely different than in unspoilt areas in other parts of the world. It is apparent that recent research results on levels of turbidity affecting biota that were documented by, for example, Rosetta (2005), would modify the deductions of EIFAC (1964), and lower the “no evidence of harmful effects” level of ≤25 $mg{\cdot}L^{-1}$ suspended solids. However, EIFAC did caution that even the lowest levels may not be fully protective of sensitive species such as salmon: a comment endorsed through the results of more recent research.

Yukon Placer Regime - predicted turbidity, suspended and settleable solids:

The new Yukon Placer Regime was implemented and applied to watershed protection. Levels of suspended sediment, and settleable solids in effluents were stipulated in relation to water quality objectives and differing fish life cycle stages and habitat sensitivities. In this way risk was incorporated into the management scenarios. An example of this approach is given below in relation to the highest level of protection afforded watersheds judged to be of high sensitivity.

Watersheds of higher sensitivity:

Calculated turbidity for waters relative to Water Quality Objectives and settling pond effluents in Yukon are presented in Table 12.

Table 12. Calculated turbidity levels for natural waters and effluents from placer mining activities and their relationship to water quality objectives as stipulated for the highest level of resource protection in the Yukon (Yukon Placer Implementation Steering Committee and Yukon Placer Working Committee 2005).

Habitat sensitivity	**Water Quality Objective** ($mg{\cdot}L^{-1)}$)	**Equivalent turbidity**[1] (NTU**)**	**Placer settling pond discharge** ($mg{\cdot}L^{-1)}$)	**Equivalent settling pond turbidity** (NTU)[2]
high	<25	**<6-8**	0	**0**
Moderate -H	<25	**<6-8**	<200	**<300**
Moderate-M	<50	**<12-17**	<200	**<300**
Moderate-L	<80	**<20-26**	<192-478[3]	**<288-717[3]**
Low	<200	**<50-66**	<192-572[3]	**<288-858[3]**

1 - 1 mg·L^{-1} equivalent to 0.25 – 0.3 NTU for natural river waters (based on Lloyd 1985; and Caux et al. (1997); CCME 2002; Rosetta 2005).
2 - 1 mg·L^{-1} equivalent to 1.5 NTU for land development effluent data (Table10).
3 - 192 (mg·L$^{-1)}$ equates to 0.2 ml·L^{-1} settleable solids and 288 NTU based on industry performance and data analysis (new regime); upper limit is stimulus for remedial action and monitoring etc.

The example is presented to indicate an approach to watershed management from a suspended sediment discharge perspective. It was constructed on the basis of effects of sediment alone and not the associated effects of turbidity. The example serves to emphasize the need to address both suspended sediment and turbidity variables for resource protection and management. Ideally, source control, and effluent and receiving water criteria should be used in concert.

Without reference to turbidity *per se* such an approach does not confer a high level of protection from the effects of this variable aside from issues of suspended sediment discharged from well-operating settling ponds.

The advent of new information on the effects of turbidity in particular would revise these assessments and criteria, and particularly so at the lower levels of turbidity. Interestingly, the latter point was noted by Ryan (1991) in his review of environmental effects of sediment. He commented that the criteria levels stipulated (200 mg·L^{-1}) in the Yukon Placer Mining Authorization (Government of Canada 1993) were “unacceptably high” based on the then-current literature. Furthermore, a variety of sub-lethal effects which are evoked by elevations in turbidity support the need for more conservative measures to protect ecological integrity.

National and Provincial (British Columbia) receiving water criteria for turbidity:

The primary objective of regulating the release of turbid waters from land development sites is to ensure the protection of aquatic resources in the receiving environment. The criteria presented here reveal some current approaches to resource protection from turbid conditions.

CME and BCMELP Guidelines:

The current CCME (2002) criteria (the same as those for British Columbia – BCMELP (1998); Singleton (2001) revision) are appropriate for use and supported by the reviewed information (Table 13). These criteria will confer a high level of protection upon aquatic resources and recognize the importance of the impacts of turbidity and suspended sediment in clear and turbid-water environments:

Table 13. Canadian national (CCME 2002) and BCMELP (1998; Singleton 2001) receiving water guidelines for turbidity for protection of aquatic health.

Canadian and British Columbia Guidelines regarding suspended sediment and turbidity

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Clear flow:

Maximum increase of 8 NTU from background levels (≤8 NTU)
for short-term (e.g. <24 h) exposures,
and a maximum average increase of 2 NTU from background
for longer-term exposures (e.g. 30 d period).

High flow or turbid waters:

Maximum increase of 8 NTU from background levels

at any one time when background levels are between 8 NTU and 80 NTU.

Turbidity should not increase more than 10% of background levels

when background levels are >80 NTU.

The turbidity criteria for BC and Canada have used the suspended sediment to turbidity ratio of 1:0.3, which is probably acceptable for widespread and approximate use. However, with respect to turbidity in effluents from land disturbances due to developments and from settling ponds, the ratio should be much greater. Thus the BCMELP and CCME documents require adjustment regarding such discharges if protection is required through surrogate use of both variables; while the turbidity levels suggested appear appropriate, corresponding suspended sediment levels would appear too high for sediment laden waters from land development sites. The value of the guidelines lies in the specific use of each variable for *natural systems*.

Turbidity receiving water criteria (New Zealand and Oregon State, USA):

Ryan (1991) recommended that for a "substantial" degree of environmental and aesthetic protection" an increase of 1 NTU (equivalent to 1 $mg \cdot L^{-1}$) at ambient levels up to 10 NTU (10 $mg \cdot L^{-1}$), and a 10% of ambient level increase thereafter.

The State of Oregon (USA) Department of Environmental Quality (DEQ) (Rosetta 2005) recommended turbidity criteria for aquatic resource protection following an extensive review of the literature. Table 14 presents the recommended criteria.

The criteria allow for compliance to be measured or calculated to be met, at the edge of a "properly designed" mixing zone, or within a specified distance downstream, or away from the activity-related turbidity input.

Compliance is determined by comparing background turbidity against turbidity measured at the compliance point described below. A visible plume should not extend past the compliance point, measured as a distance from the origin of the activity.

Table 14. Maximum allowable increases in turbidity (NTU); (Rosetta 2005).

