Quantifying the Effects of Sediment Release On Fish and Their Habitats

Anderson, P.G., B.R. Taylor, and G.C. Balch.

Eastern B.C. Habitat Unit
Habitat and Enhancement Branch
Department of Fisheries and Oceans
555 West Hastings Street
Vancouver, British Columbia V6B 5G3

and

Alberta Area
Habitat Management Division
Department of Fisheries and Oceans
501 University Crescent
Winnipeg, Manitoba R3T 2N6

Canadian Manuscript Report of
Fisheries and Aquatic Sciences No. 2346

Fisheries and Oceans Pêches et Océans

Canada

Canadian Manuscript Report of Fisheries and Aquatic Sciences

Manuscript reports contain scientific and technical information that contributes to existing knowledge but which deals with national or regional problems. Distribution is restricted to institutions or individuals located in particular regions of Canada. However, no restriction is placed on subject matter, and the series reflects the broad interests and policies of the Department of Fisheries and Oceans, namely, fisheries and aquatic sciences.

Manuscript reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in *Aquatic Sciences and Fisheries Abstracts* and indexed in the Department's annual index to scientific and technical publications.

Numbers 1-900 in this series were issued as Manuscript Reports (Biological Series) of the Biological Board of Canada, and subsequent to 1937 when the name of the Board was changed by Act of Parliament, as Manuscript Reports (Biological Series) of the Fisheries Research Board of Canada. Numbers 901-1425 were issued as Manuscript Reports of the Fisheries Research Board of Canada. Number 1426-1550 were issued as Department of Fisheries and the Environment, Fisheries and Marine Service Manuscript Reports. The current series name was changed with report number 1551.

Manuscript reports are produced regionally but are numbers nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page. Out-of stock reports will be supplied for a fee by commercial agents.

Rapport manuscrit canadien des sciences halieutiques et aquatiques

Les rapports manuscrits contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui traitent de problèmes nationaux ou régionaux. La distribution en est limitée aux organismes et aux personnes de régions particulières du Canada. Il n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques du ministère des Pêches et des Océans, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports manuscrits peuvent être cités comme des publications complètes. Le titre exact paraît au-dessus du résumé de chaque rapport. Les rapports manuscrits sont résumés dans la revue *Résumés des sciences aquatiques et halieutiques*, et ils sont classés dans l'index annuel des publications scientifiques et techniques du Ministère.

Les numéros 1 à 900 de cette série ont été publiés à titre de manuscrits (série biologique) de l'Office de biologie du Canada, et après le changement de la désignation de cet organisme par décret du Parlement, en 1937, ont été classés comme manuscrits (série biologique) de l'Office des recherches sur les pêcheries du Canada. Les numéros 901 à 1425 ont été publiés à titre de rapports manuscrits de l'Office de recherches sur les pêcheries du Canada. Les numéros 1426 à 1550 sont parus à titre de rapports manuscrits du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 1551.

Les rapports manuscrits sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la converture et la page du titre. Les rapports épuisés seront fournis contre rétribution par des agents commerciaux.

Canadian Manuscript Report of Fisheries and Aquatic Sciences No. 2346

1996

QUANTIFYING THE EFFECTS OF SEDIMENT RELEASE ON FISH AND THEIR HABITATS

by

Paul Anderson[1], Barry Taylor[2] and Gordon Balch[3]

Eastern B.C. Habitat Unit
Habitat and Enhancement Branch
Department of Fisheries and Oceans
555 West hastings Street
Vancouver, B.C. V6B 5G3

and

Alberta Area
Habitat Management Division
Department of Fisheries and Oceans
501 University Crescent
Winnipeg, Manitoba R3T 2N6

[1] Golder Associates, 1011 Sixth Avenue SW
Calgary, Alberta T2P 0W1
[2] West Lochaker, RR5
Antigonish, Nova Scotia B2G 2L3
[3] RR #3
Lakefield, Ontario K0L 2H0

Cat. No. Fs 97-4/2346E ISSN 0706-6473

Correct citation for this publication is:

Anderson, P.G., B.R. Taylor, and G.C. Balch. 1996. Quantifying the effects of sediment release on fish and their habitats. Can. Manuscr. Rep. Fish. Aquat. Sci. 2346: 110 p. + 3 Append.

TABLE OF CONTENTS

SECTION	PAGE
ABSTRACT	vi
PREFACE	vii
ACKNOWLEDGMENTS	viii
1.0. INTRODUCTION	1
1.1. PROJECT BACKGROUND	1
1.2. PROJECT OBJECTIVES AND PURPOSE	2
2.0. REVIEW OF SEDIMENT EFFECTS ON FISH	5
2.1. THE LITERATURE REVIEW	5
2.2. PHYSIOLOGICAL STRESS	5
2.3. BEHAVIOURAL EFFECTS	6
2.4. PHYSIOLOGICAL EFFECTS	7
2.4.1. Growth	7
2.4.2. Blood Chemistry	7
2.4.3. Gill Trauma	8
2.4.4. Resistance	8
2.4.5. Phagocytosis	9
2.5. POPULATION EFFECTS	9
2.5.1. Egg Mortality	9
2.5.2. Juvenile and Adult Fish Death	9
2.6. SEDIMENT EFFECTS ON FISH - SUMMARY	10
3.0. SENSITIVITY OF THE RECEIVING ENVIRONMENT	11
3.1. KEY CONCEPTS AND PHYSICAL PROCESSES	11
3.1.1. Sediment Transport and Deposition	11
3.1.2. Suspended Sediments and Settleable Solids	11
3.1.3. Habitat Exclusion and Habitat Alteration	12
3.1.4. Changes in Stream Bed Porosity	12
3.1.5. Changes in Stream Morphology	12
3.2. SEDIMENTATION EFFECTS ON SPAWNING HABITATS	13
3.3. SEDIMENTATION EFFECTS ON FISH REARING HABITAT	14
3.4. SEDIMENTATION EFFECTS ON FOOD SUPPLY	14
3.5. THE COMPLICATIONS OF WINTER	15
3.5.1. Habitat Preferences of Fish in Winter	16
3.5.2. Environmental and Physiological Stresses on Fish During Winter	19
3.5.3. Impact of Sedimentation During Winter Conditions	22
3.6. SUMMARY OF HABITAT SENSITIVITY TO SEDIMENTATION	24
4.0. SEDIMENT DOSE/RESPONSE RELATIONSHIPS	25
4.1. EXISTING SUSPENDED SEDIMENT CRITERIA	25
4.2. THE DOSE/RESPONSE APPROACH	27
4.3. SPECIFIC DOSE/RESPONSE RELATIONSHIPS	28
4.4. DEVELOPING THE HABITAT EFFECTS DATABASE	31
4.5. DOSE/RESPONSE RELATIONSHIPS OF FRESHWATER HABITATS TO SEDIMENT RELEASES	31

TABLE OF CONTENTS (cont'd)

SECTION	PAGE
4.6. CONFOUNDING FACTORS	40
4.7. SUMMARY	42
5.0. SEDIMENT TRANSPORT MODELLING	45
5.1. EVALUATION OF EXISTING METHODS	46
5.1.1. Sediment Loading	46
5.1.2. Sediment Transport, Deposition, and Re-suspension	47
5.2. CONCEPTUAL MODEL DESIGN	51
5.2.1. Stream Crossing Data	52
5.2.2. Estimation of Sediment Load	52
5.2.3. Sediment Transport and Deposition	53
5.2.4. Sediment Re-suspension	54
5.3. OUTLINE FOR MODEL DEVELOPMENT AND TESTING	54
5.4. SUMMARY	55
6.0. RECOVERY	57
6.1. RECOVERY OF FISH FROM SEDIMENT EXPOSURE STRESS	57
6.2. RECOVERY OF AQUATIC ECOSYSTEMS FOLLOWING SEDIMENT EPISODES	58
6.2.1. Invertebrate Recolonization	58
6.2.2. Fish Community Recovery	59
6.3. RECOVERY OF AQUATIC HABITATS FOLLOWING SEDIMENT EPISODES	59
6.3.1. Sediment Accumulation	59
6.3.2. Sediment Removal	60
6.3.3 Factors Affecting Rate of Physical Habitat Recovery	60
6.4. SUMMARY	64
7.0. CONCEPT SYNTHESIS	67
7.1. LEVEL OF EXPOSURE	67
7.2. SENSITIVITY OF THE RECEIVING ENVIRONMENT	69
7.3. DURATION OF HABITAT IMPAIRMENT	69
7.4. SUMMARY	69
8.0. MONITORING SEDIMENT LOADS AND THE EFFECTS OF SEDIMENT RELEASE	71
8.1. SEDIMENT LOAD MONITORING	71
8.1.1. Sample Site Selection	71
8.1.2. Frequency of Sampling	73
8.1.3. Measurements of Suspended Sediment Load	74
8.1.4. Other Monitoring Parameters	75
8.2. MONITORING DATA ANALYSIS	76
8.2.1. Defining the Sediment Release Event	76
8.2.2. Calculation of the Sediment Dose	80
8.3. ESTABLISHING SEDIMENT EFFECTS CRITERIA	83
8.4. EFFECTS MONITORING	86
8.4.1. Measure of Sediment Deposition	86
8.4.2. Biological Monitoring	89
8.5. SUMMARY	90

TABLE OF CONTENTS (cont'd)

SECTION **PAGE**

9.0. FUTURE DIRECTION 91
9.1. QUANTIFYING THE EFFECTS OF VARYING GRAIN SIZE 91
9.2. PREDICTING SEDIMENT LOAD 91
9.3. SEDIMENT RE-SUSPENSION AND SYSTEM RECOVERY 91
9.4. DEVELOPING THE SEDIMENT TRANSPORT MODEL 91
9.5. DEVELOPMENT OF BETTER HABITAT EFFECTS RELATIONSHIPS 92

10.0 MANUSCRIPT SUMMARY 93

11.0. LITERATURE CITED 95

LIST OF TABLES

Table 4.1 Summary of Responses of Organisms and Their Habitats to Acute Sediment Exposure 33
Table 4.2 Statistics for the Multiple Regression Relationship (Equation 9) 38
Table 4.3 Comparison of Severity of Effects Scores (SE) Using Simple Linear Regression and Multiple Regression Equations 41
Table 8.1 Sediment Monitoring Data for Three Sediment Release Events 84
Table 8.2 Different Treatments for Estimating Central Tendency in TSS Data 85

LIST OF FIGURES

Figure 4.1 Responses of Organisms and Their Habitats to Sediment Exposure 36
Figure 4.2 Response of Organisms and Their Habitats to Sediment Release 37
Figure 4.3 Dose Response for Fish Habitat Effect as a Function of Concentration and Duration of Exposure 39
Figure 6.1 Relative Critical Discharges and Sediment Transport Capacities 62
Figure 6.2 Critical Unit Discharge for Bed Mobilization as a Function of Grain Size and Channel Slope 63
Figure 7.1 Risk of HADD 68
Figure 8.1 Stress Index from a Stream Crossing (contrived data) 78
Figure 8.2 Relationship Between Concentration (TSS in $mg \cdot L^{-1}$) and Cumulative Sediment Dose ($mg \cdot hr \cdot L^{-1}$) 82

LIST OF APPENDICES

Appendix 1 Literature Review of the Effects of Sediment on Fish and Habitat
Appendix 2 Sediment Release/Aquatic Response Database
Appendix 3 Ranking System for Assessing Silt Tolerance of Fish

ABSTRACT

Primary and secondary literature was reviewed to assess the effects of suspended sediment pollution on aquatic ecosystems. The intent of the review was to provide a better understanding of the effects of acute episodes of elevated suspended sediment concentration on fish and fish habitat, to aid in resource management decisions. Based on 35 data sets, a multiple regression was developed which quantifies the effect of acute sediment doses on fish habitat. In addition, a conceptual framework was developed to help predict sediment transport during and after stream disturbances such as construction. This framework is a first step toward a pragmatic model to predict the sediment loads, and hence the severity of habitat effects, downstream from construction sites. The effect of sediment releases on fishes downstream depends on the timing of the releases relative to fish habits and life-cycles, and the duration of habitat impairment. The latter, in turn, depends on physical properties of the watercourse such as discharge and gradient, as well as composition of the streambed and the deposited sediments, which together determine the rate of habitat recovery. Careful monitoring of sediment releases and physical and biological disturbance downstream is required to support informed management decisions and to gain further insights into effects of sediments on fish and fish habitat.

RÉSUMÉ

Nous avons examiné des sources primaires et secondaires d'information pour évaluer les effets sur de la pollution par les sédiments en suspension les écosystèmes aquatiques. L'objet de l'examen était de mieux comprendre les effets d'épisodes aigus de forte concentration de sédiments en suspension sur le poisson et son habitat afin d'aider à la prise de décisions en matière de gestion des ressources. A partir de 35 séries de données, nous avons effectué une régression multiple qui quantifie l'effet de doses aiguës de sédiments sur l'habitat du poisson. De plus, nous avons élaboré un cadre conceptuel qui aide à prédire le transport de sédiments pendant et après la perturbation d'un cours d'eau tel que, par exemple, un travail d'aménagement. Ce cadre est un premier pas vers la construction d'un modèle pragmatique qui permettra de prédire les charges en sédiments, et par là, la sévérité des effets sur l'habitat, en aval de travaux d'aménagement. L'effet de la libération de sédiments sur les ressources halieutiques en aval dépend du moment de cette libération par rapport aux habitudes et au cycle de vie des poissons, ainsi que de la durée de la perturbation de l'habitat. Cette dernière dépend elle-même des propriétés physiques du cours d'eau comme le débit et le gradient, ainsi que de la composition du lit et des sédiments déposés, qui conjointement déterminent les chances de rétablissement de l'habitat. Il est nécessaire de surveiller de près les libérations de sédiments et les perturbations physiques et biologiques en aval pour aider les gestionnaires à prendre des décisions éclairées et pour mieux comprendre les effets des sédiments sur le poisson et son habitat. Le rapport est assorti d'une bibliographie commentée et d'un sommaire des données sur les relations dose-effet.

PREFACE

This study was, in part, undertaken to provide background information to assist the Department of Fisheries and Oceans, Eastern B.C. Unit, in development of a management model. When finalized the model's purpose will be to facilitate standardized decision making with respect to specifying fish habitat compensation measures and protocols for monitoring sediment releases.

A previous version of this report was released as a contractor's report. It was prepared by Golder Associates Ltd. (Report Number 952-2207) for the Department of Fisheries and Oceans, Pacific Region, Habitat and Enhancement Branch, Eastern B.C. Unit, and Central and Arctic Region, Habitat Management Division, Alberta Area. This report includes minor editorial changes.

DISCLAIMER

The views expressed herein are those of the authors, and do not necessarily represent those of the Department of Fisheries and Oceans.

The models and relationships described in this report may serve to trigger further investigations and monitoring or assist in defining a scale for fines, penalties, compensation or remediation requirements. Not withstanding a potentially broad utility of these models and relationships, they are not intended as a guide for setting effluent criteria involving suspended sediment discharge. Any sediment release may pose a risk to fish and fish habitat.

ACKNOWLEDGEMENTS

The authors are sincerely grateful to the many people who have contributed their efforts to this project. We would like to thank H. Klassen[1] and G. Hopky[2] for presenting us with this interesting challenge and allowing us to tackle it in our own way. Thanks are also due to fellow study team members M. Digel[3] and J. Anderson[4] for their contributions to the sediment modelling section, A. McConnell[3] for her efforts in obtaining and summarizing the literature and S. Holroyd[3] for assembling the literature database. The authors are sincerely thankful to K. Brewin[5] for supplying his literature database on winter and fish and to I. Birtwell[6], S. Kerr[7], B. Chilibeck[8], F. Hnytka[2], K. West[1], B. Antcliffe[1], L. Powell[9], G. Hopky, H. Klassen and D. Fernet[3] for providing comments on an earlier version of this report. Finally, a great deal of thanks is extended to C. Newcombe[10] for providing us with his dose/response database, release of draft reports, insightful comments, and for his pioneering efforts in addressing these complex issues.

[1] Department of Fisheries and Oceans, Habitat and Enhancement Branch, Eastern B.C. Habitat Unit, Vancouver, B.C.
[2] Department of Fisheries and Oceans-Habitat Management Branch, Alberta Area, Winnipeg, MN.
[3] Golder Associates - Calgary, AB
[4] Golder Associates - Mississauga, ON
[5] Trout Unlimited Canada - Calgary, AB
[6] Department of Fisheries and Oceans - Fisheries Research Branch, Vancouver, B.C.
[7] Ontario Ministry of Natural Resources, Southern Region Science and Technology Transfer Unit. Brockville, ON
[8] Department of Fisheries and Oceans, Habitat and Enhancement Branch, Vancouver, B.C.
[9] Department of Fisheries and Oceans, Habitat and Enhancement Branch, Prince Rupert, B.C.
[10] B.C. Ministry of Environment, Lands and Parks, Habitat Protection Branch, Victoria, B.C.

1.0. INTRODUCTION

1.1. PROJECT BACKGROUND

Instream construction within a natural watercourse inevitably suspends sediment into the aquatic environment. The suspension and subsequent transport of fine-grained materials can have impacts on the aquatic biota living within the system and on the habitats upon which they rely. The potential effects of suspended sediments on aquatic organisms can be substantial; however, in general it is the potential for alterations to aquatic habitats which poses the possibility for long-term impacts to fish populations.

Despite the potential for aquatic system impacts which the suspension, transport and deposition of sediments pose, there is limited information which can be used directly to assess the likely effects that a given sediment pollution episode has had on the aquatic biota and aquatic habitats. As a result, management decisions both for prescribing mitigative measures prior to a sediment release event and for determining compensation requirements post-event are often difficult to make.

Regulatory agencies, as well as individuals conducting activities in and around watercourses, act within the confines of legislation in providing the necessary protection to fisheries resources. The Canada *Fisheries Act* contains provisions concerning the conservation and protection of fish habitat, paramount of which is Section 35. Subsection 35(1) is a direct prohibition which states that no person shall carry on any work or undertaking that results in the harmful alteration, disruption, or destruction (HADD) of fish habitat. However, where HADD cannot be avoided or mitigated, subsection 35(2) of the *Act* also provides latitude for the Minister of Fisheries and Oceans to authorize the means and conditions for allowing development projects to take place. The DFO policy for the Management of Fish Habitat (the Habitat Policy, DFO 1986) provides policy direction for interpreting the broad powers mandated in the habitat provisions of the *Fisheries Act*. The objective of the Habitat Policy is the achievement of an overall net gain in the productive capacity of fish habitat, and promotes habitat conservation and protection through the application of the guiding principle centered on achieving No Net Loss of habitat's capacity to produce fish.

When reviewing proposals for activities in and around watercourses, decision-makers must address whether the project will cause a HADD to fish habitat. HADD may be defined as any change in one or more fish habitat components that causes a reduction in the capacity of the habitat to support the life requisites of fish. Based on the potential of causing HADD to aquatic habitats, reviewers must make decisions on management actions related to the proposal.

Management actions can range from requesting more information, through to the issuance of letters of advice or Subsection 35(2) authorizations specifying the means to achieve No Net Loss, or, possibly, rejection of the proposal (e.g., DFO 1986, page 25). These actions are based on the judgement of decision-makers, using past experience and best professional judgement. In addition to the Habitat Policy (DFO 1986), DFO has recently developed the following guidance documents to aid in making decisions about the appropriate management actions:

- Draft Decision Framework for the Determination and Authorization of Harmful Alteration, Disruption or Destruction of Fish Habitat (DFO 1994).

- Fish Habitat Conservation and Protection, What the Law Requires. The Directive on the Issuance of Subsection 35(2) Authorizations. (DFO 1995a).

- Fish Habitat Conservation and Protection, Guidelines for Attaining No Net Loss (DFO 1995b).