Maximum criteria*		**Monthly average critieria**	
Background turbidity	Allowable increase above background	Background turbidity	Allowable increase above background
≤ 33	5	≤ 30	3
> 33	15%	> 30	10%

* may exceed 5NTU during a single period < 8 h for each day allowed; turbidity increase may exceed > 30 NTU for < 2 h, and not exceed 50 NTU.

The scientific validity of the DEQ document was reviewed by an independent panel of experts led by C. Schreck (Oregon State University), (Independent Multidisciplinary Science Team (IMST) 2006). They reviewed the document with respect to two questions:

1. Does the technical basis provide a reasonable and objective review of the body of the available information related to turbidity effects (not solids, toxics, or other parameters)?

2. Does the technical basis provide reasonable and objective inference on risk of impairment from the available literature regarding the protection of beneficial uses?

The IMST reported that the DEQ desired a simple, practical, and flexible approach for assessing and complying with turbidity criteria.

“While IMST recognizes that Oregon’s proposed turbidity criterion of 5 Nephelometric Turbidity Units (NTU) above ambient resembles those of other states, IMST feels that there are biological risks in using those approaches for two major reasons:
(1) where multiple dischargers to large rivers choose reference/background sites immediately upriver with only the guidance provided in this document, and
(2) where criteria for clear water fishes appear less protective than may be necessary if one objective were to be protective of biological function.”
“Furthermore, most turbidity research has been conducted at turbidities higher than those shown to have behavioral effects on salmonids. This adds risk to setting protective criteria for salmonids should those behavioral effects translate into ecological effects” (IMST 2006).

These comments appear quite justified in relation to the comprehensive information provided by Rosetta, (2005), and at the same time emphasize the importance of effects at the lower sub-lethal levels of exposure.

The results of recent research studies in addition to those assessed by Rosetta (2005), are supportive of this position to restrict increases in turbidity and to include provisions that address duration of exposure, notwithstanding the option for modification of levels that will cause harm based upon the effects on certain species and life stages of fish.

All recent criteria (BCMELP 1998; CCME 2002; Rosetta 2005) that address turbid conditions recognize the importance of duration of exposure and the effect that even small increases in turbidity can have negative effects on biological communities.

If "end of pipe" or "point source" discharge criteria are adopted for use in the land development guidelines then compliance with CCME (2002) and Rosetta (2005) recommendations would be appropriate for the receiving waters. It is necessary to control turbid waters at source because the inorganic materials that cause turbidity do not degrade and therefore contribute to deterioration of the receiving environment.

To provide the highest safeguard without outright prohibition of discharges of turbid waters, it is imperative that the turbidity levels be low and the discharges be of short duration so there will be no significant increase in turbidity of the receiving waters (long-term discharges of fine particulates has led to degradation of habitat hence the focus on short-term discharges of the "non-degradable" inorganic materials in suspension).

APPLICATION OF TURBIDITY CRITERIA

The use criteria that are based upon the background turbidity level at the time(s) of discharge have practical merit. The criteria would change in response to background levels. However, to effectively utilise this option demands that there be no upstream uses that progressively alter the water quality in a manner that either instantaneously or progressively results in degradation of water quality prior to the receipt of the discharge of concern. To do otherwise and permit upstream degradation would be counter to the objectives of sustaining high quality habitat for aquatic resources unless one can predict with certainty the limits whereby incremental change may occur without undue stress on natural populations of organisms: a highly improbable task..

Compliance monitoring, effects thresholds, and related considerations

Rosetta, (2005) recognized mixing zones and their relationship for use in receiving water compliance monitoring. However, where the objective is to prevent the discharge of deleterious substances and to reduce sediment concentrations in effluents sampling at the point of discharge would probably be the most practical location for compliance monitoring. The use of a single criterion for the protection of aquatic resources from excessively turbid waters has merit in its simplicity and its practicality, either as a "point source" or "end of pipe" determination, or one in the receiving waters. A criterion may be applied under different conditions and be quite specific. The criterion may be flexible to reflect the duration of the discharge and the prevailing conditions of receiving waters. The discussion and analyses of Rosetta (2005) provide reasons behind the adoption of criteria above background levels, and where such measurements should be taken for compliance monitoring.

Point source/“end of pipe”, bioassays, and receiving water criteria:

The discharge of deleterious substances under the *Fisheries Act* has been authorized for numerous effluents and substances (e.g. Government of Canada (2002) - Metal Mining Effluent Regulations; Pulp and Paper Effluent Regulations), and it is apparent that in order to protect the aquatic environment from such substances their discharge must be constrained and effects evaluated.

Compliance with criteria has been assessed in relation to the materials/effluents discharged. This may include the use of bioassays whereby the “toxicity” or harmful nature of substances may be evaluated prior to their discharge into receiving waters (refer to Birtwell 1999).

It has been a precautionary step to ensure that the substances discharged are not considered to be acutely lethal (or otherwise harmful) at the point of discharge.

Bioassays and responses of individuals:

Application of results from most standard 96h LC50 acute lethality tests may be quite misleading if the data are used to indicate potential responses in the wild. If the objective is to have a discharge that is not acutely toxic at the point of discharge then no test organisms should succumb during the acute lethality test. Recognition of this aspect has led to refinement of bioassays to provide more ecologically meaningful data. Rosetta (2005), however, has applied the concept of 50% response levels to a variety of effects of turbidity on biota. However, some responses of organisms are not linear but exponential or power functions that may not easily be converted to acceptable threshold effect levels (e.g. Mazur and Beauchamp 2003).

At low levels of environmental constraints (e.g. low levels of turbidity), organism response will be a function of susceptibility and different individuals may respond differently leading to much variance in the data. Thus there will be increasing variance in the response data the closer the constraint approaches “normal” levels that lie close to or within the adaptive capability of the organisms. With this in mind it may be appropriate for the use of ranges of acceptability regarding the constraint. Such an approach has less value perhaps at higher levels of the applied constraint that exceed adaptive capabilities of exposed individuals. Here, the variation in response data is reduced, aiding quantification and a more accurate, but possibly less valuable, determination of the responses of populations.