1.2. PROJECT OBJECTIVES AND PURPOSE

The Alberta Area and Eastern B.C. Unit of DFO contracted Golder to undertake a study examining the effects of sediment episodes on fish and fish habitat. The goal of the study was to address specific sediment pollution-related issues and to develop decision-making criteria to aid resource managers in making decisions with respect to the effects of sediment episodes on fish and fish habitat.

The terms of reference for the project identified seven main objectives, which were to:

1. Survey and summarize primary and secondary literature sources on suspended sediment release as it relates to fish stress and HADD of fish habitat, focusing on freshwater fishes in British Columbia and Alberta.

2. Discuss specific sensitivities of fish habitats relative to sediment load increases. In particular, the influence of winter conditions on sediment release sensitivity.

3. Examine the relationship between harm to fish and HADD of fish habitat and the extent of sediment releases into streams under conditions found in British Columbia and Alberta.

4. Assess appropriate suspended sediment transport models as to their intended use, limitations, and feasibility of application in determining extent of fish stress and HADD of fish habitat under conditions normally experienced during pipeline water crossings in Alberta and British Columbia.

5. Identify the factors influencing recovery rates of fish and fish habitats following sediment pollution events.

6. Prescribe appropriate suspended sediment monitoring programs to complement the above analytical procedures.

7. Provide recommendations for future research.

Each chapter of this report focuses on one of the above objectives, with three additional chapters, including this introduction, a synthesis of key concepts and an overall manuscript summary. The report has been divided into ten chapters, presented as follows:

- Introduction

- The results of the literature review on sediment effects on fish;

- A discussion of the sensitivity of the receiving environment;

- Presentation of sediment release/aquatic response relationships;
- Assessment of sediment transport models;
- Discussion of factors influencing rate of recovery;
- A synthesis of key concepts discussed;
- Guidelines for monitoring sediment loads and effects of sediment release;
- A discussion of needs for future work; and,
- An overall summary section.

There are also three appendices, including a literature review of the effects of sediment on fish and habitat presented in bibliographic format, a sediment release/aquatic response database, and the ranking system for assessing silt tolerance of fish (Poff and Allan 1995).

The relationships of biological responses to sediment releases synthesized from this literature review provides regulatory agencies and development proponents with a post-event process to analyze impacts of a given sediment pollution episode. Foreknowledge of these relationships can also aid development proponents in planning the level of mitigation appropriate for a project which is likely to generate sediment releases to riverine environments. For additional information pertaining to this topic or to obtain additional references, the reader is directed to Newcombe (1994a), Newcombe and Jensen (1995a), Kerr (1995), and Waters (1995).

2.0. REVIEW OF SEDIMENT EFFECTS ON FISH

2.1. THE LITERATURE REVIEW

One must have detailed knowledge of the likely effects of increased sediment loads to make informed decisions regarding sediment release management actions. A literature review was conducted to identify the available information pertaining to the effects on fish behaviour, fish health and fish habitat resulting from increased concentrations of total suspended solids (TSS) and increased rates of sedimentation. The literature search was conducted on the Biological Abstracts, Aquatic Sciences and Fisheries Abstracts, Water Resources Abstracts, Compendex Plus, and Fish and Wildlife Reference Service databases. The search of U.S. Fish and Wildlife technical reports was conducted by the Fish and Wildlife Reference Service. All other searches were conducted by Golder staff.

The search resulted in the compilation of 244 references dealing specifically with the effects of increased suspended sediments and increased sedimentation rates upon fish and fish habitat. This database contains information from 62 different sources and covers a span of 45 years of publication. The annotated database contains information related to the effects of sediment on fish behaviour (larval to adult), physiological responses (blood chemistry, gill trauma), egg survival, growth and habitat effects (direct and indirect).

The literature acquired in the search has been included in a database using the Reference Manager® bibliographic software. Each entry into the database includes: the manuscript author; year of publication; manuscript title; the name of, and location within, the journal, proceedings or symposium in which it was published; the publisher (if the manuscript was a book); a list of keywords for searching and cross-referencing purposes; and, an abstract which summarizes the document. A print-out of the database has been included as Appendix 1 of this report and a diskette has been enclosed in the map pocket at the end of the report which contains the reference manager database.

A summary of the literature with respect to sediment effects on aquatic ecosystems is presented in Chapters 2 & 3. The adverse effects of sediments on aquatic resources have been divided into the adverse effects of suspended sediments on fish health (Chapter 2) and the effects of sedimentation on aquatic habitats (Chapter 3).

2.2. PHYSIOLOGICAL STRESS

Stress has been defined as "the sum of all the physiological responses by which an animal tries to maintain or re-establish a normal metabolism in the face of a physical or chemical force" (Selye 1950 cf Wedemeyer *et al.* 1990). Stress occurs when the homeostatic or stabilizing processes of the fish or organism are extended beyond the capabilities of the organism to compensate for the biotic or abiotic challenges. Acclimation to the stress can occur if compensatory physiological responses by the fish are able to re-establish a satisfactory relationship between the changed environment and the organism (Wedemeyer *et al.* 1990). There is, however, a cost to the maintenance of the compensatory responses. The ability of an individual fish to acclimate or tolerate the stress will therefore depend on the severity of the stress and the physiological limits of the individual.

Anthropogenic inputs of sediments into stream and riverine environments can cause stress, and thereby, directly and indirectly impact upon fish behaviour and health. The results of the impact can be measured at both the organism and population levels. Newcombe (1994a) summarized much of the existing literature concerning the effects of increased concentrations of suspended sediments. Increased concentrations of suspended sediments can have direct effects on fish behaviour, fish physiology and fish populations. Each of these direct effect mechanisms is discussed below.

2.3. BEHAVIOURAL EFFECTS

Changes in fish behaviour are some of the first effects evoked from increasing concentrations of suspended sediments. Behavioural changes are generally considered benign and transitory. They are easily reversed and do not exhibit a long-lasting impact (Newcombe 1994a). Typical responses include an increased frequency of the cough reflex, avoidance of suspended sediments, a reduction in feeding and temporary disruption of territoriality.

The avoidance of suspended sediment plumes is one of the first reactions. Bisson and Bilby (1982) observed this behaviour evoked in juvenile coho salmon (*Oncorhynchus kisutch*) at TSS concentrations as low as 88 mg/L. Similar results were recorded by McLeay *et al.* (1987) who found that Arctic grayling (*Thymallus arcticus*) avoided concentrations greater than 100 mg/L. Saunders and Smith (1965) found evidence of similar behaviour in brook trout (*Salvelinus fontinalis*) that avoided silt-covered areas and were associated with only silt-free spaces at the head of the riffles. During a pipeline crossing of a coldwater stream, Porter *et al.* (1974) found that increased concentrations of suspended sediments resulting from construction resulted in the downstream drift of Arctic lamprey (*Lampetra japonica*), lake chub (*Couesius plumbeus*), burbot (*Lota lota*), trout-perch (*Percina omiscamaycus*) and slimy sculpin (*Cottus cognatus*) juveniles. Interestingly, however, were the observations of Noggle (1978) who found that downstream drift was not observed in juvenile coho salmon until concentrations were between 4000 to 8000 mg/L. Noggle (1978) performed his studies in an experimental stream under coldwater, winter-like conditions.

Increased concentrations of suspended sediment have also been correlated with a reduction in feeding. The rate of feeding is believed to be a function of a reduced ability to see the prey. McLeay *et al.* (1987) states that Arctic grayling exposed to suspended sediment concentrations greater than 100 mg/L were slower to recognize the food and more frequently missed a food item as they attempted to seize it. Sigler *et al.* (1984) believes however, that a reduction in feeding is a complex mechanism which extends beyond a reduced ability to see prey items, as many fish species (especially benthic feeders) do not use sight to identify prey items.

Noggle (1978) noticed that feeding was reduced in coho salmon at suspended sediment concentrations as low as 25 mg/L and feeding stopped at concentrations greater than 300 mg/L. Gardner (1981) noticed that this behaviour was not apparent in warmwater bluegill (*Lepomis macrochirus*) until concentrations reached 423 mg/L. Porter *et al.* (1974) noticed that the stomachs of trout-perch, lake chub, slimy sculpin and longnose sucker (*Catostomus catostomus*) captured downstream of a pipeline crossing contained fewer invertebrates than did fish from upstream locations. This was interpreted by Porter *et al.* (1974) to be due to a reduction in feeding.

High concentration of suspended sediments have also been associated with the loss of territoriality and interruption of migrational movements of salmonids. Berg and Northcote (1985) found that territorial behaviour was lost at concentrations exceeding 30 NTU. They indicate that territoriality is influential in the allocation of food and habitat resources. Disruption to territoriality can occur when turbidity limits the visual distance that individuals can see, and when the downstream drift of fish avoiding increased concentrations of suspended sediment disrupts existing territories. It appears that relatively high TSS concentrations are required to disrupt the seasonal migration of salmonids. IPSFC (1964 cf Noggle 1978) noticed that the migration of sockeye salmon (*Oncorhynchus nerka*) was temporally interrupted when a landslide caused the concentration of suspended sediment to increase beyond 4000 mg/L.

2.4. PHYSIOLOGICAL EFFECTS

Physiological changes can be measured in fish as a response to the increased stress of suspended sediments. The typical measured responses include impaired growth, histological changes to gill tissue, alterations in blood chemistry, and an overall decrease in health and resistance to parasitism and disease. The effects of sediment exposure on each of these physiological effects is discussed below. Longer exposure periods and/or higher concentrations are generally required before physiological responses are expressed. In this respect, physiological responses are more of a chronic effect. The effects are usually a graded response to increasing sediment dose. Impacts evoked from lower doses can be transitory, while those resulting from higher doses can be more lasting and severe.

2.4.1. Growth

An impaired growth rate is generally one of the more sensitive physiological responses to an increase in suspended sediment concentration. Unlike behavioural responses, impaired growth generally requires a longer exposure period before effects are manifested. Sigler *et al.* (1984) found that growth was impaired in juvenile steelhead trout (*Oncorhynchus mykiss*) and coho salmon exposed to fire clay or bentonite clay at concentrations between 84 and 120 mg/L during a 14 to 21 day exposure period. Similar concentrations of 100 mg/L or greater were found to significantly impair growth in Arctic grayling under-yearlings (McLeay *et al.* 1987), largemouth bass (*Micropterus salmoides*), bluegills, and redear sunfish (*Lepomis gibbosus*) (Buck 1956). However, growth impairment may be related more to the metabolic demands resulting from stress caused by increased suspended sediment than from a reduction in feeding. The time required before growth impairment was measurable ranged from a low of two weeks for juvenile steelhead and coho to a high of six weeks for Arctic grayling under-yearlings (Sigler *et al.* 1984; McLeay *et al.* 1987).

2.4.2. Blood Chemistry

Alteration in blood chemistry resulting from the increased stress of suspended sediments have been found associated with concentrations ranging between 500 to 1500 mg/L (Redding and Schreck 1982 cf Newcombe 1994a; Servizi and Martens 1987). The changes most commonly recorded include an increase in haematocrite, erythrocyte count, hemoglobin concentration, and elevated blood sugar levels (hyperglycemia), plus decreases in blood chloride content, and depletion of liver glycogen (Wedemeyer *et al.* 1990; Servizi and Martens 1987). These increases coincide with the release of stress hormones (i.e., cortisol and epinephrine) and traumatization of the gill, and presumably represent a compensatory response to a decrease in gill function (Newcombe 1994a). In addition Sherk *et al.* (1975 cf Newcombe 1994a) found these changes to be associated with a reduction in the swimming endurance of white perch (*Morone americana*) exposed to 650 mg/L of TSS. Most of the observed changes resulted after four to five days of exposure (Newcombe 1994a). Exceptions to this, however, were noticed by Redding and Schreck (1982 cf Newcombe 1994a). They found a significant increase in haematocrit volume within steelhead trout after only 9 hours of exposure to 500 mg/L of volcanic ash, clay and topsoil.

2.4.3. Gill Trauma

Increased concentration of suspended sediments are known to physically traumatize gill tissue. The primary mechanisms of action is through physical abrasion of tissue and particle adsorption onto the gill. The types of tissue changes observed include swelling of secondary lamella and hypertrophy (cell swelling) of epithelial cells (Sherk *et al.* 1973); hyperplasia (increase in cell number) of gill tissue (Simmons 1984); and, tissue necrosis (Servizi and Martens 1987).

The severity of damage appears to be related to, not only the dose of exposure, but also the size and angularity of the particle. Greater damage is typically observed with larger, more angular particles (Servizi and Martens 1991). These factors could account for the large range in responses seen for different exposure rates. For example, concentrations as low as 270 mg/L are known to cause gill damage in rainbow trout after 13 days of exposure (Herbert and Merkens 1961) and yet McLeay *et al.* (1987) found no gill damage in young-of-the-year (YOY) Arctic grayling that were exposed to concentrations as high as 1300 mg/L; the duration of exposure was, however, only 4 days.

Secondary effects resulting from an infestation of parasitic protozoans were found in juvenile rainbow trout that were exposed to extremely high concentrations of suspended sediments. The trout were exposed to 4887 mg/L for a period of 16 days (Goldes 1983). This author did note that the protozoan infection and gill architecture was found to be normal 58 days after the exposure had ceased.

2.4.4. Resistance

Increased concentrations of suspended sediments have been associated with an overall decrease in the ability to defend against disease and to tolerate chemical toxins. For example, Herbert and Merken (1961) observed rainbow trout to be more susceptible to infestations of fin rot when fish were exposed for 121 days to concentrations of 270 mg/L of diatomaceous earth. Likewise, Servizi and Martens (1991) found a correlation between the prevalence of a viral kidney infection and an increased concentration of suspended sediments in coho salmon. When concentrations of suspended sediments exceeded 100 mg/L, the tolerance of Arctic grayling to the toxicant pentachlorophenol (PCP) decreased (McLeay *et al.* 1987). This observation by McLeay *et al.* (1987) indicates a general decrease in tolerance to increased environmental stressors.

2.4.5. Phagocytosis

A process which may be closely linked to reduced resistance, is phagocytosis. Newcombe and Jensen (1995a) discuss the process by which fine particles are enveloped by cells within fish gill and gut tissues and are transported to internal repository tissues. The main organ of repository in fish is the spleen (Newcombe and Jensen 1995a). It is hypothesized that through this process, particles could reduce resistance to other stressors by impairing fish health. In addition, particles could trigger tumorigenesis, especially in circumstances where contaminants were adsorbed to particles in suspension (Newcombe and Jensen 1995a).

2.5. POPULATION EFFECTS

Increased concentrations of suspended sediments and increased sedimentation rates have the potential to affect fish populations. The primary mechanisms of action are through increased egg mortality, reduced egg hatch, a reduction in the successful emergence of larvae, plus the sediment-induced death of juvenile and adult fish.

2.5.1. Egg Mortality

The primary cause of egg death is from burial by settled particles. Thin coverings (a few mm) of fine particles are believed to disrupt the normal exchange of gases and metabolic wastes between the egg and water. Sedimentation rates of 0.03 to 0.14 g dry weight sediment/cm^2 (i.e., 1-4 mm depth of silt and clay) significantly reduced the survival of lake whitefish (*Coregonus clupeaformis*) eggs (Fudge and Bodaly 1984). The effects upon egg mortality appear to be more closely related to the sedimentation of particles and less related to the concentration of suspended sediments. Zallen (1931) observed that concentrations of 1000 to 3000 mg/L had no effect upon the survival of mountain whitefish eggs (*Prosopium williamsoni*). Campbell (1954 cf Singleton 1985), however, found 100 percent mortality in rainbow trout eggs exposed to TSS concentrations of 1000 to 2500 mg/L. Campbell (1954 cf Singleton 1985) suggests that the primary mechanism of death was from sedimentation.

The concentration of suspended sediments and the duration of exposure appear to be key factors in determining the effect to egg survival. Slaney *et al.* (1977 cf Newcombe 1994a) noticed that hatching success was reduced in rainbow trout eggs after 2 months of exposure to 57 mg/L. A significant reduction in the hatching success of white perch and striped bass (*Morone saxatilis*) was observed in only 7 days after exposure to much higher TSS concentrations that approached 1000 mg/L (Auld and Schubel 1978 cf Newcombe 1994a). The dose of sediment required to induce egg mortality is greatly influenced by the physical characteristics of the stream which affect flow rates and the capacity to maintain sediments in suspension or otherwise to result in their deposition.

2.5.2. Juvenile and Adult Fish Death

Juvenile and adult fish generally appear to be more resilient to the stress of suspended sediments than other age classes. Short term increases in TSS concentrations between 11000 and 55000 mg/L appears to be the point at which salmonids mortality significantly increases (Stober *et al.* 1981 cf Newcombe 1994a; Servizi and Martens 1987; Smith 1940 cf Newcombe 1994a).

2.6. SEDIMENT EFFECTS ON FISH - SUMMARY

A review of the literature suggests that broad generalizations can be presented concerning the impact that suspended sediments exert on fish. Like all generalizations, there are exceptions. A summary of the major trends, however, indicates that:

- Behavioural responses are typically the first impacts evoked by increased concentrations of suspended sediments. Most behavioural responses are temporary and do not result in health effects. However, alterations in behaviour can alter growth patterns or increase susceptibility of fish to predation. The magnitude of the physiological change is a graded response and is dependent on the concentration of sediment release, duration of exposure, water quality parameters (e.g., temperature) and physical properties of the sediment particle. Low concentrations or short exposure periods generally result in minor physiological changes which revert to normal conditions once the sediment concentration returns to background levels. The impact of exposure to higher concentrations or longer exposure periods are manifested in a greater severity of change. In the extreme case this will lead to fish death.

- Juvenile and adult fish are often able to tolerate moderately elevated concentrations of suspended sediments over short time periods with minor physiological impact (Newcombe 1994a). Fish of these life stages are often able to move away from the highest concentration and therefore minimize the impact. The long-term indirect impacts resulting from a reduction in food supplies may have a greater significance than the direct physiological impact.

- Long-term exposures to low concentrations of suspended sediments may result in physiological changes and indirect effects that are similar in severity to those caused by short-term exposure to high concentrations. Under this scenario, the rate of impact may be gradual enough to allow juveniles and adults to seek alternative habitat. The long-term, cumulative impact on eggs and larvae may, however, be similar to the effect resulting from a short-term exposure to high concentrations.

- The larval life stage of salmonids is the most sensitive to increasing concentrations of sediments. Salmonid eggs are marginally more tolerant. The sensitivity of these two life stages is likely related to an inability to avoid the sedimentation and strict habitat requirements.

3.0. SENSITIVITY OF THE RECEIVING ENVIRONMENT

A main consideration of resource managers when determining the potential for risk to aquatic systems posed by a sediment release event is the sensitivity of the system during the sediment release episode. Flow condition is an important consideration in determining the sensitivity of a sediment release event, since the flow present within the watercourse during the period of elevated sediment load is the key factor in determining the concentrations of suspended sediment, the transport characteristics of the sediment and the ability of fish to emigrate from areas of elevated sediment load. In addition to the discharge conditions during construction, a second (and related) factor of consideration in determining specific system sensitivity is the season in which construction activities occur and life stages and habitat requirements of the fish in the receiving environment.

In this chapter we investigate the effects of sediment exposure on fish habitat. We discuss the relative sensitivities of certain habitats to increases in sediment loads or increased deposition, and relate how the habitat requirements of particular fish species and life stages effect their sensitivity to sediment exposure.

3.1. KEY CONCEPTS AND PHYSICAL PROCESSES

3.1.1. Sediment Transport and Deposition

At a certain water velocity, large sediment particles may travel downstream by bouncing and sliding along the stream bed; this mechanism of transport is known as bedload transport. At the same water velocity, smaller particles may be transported in suspension by the turbulence of the water; this component of the transported sediment load is known as suspended load. The suspended load also includes finer particles in near-permanent suspension (which is referred to as the wash load fraction). Bed load and suspended load may occur simultaneously, but the borderline between the two is not well defined. As sediment is transported through a watercourse, it sometimes encounters areas where the stream no longer has sufficient energy for its transport, at which point the sediment particle is deposited. There are two main mechanisms through which material being transported will be deposited. These mechanisms are direct settlement (which refers to the settlement of a particle by the force of gravity), or entrapment of a particle within the interstitial areas of a stream bed.