Environmental relevance:

Most laboratory bioassays do not relate well to the natural environment wherein the added complexities of life in the wild may further constrain the abilities of otherwise test subjects to cope with the added constraints of exposure to the substance being evaluated. Even effects at the sub-lethal level can be detrimental and lead to “ecological death” (Kruzynski and Birtwell 1994; Kruzynski et al. 1994).

There has been progressive recognition of the need to adopt suitable endpoints in toxicity testing whereby not only sensitive representative organisms for the receiving environment are used but sensitive life stages of those species are used, under realistic duration of exposure and relevant environmental conditions. With respect to turbidity and suspended sediments there is much information regarding impacts on biota, and recent assessments have facilitated the formulation of criteria for biological resource protection.

There is probably sufficient general information to permit broad statements to be made regarding the impacts of turbid conditions but site specificity will always influence these conclusions.

Mixing zones and background levels of turbidity in receiving waters:

The dilution capacity of receiving waters may be used as the safeguard to protect from elevated levels of turbidity. However, it will not safeguard against cumulative depositional effects of the non-degradable inorganic sediments. For optimal protection of resources the discharge should not be harmful (the level of harm may be selected depending upon the circumstances and the organisms/ecosystem in question): clear-water fishes, for example, require a greater level of protection from turbide conditions than those adapted to, and/or tolerant of, higher turbidity.

If the protection of aquatic resources is of paramount concern then it is only logical that there be no harmful effects at the point of discharge into receiving waters.

Migrating organisms do not, of course, have apriori “knowledge” of mixing zones within which there may be gradients and dilution. Therefore it would be most inappropriate to set low risk criteria outside of such regions while there could be harmful high risk effects on aquatic organisms within such “mixing” zones. Fish will, because of innate requirements, use sub-optimal habitats on occasion (e.g. Quigley 2000), and may be harmed as a consequence.

This somewhat philosophical approach has value depending upon the worth that is placed on the aquatic receiving environment. It is possible to develop scenarios where greater or lesser risk may accrue to aquatic organisms depending on the acceptability of the materials discharged and the subjective value placed on the receiving environment (refer to the Yukon Placer Implementation Steering Committee and Yukon Placer Working Committee 2005). Determination of “acceptable levels of risk” often appear to be highly subjective and typically not amenable to scientific validation.

With respect to turbidity and its natural occurrence, it is only sensible to also consider the levels and duration of turbid conditions to which aquatic organisms are exposed in the receiving environment. If this is done one may be able to set realistic limits at the point of discharge such that there is no measurable elevation of continuous and seasonal natural variations (this is not to imply that certain natural changes occur without adverse effects).

This is most likely an onerous approach for most circumstances where land use practices (e.g. sub-division construction) are occurring. It would require knowledge of background data over time and the responses of organisms and the habitat that needs to be protected. Where such data are available watershed-specific criteria can be derived in relation to duration of exposure to different levels of turbidity (e.g. Quilty and Flemming 2005).

Practical aspects

Point source monitoring:

The most practical approach for effluent compliance monitoring, would be to use "point source discharge" or "end of pipe" criteria. Two options are apparent:

1. Use an elevation in turbidity in relation to receiving water background values thereby recognizing that variation in turbid water is a naturally occurring phenomenon.

2. Use a range of selected turbidity values (thresholds?) that recognize that there are various levels of risk to biota and habitat depending on the criteria selected for application.

The latter may be linked with the former approach assuming that there are adequate data. Both are amenable to modification due to the recognized dose-dependency relationship- that acknowledges increasing effects due to increasing exposure duration (Newcombe and Jensen 1996; Newcombe 2003; Quilty and Fleming 2005).

As can be seen from the above information, the level within the effluent that could be deemed to be not acutely harmful at the point of discharge would be ≤5 NTU. Such a level is likely unattainable without the use of additional treatment of site run-off and settling pond effluents: treatments that may themselves create additional issues regarding waste disposal.

The acceptance of turbid water discharges >5 NTU confers some degree of risk to aquatic communities as revealed in the information provided in this report. The inherent mixing/dilution capabilities of specific receiving waters would provide additional safeguards thereby suggesting that higher initial effluent turbidity levels could be acceptable, and especially so depending on the turbidity and flow of receiving waters. This does not apply however to lakes wherein small changes in turbidity can have profound effects on euphotic volume and productivity.

Using this compliance monitoring scenario it is possible to recommend levels for compliance depending on prevailing ambient conditions (related to e.g. dry and wet weather), as was done for settleable solids in the Land Development Guidelines (DFO/MELP 1992) and recently enacted through Bylaw for the City of Langley, BC (see Appendix 3).

Use of reference background levels:

Secondly the use of criteria that reference background levels has practical merit, especially when baseline upstream values can be determined. Baseline is intended as natural background levels however and as such would be independent of other upstream inputs of turbid waters.

. This approach is the basis for the BC (BCMELP 1998; Singleton 2001) and Canadian criteria (CCME 2002) and those proposed by Rosetta (2003) for Oregon.

Compliance monitoring demands knowledge of fluctuations in background levels of turbidity and cannot be used where baseline conditions upstream are subject to other anthropogenically induced turbid inputs. The criteria mentioned here do, however, recognize the appropriateness of using different turbidity criteria related to ambient clear and turbid-water flows.

Dose-dependent considerations:

The effect of duration of exposure has been recognized as an important issue for incorporation into turbidity and suspended sediment criteria (e.g. BCMELP 1998; Singleton 2001); CCME (2002; Rosetta (2003).

Based upon realistic land development practices the predicted severity of effects could be simply calculated using the information supplied by Newcombe (2003). Thus, the inclusion of duration of exposure could also be applied to point source and water quality objectives.

Risk:

The risk to the biological resources through the adoption of particular criteria would be based upon cause-effect relationship information and there is little specific information on field determinations to guide such selections. Risk also includes some assessment of the values that humans place upon fish and their habitat. Only long-term thorough assessments can provide the appropriate information for establishing risk thresholds, and without this, decisions will include degrees of risk. Accordingly there are inherent risks to biological communities through the specification of turbidity levels for use in Land Development Guidelines. It is hoped, however, that such are recognized and turbid water discharges minimized through the application of best practicable site design, erosion source control and effluent management technology.