3.1.2. Suspended Sediments and Settleable Solids

There is not a clear distinction between that fraction of the sediment load which remains in suspension and the fraction which deposits on the stream bed. For the purposes of this discussion, the sediment load will refer to the entire increase in sediment transported that result from the sediment release event. The suspended sediment fraction will be that portion of the sediment release which can be transported in suspension (mainly silts and clays). The settleable solids portion will be considered that portion of the sediment release which returns quickly to the stream bed and, if it does not remain there indefinitely, moves downstream mainly via bed load transport processes. Kerr (1995) classifies the suspended sediment load as silt-clay sized particles (< 62 microns); therefore, settleable solids would be classed as particles greater than 62 microns in size.

Although the distinction between suspended material and settleable material is difficult to make, this distinction is important for discussions of habitat alteration, since it is the coarser-sized material (sands) which deposit on the stream bed and smother or scour sensitive biota and habitats as they are transported through the aquatic system.

3.1.3. Habitat Exclusion and Habitat Alteration

In addition to the direct impacts of suspended sediments on fish as outlined in Chapter 2, increases in sediment loads can also alter fish habitat or the utilization of habitats by fish (Scullion and Milner 1979, Lisle and Lewis 1992). High sediment loads can alter fish habitats temporarily by affecting water quality, making a stream reach unsuitable for use by fish. This exclusion of fish from their habitat, if timed inappropriately, could have impacts on a fish population if the habitat within the stream reach affected is critical to the population during the period of the sediment release. This principle of habitat exclusion is very important in considering the timing of sediment release episodes; however, this issue is separate from the issue of direct habitat alteration which will be discussed below. Sediment episodes can have a prolonged effect on the suitability of habitats within a stream reach through increased levels of sedimentation. In fact, sedimentation is the single most important effect associated with sediment load increases, since sediment loads can alter the gross morphology of streams as well as the composition of the stream bed.

3.1.4. Changes in Stream Bed Porosity

Larger-sized materials, such as fine to coarse sand, deposit downstream of sediment release. This material may accumulate on the surface of the stream bed or filter down into the inter-gravel spaces. Interstitial spaces can become clogged by the downward or, to a lesser extent, by the horizontal movement of sediment (see Section 6.3.1).

Water movement through the stream bed materials is important for the benthic communities which reside there, and for the developing embryos of fish species who bury their eggs. Inter-gravel water movement is controlled by several hydraulic and physical properties of the stream and its bed. The permeability of the stream bed is determined by size composition of the substrate material, viscosity of the water (temperature dependent) and the packing of the substrate material (Stuart 1953, Cooper 1965). A small increase in the proportion of fine material can severely reduce the porosity and permeability of the gravel bed (Lisle and Lewis 1992).

3.1.5. Changes in Stream Morphology

In addition to altering stream bed composition, sediment derived from construction activity can also change channel geometry (Klein 1984). Sediment release can reduce the depth of pools and produce a net reduction in riffle areas. This accumulation of stream bed deposits can translate into a reduction in available habitat. For example, deposition of sediments in pools and other areas of instream cover can cause a decrease in fish holding capacity of a stream reach (Bjornn *et al.* 1977). Smith and Saunders (1965) found that decreased brook trout populations were related to infilling of available cover. As well, Alexander and Hansen (1992) noted than a decrease in sand bedload sediment was associated with an increase in rainbow and brown trout (*Salmo trutta*) populations. Changes in physical morphology of the stream can also inhibit the movement of fish or change the distribution of adult fish (Alabaster and Lloyd 1982).

Channels affected by sediment derived from anthropogenic sources are also more transitory in nature. Fox (1974) found that urban channels exhibited a 33% change in geometry per month as compared to a 5% change per month in rural drainages. Sediment material deposited within streams can be in constant motion as bedload transport processes slowly move the deposited materials through the system. This material in motion can increase bed scour and bank erosion as the sediment increases the erosive force of the water, almost as if the channel was being "sand blasted".

3.2. SEDIMENTATION EFFECTS ON SPAWNING HABITATS

River spawning salmonids typically deposit their eggs in gravel beds commonly found in the upper reaches of river systems. In the case of brown trout, eggs are typically buried in the interstitial spaces of the substrata to a depth between 9 to 12 cm (Grost *et al.* 1991). Larvae remain in the interstitial spaces until the start of exogenous feeding. The movement of water through the incubation substrate is a key factor in determining the survival rate of incubating eggs.

An increase in percent of fine material in the stream bed can have impacts on egg survival rates (Shaw and Maga 1943, Cordone and Kelley 1961), since it reduces stream bed permeability. This reduces the interchange between stream flow and water movement through the redd, can result in a reduction in the supply of dissolved oxygen to the egg and is a hindrance to the removal of metabolites. Slaney *et al.* (1977b cf Singleton 1985) reported that rainbow trout egg survival was significantly reduced when spawning gravel contained more than 3% of fines (diameter 0.297 mm). In addition, Hall and Lantz (1969 cf Singleton 1985) determined that the hatching success of coho salmon and cutthroat trout was reduced by 40 to 80% percent when the spawning substrate contained 20 to 50% fines (1-3 mm diameter).

Even if intergravel flow is adequate for embryo development, sand that plugs the interstitial areas near the surface of the stream bed can prevent alevins from emerging from the gravel (Koski 1966, Phillips *et al.* 1975). For example, the emergence success of westslope cutthroat trout (*Oncorhynchus clarki*) was reduced from 76% to 4% when fine sediment was added to redds (Weaver and Fraley 1993).

Female salmonids clean an area of the stream bed in which to bury their eggs. This nest building activity does flush away sediments and increases the stream bed permeability. With time, sediment conditions within the redd gradually return to ambient levels (Wickett 1954; McNeil and Ahnell 1964). Under normal conditions, this slow increase in sediment intrusion is not a problem; however, increased levels of sediment within a system as a result of sediment release episodes increase the rate and level of sediment intrusion and reduces the period of time in which the redd is clean. The period of time before sediment intrusion into the redd is very important with respect to the survival of salmonid larvae. Studies by Wickett (1954) suggest that sediment accumulation during early embryonic development may result in higher egg mortalities than if deposition occurs after the circulatory system of developing larvae is functional. This may be due to the higher efficiency in oxygen uptake by the embryo with a functional circulatory system (Shaw and Maga 1942).

3.3. SEDIMENTATION EFFECTS ON FISH REARING HABITAT

Sediment deposition also affects rearing habitat of juvenile fish since young fish frequently use the interstitial spaces in the stream bed for cover. Thus, reductions in the suitability of potential rearing habitat as a result of sediment introduction is related to a reduction in the space available for occupancy (Reiser *et al.* 1985). When pools and interstitial spaces in gravel are filled with sediment, the total amount of habitat available for rearing is reduced (Bjornn *et al.* 1977). Griffith and Smith (1993) found that numbers of juvenile rainbow and cutthroat trout decreased due to lack of available cover in heavily embedded gravel substrata. Interstitial space is particularly important during winter because juvenile fish live in these areas making them especially susceptible to impacts from increased sedimentation (Bjornn *et al.* 1977). Without this inter-gravel refugia, the young fish may be forced out of the stream system or into less suitable areas where survival rate may be reduced.

3.4. SEDIMENTATION EFFECTS ON FOOD SUPPLY

Sedimentation can have an effect on fish populations through an alteration in the available food supply. The effects of increased sediment load and increased sedimentation on primary and secondary productivity are discussed below.

Primary Productivity

Increased concentrations of suspended sediments and increased rates of sedimentation can reduce the primary productivity of the impacted area. Periphyton communities are likely the most susceptible to the scouring action of suspended particles or burial by sediments. At concentrations exceeding 115 mg/L, suspended sediments can reduce light penetration (Hollis *et al.* 1964 cf Singleton 1985) and in turn reduce primary productivity (Singleton 1985). A reduction in primary productivity has the potential to appreciably decrease the food supply of macrobenthos which graze on periphyton. Many macrobenthic organisms are, in turn, used as a food source by fish.

Secondary Productivity

Increased sediment loads in streams can also have an effect on zooplankton and macrobenthos. Sediment release can effect the density, diversity and structure of resident invertebrate communities (Gammon 1970, Lenat *et al.* 1981). A number of studies have demonstrated decreases in invertebrate densities and biomass following sedimentation events (Wagener 1984, Mende 1989). Increases in sediment input may reduce the density of invertebrates by directly impacting aspects of their physiology or by altering their habitat. Suspended sediments can have an abrasive effect on invertebrates and interfere with the respiratory and feeding activities of benthic animals (Tsui and McCart 1981). Increased sediment deposition may also reduce the biomass of invertebrates by filling the interstitial spaces of the bottom substrata with sediments and by increasing invertebrate drift or covering the benthic community in a blanket of silt (Cordone and Kelley 1961, Tsui and McCart 1981). Increases in sediment deposition that affect the growth, abundance, or species composition of the periphytic (attached) algal community will also have an effect on the macroinvertebrate grazers that feed predominantly on periphyton (Newcombe and MacDonald 1991).

A change in particle-size distribution in the stream bed can alter the habitat and make it unsuitable for certain species of invertebrates. Gammon (1970) noticed that an increase in suspended sediments from 40 to 120 mg/L resulted in a 25 to 60% decrease in the density of stream macroinvertebrates. Likewise, Slaney *et al.* (1977a cf Singleton 1985) found that a 16 hour pulse of suspended sediments (2500 to 3000 mg/L) effected a 75% reduction of invertebrate biomass within the most affected areas.

Sedimentation can alter the structure of the benthic invertebrate community by causing a shift in the proportion from one functional group to another. For example, streams with good water quality normally contain a high proportion of invertebrates in the shredder group; however, if sediment deposition is substantially increased, there may be shifts to other groups such as grazers (Bode 1988) or collector-gatherers (Wagener 1984). Some studies have indicated that increased inputs of sediments cause a shift towards chironomid-dominant benthic communities (Rosenberg and Snow 1975, Dance 1978, Lenat *et al.* 1981).