COMMENTS

Turbidity is a variable that should be monitored for compliance with stipulated levels for aquatic resource protection during developments incorporated into the Land Development Guidelines (DFO/MELP 1992). The scientific and related literature reviewed for this report support the need to control both turbid water and sediments discharged from land development sites. The current evidence suggests that both turbidity and suspended sediments be monitored and controlled from development sites to provide appropriate levels of protection for aquatic resources.

We believe that the foregoing comments provide sufficient information upon which to modify the Land Development Guidelines (DFO/MELP 1992) and to align them with current criteria for the protection of aquatic organisms from excessive turbidity. Information generated since their inception in 1992 suggests that this is an appropriate revision.

There cannot be degradation of habitat if healthy populations of individuals are to survive and thrive. To allow degradation to occur is counter-intuitive and illogical. Hence degradation of habitat comes at a cost, the predicted extent of which is often more judgemental than scientifically defensible.

In the context of the Land Development Guidelines, preservation of habitat and its productive capacity from the imposition of turbid waters has been the primary focus of this report. However, it is recognized that continued land disturbance will continue to affect water run-off and with it is the potential for erosion and the transport of materials to water courses.

The scientific information indicates that there will be consequential harmful effects on biological resources exposed to turbid waters and it has been the intent of this report to reveal these. Prohibition of turbid effluents would be an ideal way to avoid risks to aquatic communities, however, this is unrealistic under most land development scenarios and, accordingly, every effort must be made to minimize the effects of turbid water discharges to watercourses.

Compliance with turbidity criteria will not eliminate adverse effects but will assist in minimizing or controlling them. This approach recognizes the legitimate need for temporary land disturbance and development, and accepts that compromises will occur regarding the affording of maximum protection to aquatic communities and site-specific circumstances will often determine the extent to which the turbidity criteria may protect aquatic resources.

Contrary to our expectations, the compensatory mechanisms expected to emerge within aquatic systems that would result in the acceptability of higher turbidity values without loss of production were not apparent when viewed in relation to the total impacts of turbidity and also the inescapable link to suspended sediment. The effect of turbidity on primary production is probably one of the most sensitive indicators for protection of aquatic resources.

SUGGESTED OPTIONS FOR CRITERIA AND COMPLIANCE MONITORING

For simplicity and practicality, it is suggested that compliance with turbidity criteria be monitored at point of discharge, but results should be assessed in relation to true upstream background levels, reflective of dry or wet weather, and also incorporate the expected duration of exposure to excessive turbidity.

This approach is suggested to link with the requirements within the current Land Development Guidelines (DFO/MELP 1992) for the monitoring of suspended sediments from land development sites.

The risk to biological resources from turbidity should be viewed in relation to levels of risk of harm. Table 15 indicates what such impairment might be based on exposure of clear-water fish to turbid waters.

Table 15. Tiered risk of significant impairment to clear water fishes from exposure to waters of different turbidity and for different duration of exposure (adapted from Newcombe 2003).

Risk of significant impairment	Receiving water turbidity (NTU)	Duration
none	Ambient - <3	
low	>3-<8	>3 weeks to <10 months
moderate	9-20	5 d to 3 weeks
significant	21-100	3 h to 5 days
unacceptable	>100	<3h

The results of monitoring suggest that it is possible for effluents from well-designed erosion control measures and operating settling ponds to discharge waters of 20-30 NTU under dry weather conditions, and 100 NTU or less during wet weather conditions. Dry weather is defined as <25 mm rainfall in the previous 24h, while wet weather is > 25 mm in the previous 24 h (unpublished analyses and deductions from A. Jonsson, Fisheries and Oceans Canada; Township of Langley Bylaw 2007, Appendix 3)).

It is recognized that the stipulated effluent turbidity levels would be harmful to aquatic organisms exposed to them for a period of hours to days without dilution. (see table 16) Implicit in this understanding of harm and risk is the additional requirement to manage suspended sediment because of its effects on aquatic organisms while it is suspended and also its long-term effects once deposited.

Table 16. Dilution of turbid effluent at 25 NTU and 100 NTU, and approximate onset and duration of increasing risk of impairment to clear-water fishes (adapted from Newcombe 2003).

	DRY CONDITIONS		WET CONDITIONS	
Effluent dilution factor	Effluent @ 25 NTU)	Approx. range in time:- increasing and significant impairment*	Effluent @ 100 NTU)	Approx. range in time: - increasing and significant impairment*
1x	25	1wk - >1 y	100	7 h - <2 wk
2x	12.5	2 wk - >1 y	50	1 d - <8 wk
3x	8	7 wk - > 1 y	33	2 d - <5 mo
5x	5	>11 mo - NA	20	1wk - >1 y
10x	2.5	NA	10	2 wk - >1 y

* Prediction of "severe impairment" with longer duration of exposure, and "slight impairment" to "ideal conditions" with lesser duration of exposure.

The suggested approach is a refinement of existing criteria for resource protection based on suspended sediment concentrations alone. The levels assume immediate mixing of effluents in receiving waters to the extent that CCME (2002) and BCMELP (1998; Singleton 2001) guidelines for turbidity in receiving waters are not exceeded. That is, under dry (clear-flow) conditions a maximum increase of 8 NTU for <24h, and 2 NTU for longer exposures; wet (turbid-flow) conditions a maximum increase of 8 NTU when background levels >8-<80 NTU, and ≤10% increase when background levels >80 NTU.

The scenario of predicted effects provided in Table 16 with respect to the onset of "significant impairment" is based on Newcombe's analyses (2003). In this example, increasing impairment is predicted with increasing exposure to turbid waters and eventually will lead to "severe impairment". Reference to these deductions and those of Rosetta (2005) must also be cognisant of the similar effects of suspended sediment on aquatic organisms (Newcombe and Jensen 1996) so that appropriate decisions are made regarding the combined and related impacts of suspended sediment and turbidity.

Land development and disturbance is generally of a temporary nature and consequently the discharge of turbid waters and suspended sediment from development sites is also expected to be temporary. In that land developments are typically weeks to months in duration the receiving water objectives should be achievable. It is expected that immediate mixing/dilution of run-off and settling pond effluents will account for turbidity reductions to levels that would not cause immediate harm beyond the dilution zone.