Macroinvertebrate Drift

Benthic fauna possess behavioural and morphological adaptations which limit them from being displaced in a unidirectional flow environment (Hynes 1973). Invertebrate drift, however, is a continuous redistribution mechanism that occurs in most stream ecosystems. It is an important factor in the regulation of population density (Williams and Hynes 1976), in the dispersion of aggregations of young larvae (Anderson and Lehmkuhl 1967), in the abandonment of unsuitable areas (Williams and Hynes 1976, Gore 1977) and in the recolonization of disturbed areas (Barton 1977).

The rate of macroinvertebrate drift can be variable and is influenced by several factors, including hydraulic conditions of the watercourse, diurnal periodicity and season (Anderson and Lehmkuhl 1967, Rosenberg and Wiens 1978). The seasonal variation encountered in macroinvertebrate drift may reflect the life histories of the invertebrates involved (Elliott 1967a, 1967b).

There is some evidence to suggest that increases in invertebrate drift may be induced by elevated suspended sediment levels (Rosenberg and Weins 1978). Increased rates of downstream drift by macrobenthos is known to be induced by concentrations as low as 23 mg/L (Rosenberg and Snow 1975). Drifting affords invertebrate taxa that are sensitive to increased sediment loads the opportunity to avoid areas which become unsuitable as a result of the high suspended sediment levels. Conversely, invertebrate drift is considered to be the most important component of ecosystem recovery following stream disturbances (Williams and Hynes 1976, Barton 1977, Young 1986). This is especially true in areas of swift-flowing waters (Waters 1964).

3.5. THE COMPLICATIONS OF WINTER

The winter season is a period in the life cycle of aquatic communities for which comparatively little information is known. In addition, winter is a favoured time for instream construction activities due to ease of access to remote or wet areas. The relative effects of sediment releases in the winter is, therefore, a topic of specific interest to resource managers and decision makers. As a result, a large part of this chapter on sensitivity to sediment release has been dedicated to the investigation of winter habitat preferences, condition of fish in the winter and the effects of sediment introduction on fish overwintering habitat.

The first undertaking within this study component was to assemble relevant literature related to winter effects on fish habitat preference and physiological condition. Kerry Brewin (pers. comm. Trout Unlimited Canada) has been assembling a literature database related to fish during winter conditions. Mr. Brewin provided us with this database, which was expanded upon where possible over the course of this investigation. A summary of the most pertinent literature on this topic is summarized below.

3.5.1. Habitat Preferences of Fish In Winter

The study of fishes in running water during the winter season has been given much attention over the past thirty years in the fisheries related literature (Hartman 1965; Power and Coleman 1967; Chapman and Bjornn 1969; Hunt 1969; Bustard and Narver 1975; Butler 1982; Rimmer *et al.* 1983; Cunjak and Power 1986; Chisholm *et al.* 1987; Swales *et al.* 1986, 1988; Cunjak 1988, 1995; Cunjak and Randall 1993; Brown 1994). However, due to the limitations of standard fisheries investigations, the logistical difficulties in conducted field work, and the difficulties in observing fish during these periods, our understanding of winter habitat preferences and the factors influencing habitat selection remains quite incomplete.

The characteristics of overwintering habitats used by fish are significantly different from those sites selected at other times of the year. Fish physiology during winter conditions is characterized, particularly in young fish, by a reduction in metabolic activity with growth being negligible or non-existent (Metcalfe and Thorpe 1992; Cunjak 1996). This is in direct contrast to summer conditions when growth and reproductive maturity occurs. The selection of winter habitat is governed primarily by a need to mininize energy expenditure and thus conserve energy reserves during a time that is typically stressful to fish (Cunjak 1996). The availability of winter habitat is often limited within stream environments and is therefore frequently considered to be the primary factor regulating abundance within lotic fish populations (Cunjak 1996). The characteristics associated with preferred winter habitat are those that provide the fish an environment in which energy expenditures are minimized:

1. Protection from adverse physical/chemical conditions (i.e., low oxygen, ice);
2. Protection from predators;
3. Access to refugia and alternative habitats; and,
4. Access to food (Cunjak 1996).

Fish have developed strategies for minimizing the effects of extreme conditions and stresses associated with winter. The strategies differ between different fish taxa and life stages. For example, Cunjak (1996) states that most salmonids remain active and continue to feed during the winter, while catostomids (suckers), blacknose dace (*Rhinichthys atratulus*), juvenile brook trout, darters and gasterosteids (sticklebacks) significantly reduce their metabolic activity and food intake. Others, such as most cyprinids (minnows) and some centrarchids (sunfishes) burrow into the stream bed and enter a state of hibernation. Arctic char (*Salvelinus alpinus*), some *Oncorhynchus* spp. and adult Atlantic salmon (*Salmo salar*) tend to travel long distances in late autumn or early winter to lentic habitats (e.g., lakes, estuaries) where environmental conditions are, presumably, not as harsh as those associated with winter stream environments. Small-bodied fish such as juvenile salmonids remain in streams but seek cover in the bottom rubble and debris were flow velocities are low. Large-bodied, adult fish (such as salmonids, catostomids, percids and esocids) seek deep pool areas presumably because of the low water depth, high water velocities and a lack of suitable cover that often characterizes many riffle areas during low flow conditions of the winter period.

Ice

A primary factor affecting winter habitat preference is the presence, type, abundance and characteristics of ice formation. There are many types of ice which form on or in a watercourse. Two types of subsurface ice which are relevant to winter habitat preferences are frazil and anchor ice.

Frazil ice is a type of ice crystal which is generated in areas with turbulent flow where water temperatures can be depressed slightly (hundredths of a degree Celsius) below the freezing point. In these areas, frazil ice forms throughout the water column. When frazil ice is first formed it is referred to as the active state. In this state, frazil ice crystals can be described as "sticky" and will attached to any object, including the substrata, surface ice, and other ice crystals. As a result, frazil ice can "grow" as more and more crystals attached together. This growth of frazil ice can have dramatic consequences for the development of other types of river ice, and on the aquatic community (Prowse and Gridley 1993).

Anchor ice is defined as ice which is either established or deposited on the river bed. This type of ice formation can consist of frazil ice which adheres to the substrata, or other ice crystal types. Anchor ice can be found attached to any type of underwater object, including aquatic vegetation and river bed substrata. Anchor ice formation in a river is an important characteristic influencing the distribution of fish under winter conditions and governing the survival of incubating eggs of fall-spawning fishes which are buried within the stream substrata.

Winter habitat selection by fish may be largely dictated by the amount and type of ice in a specific area. It is likely a combination of the influences of ice and energy expenditure which determine the selection of winter habitat. Water depth, flow velocities, cover and temperature can greatly influence energy expenditure. The significance of these parameters with respect to winter habitat preference is discussed below.

Water Depth

Areas of relatively deep water have been reported to be preferred overwintering sites of many large-bodied salmonids (Chisholm *et al.* 1987 cf Brown 1994). Other studies have reported that the change from summer to winter habitats leads to a preference for areas with decreased water depth (Heggenes *et al.* 1991 cf Brown 1994). Brown *et al.* (1993), in a study of cutthroat trout, found that while one population overwintered in deeper pools compared to summer, the mean water depth selected by a second population decreased significantly. The most frequent range of water depth used was between 40 and 80 cm and Brown (1994) concluded that trout may prefer water depths over a minimum threshold. Habitat preference and selection does not appear to be governed by water depth alone. Increased water depth is typically associated with decreased flow velocities, and hence, provides fish with a means to conserve energy expenditures.

Water Velocity

The use of deeper pools is related to water velocity. Water velocity typically decreases as water depth increases. Numerous studies have reported that fish occupy low velocity sites over winter (Cunjak, 1995). Brown and brook trout occupy areas where velocity is less than 15 cm/s (Cunjak and Power 1986). Beaver ponds and temporary side channels may be additional low-velocity winter habitats depending on the magnitude of ice formation (Peterson 1982a, 1982b cf Sheehan *et al.* 1990). Decreased metabolism dictates the use of sites with decreased water velocity. As water temperature decreases, so does metabolism, and the need to conserve energy drives habitat selection in the winter (Cunjak and Power 1986).

Cover

Overwintering habitats generally have greater cover than summer sites (Cunjak and Power 1986; Chapman and Bjornn 1969 cf Marcus *et al.* 1990) with a preference for those sites exhibiting a greater cover complexity (McMahon and Hartman 1989 cf Cunjak 1996). A more recent study by Brown (1994) reported that cutthroat trout of Alberta exhibited a two-stage shift in habitat use from summer to winter. Cutthroat trout moved to large pools with abundant sources of cover in late summer-early fall. As temperatures decreased further, the trout migrated to deeper pools absent of cover (other than that afforded by ice). Snow-covered stream sections were also preferred locations. Brown (1994) postulated that the presence of frazil and anchor ice may have been major determinants of habitat selection in late fall. Since frazil ice adheres to woody debris, the majority of trout selected sites free of large organic debris, and the presence of ice and snow protected the areas from supercooling and the resulting formation of ice. The characteristics of frazil and anchor ice formation may therefore lead fish to select overwintering areas generally free of woody debris cover.

Water Temperature

Water temperature plays an important role in the selection of overwintering sites. Brook and brown trout have been found to aggregate in locations where the influx of groundwater maintained the temperature 2-6°C warmer than the rest of the river (Cunjak and Power 1986). These areas, often recognized as important thermal refugia during warm periods of the summer, are now being recognized as important areas during harsh winter conditions (Cunjak 1996). Brown (1994) observed that the majority of the cutthroat trout in an Alberta stream overwintered in areas receiving inflows of warmer groundwater. Brown (1994) also concluded that these areas are particularly important in situations where the formation of frazil and anchor ice serves to limit the number of available winter habitats. Water temperature alone is not always the dominant factor in the selection of groundwater influxes. Cunjak and Power (1986) noticed that brook trout abundance during winter conditions in the Credit River was negatively correlated to increasing pressure head. In this situation, it appears that the selection for warmer water was offset by an avoidance of higher flow velocities. The importance of thermal groundwater refugia during winter conditions is also supported by a study conducted by Sheehan *et al.* (1990).

3.5.2. Environmental and Physiological Stresses on Fish During Winter

The behavioural and physiological responses of fish to increasing concentrations of suspended sediments vary from avoidance behaviour and mild cough reflexes, to more severe physiological changes such as reduced growth and death. These effects are often observed within individual organisms but may also have an indirect impact upon the age-class distribution of the population and changes within the fish community structure. The severity of the impact at the organism, population and community level is influenced by many seasonally independent and seasonally dependent parameters, as follows:

Seasonally Independent

- concentration of suspended sediments
- duration of exposure
- particle size and angularity

Seasonally Dependent

- environmental conditions
- physiological condition of the fish
- habitat availability
- critical life stages

3.5.2.1. Seasonally Independent Factors (direct effects)

The stress levels and health effects on fish resulting from increased concentrations of suspended sediments are directly influenced by sediment concentration, duration of exposure and particle size and shape (Newcombe 1994a, Newcombe and Jensen 1995a, Servizi and Martens 1991). These factors are generally independent of seasonal changes in that the behavioural and physiological responses evoked from fish appear to be similar between summer and winter conditions. Chapter 2 provides a summary of the behavioural and physiological changes observed in fish exposed to increased concentrations of suspended sediments.

3.5.2.2. Seasonally Dependent Factors (indirect effects)

Seasonal changes are often accompanied by corresponding changes in the physiological condition of the fish and the surrounding environment. The conditions experienced by fish during the winter are quite different from those experienced during the summer. The major differences are summarized as changes in: a) environmental conditions; b) fish physiological conditions; c) habitat availability; and, d) critical life stages. All four categories are dependent upon the season and hence have been termed "seasonally dependent factors". Each of these factors affect the ability of the fish to acclimate to, or tolerate, the stresses associated with exposure to increased concentrations of suspended sediments and increased rates of sedimentation during winter.

Construction operations during winter has the potential to reduce environmental impact in four general ways. The first factor is that the frozen soils generally offer greater accessibility to the site by heavy construction equipment. Secondly, winter construction is often preferred since merchantable timber is more easily salvaged. Thirdly, construction during the winter when the ground is frozen has the potential to reduce the amount of suspended sediments entering the water from bank side disturbances. Finally, lower water temperatures favour increased oxygen saturation levels (assuming that the area is free of ice cover) during a period when the metabolic demands of the fish are at a yearly low. The severity of the impact is, however, often dependent upon the ability of the fish to tolerate the stress. Tolerance levels of fish change with the season and life stage.

Environmental Conditions

Changing environmental conditions are known to be stressful to fish. During the winter, fish are required to adapt to declining water temperatures, variability in dissolved oxygen concentrations, ice, restricted movement and lower flows. These parameters individually, or in combination can be stressful to fish and therefore lower their tolerance, or the ability of the fish to acclimate to the increased stresses associated with suspended sediments. Acclimation to declining water temperatures is one of the major challenges know to be stressful to fish. Cunjak *et al.* (1987) found that acclimation to declining water temperatures is quite stressful to brook trout and may significantly reduce the energy reserves of the fish.

The saturation levels for dissolved oxygen increase with declining water temperatures. As such, the water has a greater capacity for "holding" dissolved oxygen. Oxygen levels are, however, influenced by a variety of parameters and have the potential to vary significantly between locations. The biochemical oxygen demand (BOD) of the water and the extent of ice cover are two primary factors influencing dissolved oxygen concentrations during winter periods. These factors may significantly reduce dissolved oxygen concentrations in situations where there is an elevated BOD in combination with thick ice cover that impedes replenishment of the water with atmospheric oxygen. Lower levels of dissolved oxygen are known to be stressful to fish and the ability of the fish to tolerate oxygen depletion can be dependent upon the effects of prior stress (Wedemeyer *et al.* 1990). Another compounding factor related to low dissolved oxygen concentrations is the fact that fish are less tolerant in winter periods to low concentrations of oxygen than they are during summer months (Hlohowsky and Wissing 1987). Riera *et al.* (1993) determined that the blood of brook trout has a greater ability to absorb oxygen during the summer. They concluded that this condition was a physiological adaptation to the typically lower summer dissolved oxygen levels.

Ice formation (frazil and anchor) can impose a significant physical stress upon fish. Ice occurring below the water surface in the form of ice crystals and other ice formations are generally considered to have the most detrimental effects on resident fish communities in the winter. Subsurface ice can potentially cause direct mortalities on the fish communities present in a river. Free floating frazil ice crystals have the potential to plug the mouth and gills of fish and can lead to reduced feeding, and potentially suffocation and death. This phenomenon was documented by Tack (1938).

In addition to direct effects on fish, subsurface ice can also effect resident fish communities by altering available habitats during winter. Alteration of habitats can occur in many ways and can affect all fish life stages. Ice dams can form which can dewater entire stream reaches. In addition, surface ice formations can result in reduced levels of dissolved oxygen, limiting the distribution of low oxygen intolerant fish species or life stages. The most significant effect of surface ice on fish likely occurs during ice break-up in the spring. This period of increased river discharge, scouring of bed and banks, frequent ice jams and dams and increased turbidity can be taxing to the aquatic community.

Reductions in channel depth and width resulting from reduced flow volumes and ice cover can also reduce the abundance and availability of suitable fish habitat. All of these factors have the potential to contribute to the stress burden experienced by fish during winter conditions. Changes to the physical environment and habitat can limit the ability of the fish to respond to and tolerate the increased stress resulting from elevated sediment loads at a time when most fish experience the lowest energy levels.

Physiological Condition of Fish

The physiological condition of fish in winter months is drastically different from that of summer. Winter physiological conditions are often characterized by a reduction in metabolism and the amount of energy required to maintain basic metabolic functions (Winberg 1956). Fish are also typically less active (Cunjak and Power 1986) and feed less frequently (Cunjak *et al.* 1987). Despite a lower metabolic demand, many species still experience reduced energy reserves and a general decrease in body condition (Cerven 1973, Hunt 1969). During a study on brook trout and brown trout, Cunjak and co-workers (1987, 1988) concluded that winter conditions are very stressful to salmonids. They found that the condition factor and energy reserves were significantly reduced in both immature and mature fish during the period between late summer and early winter. Blood serum protein levels were also significantly reduced (Cunjak and Power 1986) and the lipid content of the fish decreased to between 2 to 4% of body weight. The decrease was observed despite the fact that the fish continued to feed throughout the winter and the metabolic requirements of fish at this time were considered to be only two times the rate required for fish at a resting stage. Lower body temperatures and the slower rates of food digestion and assimilation were considered to be the primary cause of the depleted energy reserves (Cunjak *et al.* 1987). Secondary causes were related to decreased food abundance and lower caloric value of the winter food (Cunjak *et al.* 1987).

The ability of the fish to tolerate increased concentrations of suspended sediments is influenced by the energy reserves available for allocation to the bioenergetic cost required for compensatory behavioural or physiological responses. Although metabolic demands upon fish are typically lower in the winter, the amount of reserve energy available to spend on increased stress levels may be critically low.

Habitat Availability

Sheltered areas of low current velocities appear to be the major overwintering habitats sought by the juvenile and adult life stage of many coldwater species (Calkins 1989, Cunjak 1995, Hillman *et al.* 1987). Cunjak and Power (1986) suggest that fish seek these areas as an adaptive measure to compensate for lower energy reserves. Access to a variety of winter habitats is important for the overwintering survival of fish because of the dynamic nature of streams during winter conditions (Cunjak 1996). The availability of, and accessibility to, critical winter habitat may be limited by decreased flows and resulting decreases in channel width and depth. In addition, movement between suitable and alternative habitat areas may also be restricted by lower water depths and/or ice cover (Cunjak and Randall 1993).

Ice formation can exclude fish from overwintering sites and restrict movement between habitat refugia. Adult fish which live in watercourses with extensive subsurface ice formation can often be excluded from otherwise suitable overwintering refugia by the formation of anchor and frazil ice.

Extensive anchor ice formation can reduce the area available to fish in the winter and force fish into areas with higher water velocities. Large quantities of frazil ice can attach below established surface ice formations to further reduce area available to overwintering fish. In addition, anchor or frazil ice formations can break away and can injure fish or cause them to leave preferred habitats.

Subsurface ice can affect the survival of incubating salmonid eggs. The types of habitats normally selected by salmonids for spawning habitat can be characterized as areas with coarse substrata, with shallow swift-flowing water. These areas are also conducive to anchor ice formation. Anchor ice can reduce egg survival by killing developing eggs via freezing or by blocking the entry of oxygenated waters into the inter-gravel areas where eggs are incubating. Frazil ice attachment to surface ice formations can also increase scour of the stream bed in localized areas which can dislodge incubating embryos from the gravel.

Preferred winter holding habitat for stream fish, by nature, is often characterized by low flow velocities which may in turn predispose these areas to sediment deposition and prolonged residency times of suspended sediments. As such, the duration of exposure in these areas may be longer than would be experienced during summer conditions when there is a greater abundance and greater access to alternative habitat locations. The bioenergetic cost of seeking alternative, and possibly less suitable habitat may pose a significant energy drain on an already depleted energy reserve.

Life Stage

Life-history stage is an important factor to consider when attempting to predict the impact of suspended sediments in winter. Newcombe (1994a) indicates that salmon larvae are typically the most sensitive life stage to the effects of suspended sediments, with eggs being marginally more tolerant. Many of the coldwater species spawn in the fall and the eggs and/or larvae remain in the substrata till late winter or early spring. Eggs and larvae are sensitive to sedimentation and are not able to avoid the effects as are older fish. The effects of sedimentation on this life stage of fish during winter conditions can be significant if the eggs and larvae are within the zone of deposition.