Modification of the above scenario could occur based upon predicted risks from turbid waters at the discretion of regulatory authorities but at no time should Canadian national guidelines be exceeded for receiving waters:

The above suggestions for the control of turbid water discharges into receiving waters is based on the expectation that the primary objective of erosion and effluent control measures at land development sites is to minimize the discharge of turbid water to the most practical extent possible to maintain, and not diminish, the receiving water habitat productive capacity thereby assist in the perpetuation of healthy biological communities

The establishment of effluent standards that are cognizant of receiving water objectives are not only worthwhile but essential management tools. They establish performance targets for erosion and sediment control works on development sites required to balance legitimate development of land for human needs, with the need to minimize risks to the aquatic environment.

CONCLUSIONS AND RECOMMENDATIONS

1. Scientific studies reveal that increases in turbidity can have adverse effects on aquatic organisms at all trophic levels, and increasing harm generally occurs with increasing duration of exposure.
2. Turbidity is a scientifically justifiable variable to include in land development monitoring programs in order to protect receiving water biota and their habitat.
3. Source control of effluent turbidity is necessary to minimize direct effects in the receiving waters and cumulative depositional effects associated with the non-degradable inorganic fraction of sediments that contribute to turbidity.
4. Practical and achievable turbidity levels in effluents from land developments should be <25 NTU and <100 NTU at point of discharge under dry and wet conditions respectively. Dry and wet weather are considered < 25 mm and >25 mm rainfall the over preceding 24 h respectively. These levels will confer a level of protection and risk related to the degree of immediate mixing/dilution in receiving waters.
5. Canadian national and BC receiving water criteria for turbidity must not be exceeded downstream of the effluent discharge if receiving water quality, aquatic biota and habitats are to be protected. These receiving water quality criteria are: a maximum increase of 8 NTU for <24 h and 2 NTU for longer exposures under dry (clear-flow) conditions; a maximum increase of 8 NTU when background levels >8-<80 NTU and ≤10% increase when background levels>80 NTU under wet (turbid-flow) conditions.
6. To determine receiving water quality for compliance and monitoring, sampling should occur at 3 locations: upstream (true baseline control) of the effluent discharge, at the point of, and immediately downstream of, the effluent discharge.
7. To determine effluent quality for compliance and monitoring, samples should be taken from the effluent stream immediately prior to its discharge to the receiving environment.

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APPENDIX

Appendix 1. A brief summary of research results from Birtwell and Korstrom (2002): exposure of juvenile chinook salmon to suspended sediment and turbidity

Sediment

The particle sizes of sediment for this research were the same as that which are discharged from a well operated settling pond (silts and clays). Furthermore, these size fractions of sediment have been recorded from active and abandoned mine sites such as along Haggart Creek (Pentz and Kostaschuk 1999).

Feeding and growth

The research focussed on the growth and feeding of the juvenile chinook salmon after 3 and 9 weeks exposure to control waters and to waters of 132, 455, 1270 NTU; 100, 300, and 1000 $mg \cdot L^{-1}$ nominal concentrations of suspended sediment.

The fish were fed a diet of artificial food, live brine shrimp and freeze-dried krill. Feeding success and efficiency was examined at the end of 3 and 9- week exposure to the selected turbidity/suspended sediment levels to determine if different exposure periods changed the feeding of the chinook salmon.

Increases in turbidity have been determined to affect the feeding of fish (refer to Birtwell 1999, Newcombe 2003). It would be expected that any adverse effects on feeding due to elevated turbidity and suspended sediment would potentially affect growth, and this was examined.

Duration of exposure

Recent data analyses (Newcombe and Jensen 1996) predicted an increase in harm (Severity of Ill Effect {SIE}) with increasing exposure to sediment, and that exposure to even “low” levels of sediment would, with time, become harmful. Newcombe (2003) predicted a similar scenario of events in relation to exposure to turbid conditions.

With these considerations in mind research was designed to examine the effects of turbidity/suspended sediment on different aspects of the physiology of the chinook but using the same SIE produced through exposure to a high suspended sediment concentration for a short period of time as well as from a longer exposure to a lower concentration of suspended sediment.

We chose a 3-week and 9-week exposure period to turbidity/suspended sediment. The SIE for the 3 weeks exposure resulted in values of 8.4, 9.2, and 10.0, for 132, 455, 1270 NTU (100, 300, and 1000 $mg \cdot L^{-1}$ suspended sediment), respectively.

Nine weeks exposure to the same conditions resulted in SIE values of 9.2, 9.9, and 10.8, respectively. At level 8 Newcombe and Jensen (1996) predicted increased physiological stress, reduced feeding rate and success, at level 9 reduced growth, and level 10 would see the onset of mortality, increased predation, and more severe consequences.

Growth of juvenile chinook (weight %) relative to controls (optimum ration, 3-week exposure)

Over a 3-week period the growth of juvenile chinook salmon was found to be dependent upon the exposure to turbidity/suspended sediment concentration. Fish in the highest turbidity/suspended sediment concentration grew the slowest while those in the control waters grew the fastest.

The results were similar between 2 years of experimentation, and the combined data set reveals that there was a reduction in growth relative to controls of 1.9 %, 8.1%, and 21.1%, in waters with turbidity values of 132, 455, 1270 NTU (100, 300, and 1000 mg·L^{-1} suspended sediment), respectively. These results are consistent with the prediction of nature of effects based on Newcombe and Jensen's (1996) analyses of the literature, and relate to the findings of impaired feeding (Newcombe 2003).

Feeding of juvenile chinook

After 3 weeks exposure:

Sediment concentration (mg·L^{-1})	0	100	300	1000
Turbidity (NTU)		132	455	1270
*Time (s) to capture surface prey**	3.3	8.3	15.4	73.7
Capture duration relative to controls*	0	2.5x	4.6x	22.3x
*Mean # of strikes per capture**	1.1	1.3	1.2	1.8
Capture success (%)*	89.1	76.9	84.9	54.3
*Theoretical 100% successful capture of prey/min**	20.4	9.4	4.6	1.5
Feeding efficiency (Number of prey actually captured/min)*	18.2	7.2	3.9	0.8
Reduction factor relative to controls*	0	2.5x	4.7x	22.8x
% *Decrease in feeding efficiency* relative to controls **	0	60.4	78.6	95.6

* tests conducted with 19 fish, n=90
** 100 – {(feeding efficiency treated)/(feeding efficiency control)}

After 9 weeks exposure:

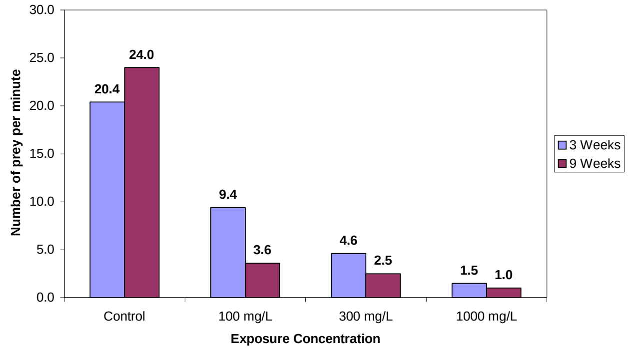
Sediment concentration (mg·L^{-1})	0	100	300	1000
Turbidity (NTU)		132	455	1270
*Time (s) to capture surface prey**	2.5	20.3	44.0	134.5
Capture duration relative to controls*	0	8.1x	17.6x	53.8x
*Mean # of strikes per capture**	1.0	1.2	1.8	2.5
Capture success (%)*	96.8	84.9	56.3	40.8
*Theoretical 100% successful capture of prey/min**	24.0	3.6	2.5	1.0
Feeding efficiency (Number of prey actually captured/min)*	24.0	3.0	1.4	0.4
Reduction factor relative to controls*	0	8.0x	17.1x	60.0x
% *Decrease in feeding efficiency* relative to controls **	0	87.5	94.2	98.3

* tests conducted with 19 fish, n=90; ** 100 – {(feeding efficiency treated)/(feeding efficiency control)}

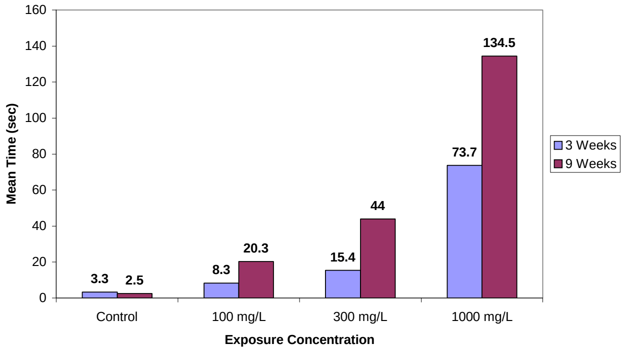
Capture of surface prey (seconds) by juvenile chinook salmon following sediment addition (1270 NTU); results from 6 replicates of each group of 20 fish:

Time (h) after sediment added	24	48	72	96	168	240
Treated	157	137	132	136	138	128
Control	7.3	9.2	5.9	5.4	5.1	5.9
Capture time relative to controls (longer*)*	21.5x	14.9x	22.4x	25.1x	27.0x	21.7x

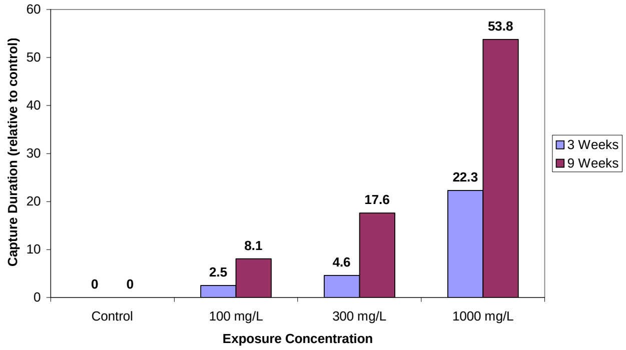
Theoretical 100% Successful number of prey captured per minute at the water surface, by 19 juvenile chinook



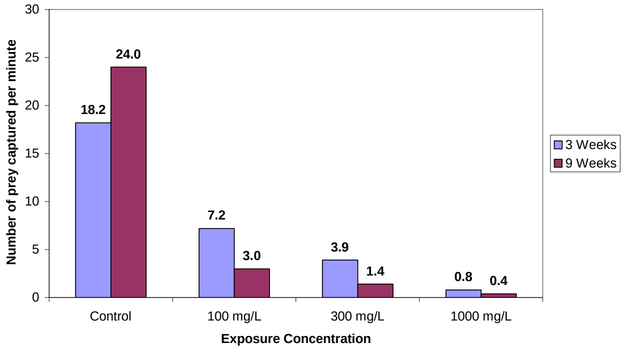
Mean time for 19 juvenile chinook to consume on prey item (krill) at the water surface after 3 and 9 weeks of exposure, n = 90



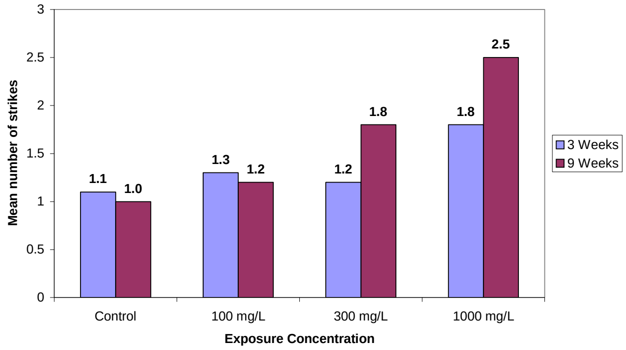
Capture duration relative to controls, of 19 juvenile chinook to capture one prey item at the water surface, n= 90



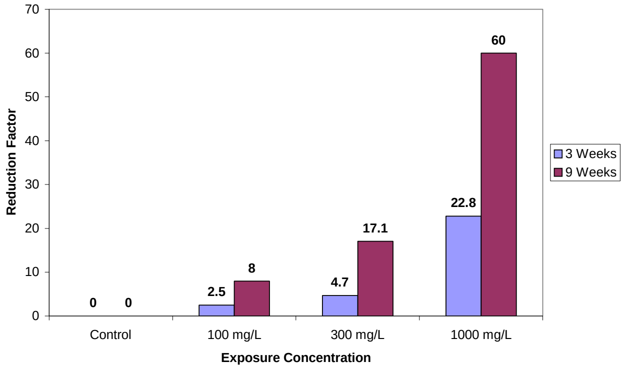
Feeding efficiency (number of prey captured at the water surface per minute by 19 juvenile chinook)



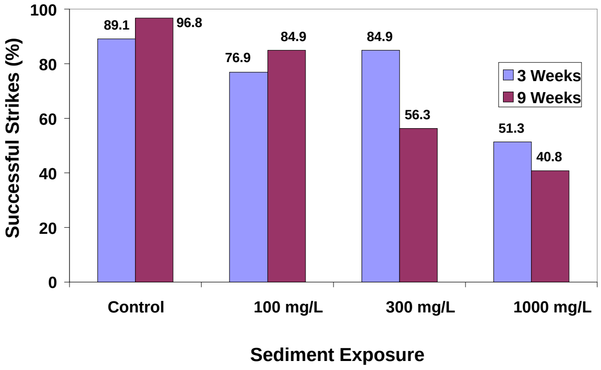
Mean number of strikes per prey item captured at the water surface by 19 juvenile chinook



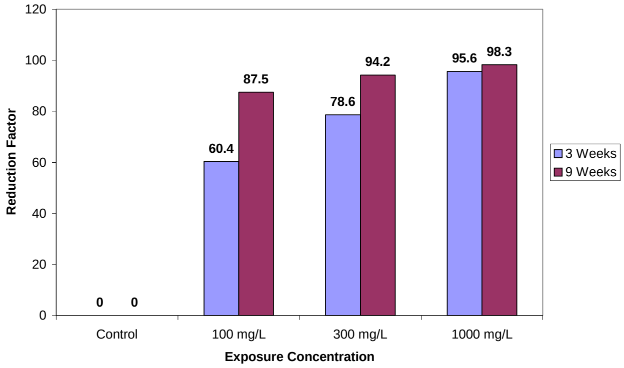
Reduction factor of feeding efficiency relative to controls



Percent successful strikes of 19 juvenile chinook salmon on one prey item (krill)at the water surface after 3 (2001) and 9 (2000) weeks exposure to suspended sediment



Percent reduction of feeding efficiency relative to controls



Irrespective of the experimental period and conditions juvenile chinook captured prey from the water surface, however, the efficiency with which this occurred was markedly affected by exposure to the turbid conditions and suspended sediment.

Control fish captured the prey faster than all turbidity/sediment-exposed fish and their success was higher (fewer miss-strikes). Over a 10-day period and relative to the results for control fish, there was no apparent change in the prey capture time by juvenile chinook upon exposure to 1270 NTU (1000 $mg \cdot L^{-1}$ suspended sediment).

The exposure period of 3-weeks resulted in significant reductions in feeding success, which was dose dependent. This effect was even more marked after turbidity/suspended sediment exposure of 9 weeks.

These results are consistent with an anticipated reduction in growth rate of the chinook salmon over the exposure period and in relation to turbidity/suspended sediment concentration, and also fit the prediction of reduced feeding success and rate (Newcombe and Jensen 1996; Newcombe 2003).

That the juvenile chinook were able to grow in sediment laden waters is probably related to their feeding behaviour, for they will forage upon the benthos and in mid- and surface-waters. They are opportunistic and facultative predators.

The results of our research imply that chinook salmon may feed and grow (albeit slower than controls in clear water) in waters where food rations are not limited. However, in that the imposition of sediments to streams typically results in increased turbidity and increased drift and a reduction of benthic invertebrates (typically those favoured as prey by juvenile salmonids), it is likely that food would not be unlimited, and instead it would probably be limiting. Accordingly, and under such circumstances we predict that these conditions would reduce the growth rate of juvenile chinook salmon (and other fish), which in turn would have consequences to their survival.

Cover (fright response) tests

The cover seeking response of fish, and especially once frightened, is an adaptive behaviour that caters to their survival Sigismondi and Weber (1988). The rapidity of the response is affected if the fish is performing sub-optimally, and therefore may be used as a measure of performance with a link to survival (fish that behave abnormally or are conspicuous tend to be consumed in preference to those behaving “normally” {Coutant et al. 1979}).

This behavioural trait was examined and in a series of tests fish behaviour and the time (seconds) for individuals to seek cover was examined. The results were based on 100 trials for each experimental group following 47h exposure to 30,000 $mg \cdot L^{-1}$; equivalent to a SIE of 10.8, or 9-weeks exposure to 1000 $mg \cdot L^{-1}$; Newcombe and Jensen 1996).

	Control	Treated
Mean* (s)	25	93
Median* (s)	4	92
Not entering in 5 min (%)	22	39
Stuporous **(%)	3	19

**Excluding those fish that did not enter cover in 5 min:* treated fish took 3.7x longer to seek cover, based on mean response; 23x longer when based on median results;

Including those fish that did not enter cover within 5 min: treated fish took 2x longer to seek cover, based on mean response, 20.4x longer when based on median results. 17% more treated fish did not seek cover; 3% of control fish did not move**, and 6 times (19%) more treated fish were also stuporous**.

The results reveal that the more of the treated fish behaved abnormally. Not only did they take longer to find cover overall, but 17% more than those in the control group never went to cover. Similarly, the number of fish that did not move at all once challenged to seek cover was 16% greater than fish that behaved similarly in the control groups.

The conclusion from this component of the research was that the turbidity/suspended sediment treatment was acutely stressful to the fish and resulted in performance deficits and abnormal behaviour, which would jeopardize survival in the wild. Refer to Korstrom and Birtwell (2006) for more details of this study component.

Susceptibility to predation

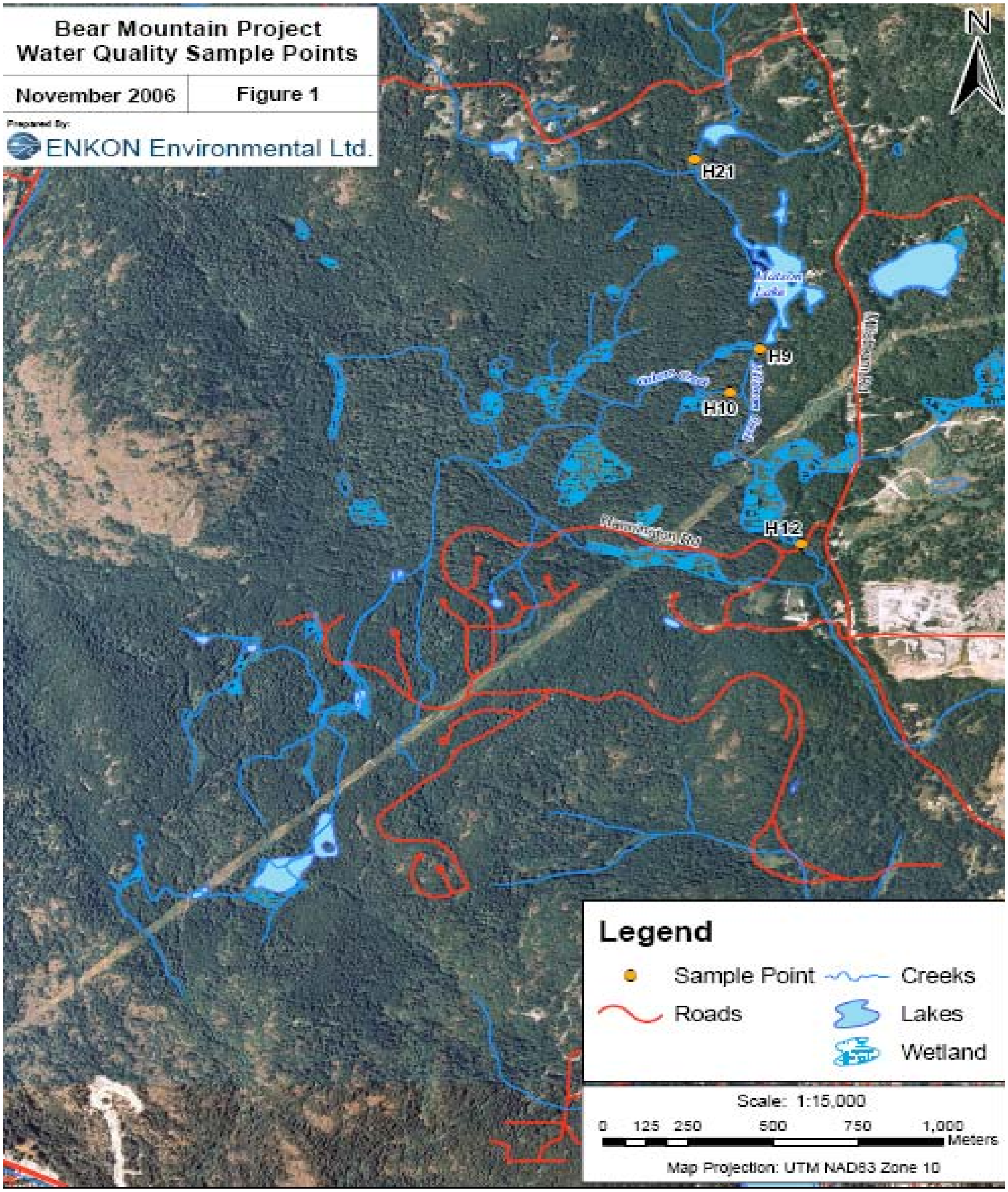
The significance of a SIE of 10 to the well being of the salmon was investigated through the use of a predation trial (120 min) with Burbot (*Lota lota*). Because fish live in a competitive environment in which the maintenance of health and performance are prerequisites for survival, fish that perform or behave abnormally or sub-optimally are potentially at greater risk form a predator than those not so affected. A SIE of 10 predicted that there would be an increase in susceptibility to predation.

Treated fish were exposed for 47h to 30,000 mg·L^{-1} suspended sediment {equivalent to a SIE of 10.8, or 9-weeks exposure to 1000 mg·L^{-1}; Newcombe and Jensen 1996}). Based on 12 experiments (20 control and 20 treated fish per trial).

Percentage of treated fish consumed	55.8 (134 of 240)
Percentage of control fish consumed	50.8 (122 of 240)

A 5% increase in predation of sediment-exposed fish was recorded relative to control fish, but variance in the data did not confer significance (α=0.05).

Appendix 2. Photograph of Bear Mountain golf course project Vancouver Island



Appendix. 3. Township of Langley adopted an Erosion and Sediment Control (ESC) Bylaw

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Erosion and Sediment Control Bulletin

Community Development Division
Development Engineering Department - Phone 604-533-6034
November, 2007

In September of 2006, the Township of Langley adopted an Erosion and Sediment Control (ESC) Bylaw. This bylaw included turbidity limits for runoff leaving development sites. The limits are:

- 25 Nephelometric Turbidity Units (NTU's) during normal weather (less than 25 mm of rain in the previous 24 hours) and
- 100 NTU's after a "significant rainfall event" (more than 25 mm of rain in the previous 24 hours.

Regular monitoring of discharge leaving development sites within the Township of Langley began in October of 2007.

To date,(November 2007) we have made 85 observations of discharge over 24 locations and 12 sampling days (not every location was observed on every sampling day).
For 60 of the 85 observations, discharge from the development site was occurring and a measurement of turbidity was taken. The remaining 20 observations found no discharge from the development site being observed and as such would automatically count as "in compliance" with the discharge limits of the Bylaw.
It must be taken into consideration that all of the sites observed began construction before the full implementation of ESC Permit requirements. It is likely that the level of ESC's at these sites is less than what will be found on sites developed after September 2007, which are required to obtain and adhere to an ESC Permit in accordance with the Bylaw.

Overall, the sites observed to date managed to comply with the Bylaw limits under most conditions. The exact rates of compliance are:

- Percentage of observations in compliance during normal weather conditions 73%
- Percentage of observations in compliance during a significant rainfall event 86%

If you only wish to consider sites that were discharging at the time of observation, the percentages change as follows:

- Percentage of discharges in compliance during normal weather conditions 62%
- Percentage of discharges in compliance during a significant rainfall event 47%

Overall compliance with bylaw limits (regardless of weather and discharge) 70%

For further information please contact the Erosion and Sediment Control Coordinator at (604) 533-6055.
Dave Anderson, Acting Manager Development Engineering Department
Township of Langley
Phone: 604-533-6047