3.5.3. Impact of Sedimentation During Winter Conditions

The magnitude of impact upon fish resulting from increased concentrations of suspended sediments and levels of sedimentation can vary between summer and winter periods. It has been argued that the lower metabolic requirements during winter conditions may in some ways provide a protective influence to conditions such as gill trauma and decreased gill function (C. Newcombe pers. comm.). However, the ability of the fish to tolerate the stress of suspended sediments will be influenced by the physiological condition of the fish and the ability to avoid the stress.

Direct effects resulting from increased concentrations of suspended sediments and the deposition of fines was discussed in detail previously. In brief, early live stages (i.e., eggs, alevins) of many salmonid fish are found in the stream bed during the winter months. These stages are particularly sensitive to the effects of increased concentrations of suspended sediments and the deposition of fines. The introduction of sediments during the winter period therefore has the potential to appreciably impact upon these early life stages. Bjornn *et al.* (1977) found that the number of juvenile salmon that a stream can support in winter was greatly reduced when the inter-cobble spaces were filled with fine sediment. The decreased carrying capacity was a function of both a loss of substrate cover for juvenile fish and a reduction in food as benthic invertebrate communities changed. Bjornn *et al.* (1977) suggested that the summer rearing or winter holding habitat may be more influential to the carrying capacity of a stream reach than embryo survival.

During winter conditions fish generally experience decreased energy reserves and as such search for habitat that allows them to reduce energy expenditures and hence conserve energy (Clapp *et al.* 1990, Nickelson *et al.* 1992). The preferred habitat is species dependent; however, for most salmonids this preferred habitat is located in low velocity areas such as pools and behind instream cover were focal velocities are low (Vondracek and Longanecker 1993, Griffith and Smith 1993, Modde *et al.* 1991, Heggenes and Saltveit 1990, Cunjak and Power 1986). By remaining in low velocity areas, fish are able to minimize their energy expenditures and hence reduce the rate of metabolic depletion (Cunjak and Power 1986).

Land use activities which increase the introduction of fines into streams have the potential to significantly affect the overwintering survival of resident fish. A major mechanism of potential impact is a depletion of critical energy reserves as a result of increased physiological stress, alterations in behaviour and/or exclusion from preferred sites of overwintering habitat. This is particularly deleterious to those fish species and life stages which prefer to overwinter within the interstitial spaces provided in medium to large sized substrate (i.e., cobble - boulders). The net loss in energy reserves will depend on the concentration of sediment and the duration of impact. Dependent upon existing energy reserves, the fish may be able to tolerate the energy depletion attributable to an increase in the cough reflex and reduced feeding, but may not be able to tolerate the energy depletion associated with displacement from critical habitat.

Preferred winter habitat areas of low current velocity are often predisposed to sedimentation (Cunjak 1996), and the lower flows experienced during winter conditions may result in higher suspended sediment concentrations, a reduced time of travel of the sediment plume and hence longer, more concentrated exposure to elevated concentrations of suspended sediments. Bjornn *et al.* (1977) found, during sediment experiments, that the spring freshet from snow melt was rarely sufficient to transport sediment out of the pools and therefore the damage to these areas appears to be long-term. Due to natural factors, the availability of winter habitat is generally less than that of summer habitat and may be more influential in the determination of the stream's carrying capacity (Cunjak 1996). A further reduction in the abundance of an already limited winter habitat may significantly hinder the ability of the fish to avoid the negative impact of increased sedimentation. The energy cost to fish unable avoid the impact, in terms of increased stress and reduced food supplies, may be critical to their ability to overwinter (Cunjak *et al.* 1987). Likewise, those fish displaced to areas of higher flow velocities may not have the energy reserves necessary to remain in these areas for extended periods of time. Additive to this problem may be a reduction in food supply resulting from benthic drift or burying of food supplies. Elwood and Waters (1969) observed that increased sedimentation reduced the population of invertebrates and hence the capacity of the stream to support brook trout. A reduced food supply, and a greater expenditure of energy in food search and avoidance of higher concentrations of suspended sediments may significantly impact upon the fish's ability to tolerate negative physiological changes or the ability to overwinter.

3.6. SUMMARY OF HABITAT SENSITIVITY TO SEDIMENTATION

Sediment loads can alter the composition of the stream bed, the inter-gravel movement of water as well as the gross morphology of streams. When sediments are deposited on the stream bed they fill in the interstitial spaces. This process can affect spawning and nursery habitat of fish, particularly salmonids. It can also cause changes in invertebrate communities, thereby altering food supplies for fish.

The effects of a sediment exposure are affected by water temperature. Adverse effects of a sediment exposure increase with increased temperature (Newcombe and Jensen 1995a). However, warmwater species are typically more tolerant to increased concentrations of suspended sediments. Coldwater species generally have a lower tolerance to depleted oxygen supplies in the water (Taylor and Barton 1992) or reduced oxygen exchange resulting from traumatization of the gill. During winter, fish metabolic rates are generally reduced and in ice-free areas, dissolved oxygen levels may be higher due to the higher oxygen holding capacity of water at colder temperatures. These factors could reduce sediment effects on physiological consequences resulting from factors such as gill laceration.

However, the above factors are offset by other winter considerations. Energy stores of fish in winter are at there lowest levels and abilities of fish to tolerate stress are correspondingly reduced. Displacement of fish due to sediment plumes may result in fish using habitats which are less suitable (i.e., which require the expenditure of more energy). The use of less preferred habitats may result in fish being less able to cope with the additional stress of elevated sediment exposure. In addition, fish tend to prefer areas with low velocity and increased water depth during winter. This habitat preference may prolong sediment exposure durations.

Overwintering areas are primary locations for sediment deposition; therefore, these areas are at elevated risk of alteration due to sedimentation. In addition, since many fish species and life stages utilize interstitial spaces during winter, these fish are at a higher risk of death due to suffocation compared to other times of the year. The formation of frazil and anchor ice may limit the habitats suitable for overwintering use and the ability of fish to emigrate from areas of elevated sediment exposure.

Since sediment can have long-term impacts on fish populations by altering critical habitat, it is elevations in sedimentation levels which could potentially pose the most severe threat to a fish community. As a result, the amount of settleable solids is an important consideration with respect the effects on fish communities vis-à-vis the physical alteration of fish habitat.

4.0. SEDIMENT DOSE/RESPONSE RELATIONSHIPS

As discussed in Chapters 2 & 3, there are numerous ways in which aquatic biota respond to elevated suspended sediment concentrations and increased rates of sedimentation. In an effort to protect aquatic resources from the potential impacts of elevated suspended sediment loads, water quality standards have been developed. Some of the established criteria for the protection of Canadian freshwater lentic and lotic environments are summarized below.

4.1. EXISTING SUSPENDED SEDIMENT CRITERIA

There is no easily defined concentration of suspended sediment above which fisheries are damaged and below which fisheries are protected (Alabaster and Lloyd 1980). Kerr (1995) identifies the problems of establishing fixed standards or guidelines for sediment release. These include:

1. There are substantial daily and seasonal variations in suspended solids in most flowing waters;
2. Acute effects on aquatic organisms are often difficult to demonstrate;
3. Tolerance varies according to the species and life stage of various aquatic biota;
4. Impacts to aquatic biota depend not only on the concentration of suspended materials but also on the duration of exposure and size of materials in suspension;
5. Impacts differ depending on whether solids remain in suspension or settle to the substrate (standing vs. flowing waters); and,
6. Impacts on fish habitat are strongly influenced by sediment availability and transport dynamics through the system. (Taken from Kerr 1995)

Despite the difficulties, however, numerous reviews have been conducted on TSS and sedimentation in aquatic environments and their effects on fish, in an attempt to provide guidelines or criteria for the protection of fish populations. The conclusions of most of the reviews are similar; that is, that most species of fish can withstand acute exposures to elevated levels of TSS, but physiological and habitat impairment will occur when sediment exposure increases beyond threshold values which are a function of the concentration of the sediment release and the duration of the episode. Thus, the criteria which have been developed are justifiably based on ensuring the long-term maximum protection of both fish and other organisms in the community that fish populations depend on. The European Inland Fisheries Advisor Commission (EIFAC 1965), for example, suggested the following levels of TSS relating to fish survival and sub-lethal effects:

<25 mg/L,	no effect;
25 - 80 mg/L,	slight effect on production;
80 - 400 mg/L,	significant reduction in fisheries; and,
>400 mg/L,	poor fisheries.

The Ontario Ministry of the Environment (OMOE 1994) used Secchi depth as an indicator of acceptable suspended matter. The OMOE criterion states that suspended matter added to surface waters should not change the natural Secchi disk reading by more than 10%. The Manitoba Department of Environment states that water should be free from substances that produce turbidity in such a degree as to be objectionable or to impair any beneficial use (Williamson 1983). The Manitoba DOE criterion identifies the maximum acceptable concentration for non-filterable residue as 25 mg/L (Williamson 1983). Similarly, a maximum permitted increase of 25 NTU above ambient is the maximum permitted increase for coldwater streams in Alaska (Lloyd 1987).

The Province of British Columbia has established criteria for protection of aquatic life, including fish, that states that non-filterable suspended solids should not increase by 10% over background levels with 10 mg/L being the maximum acceptable increase when background levels are >100 mg/L (Singleton 1985). Further, deposition of particulate matter <3 mm in diameter should not be increased over background levels in salmonid spawning areas (Singleton 1985). These criteria are based on a selected review of effects of particulate matter on fish (Singleton 1985). However, this kind of approach was criticized by Bisson and Bilby (1982) as it permits minor increases in TSS when the background turbidity levels are low, but allows greater absolute increases as background levels rise.

The Canadian Council of Resource and Environment Ministers (1994), provided guidelines for increases in suspended solids. These criteria indicated that suspended solids should not exceed 10 mg/L (when background levels were equal to, or less than, 100 mg/L) and should not exceed 10% of background concentrations when natural ambient conditions were greater than 100 mg/L.

In 1993, the DFO authorized the harmful alteration, disruption or destruction of fish habitat associated with placer mining in the Yukon Territory subject to compliance with standards of allowable sediment discharge (DFO 1993). The standards of allowable sediment discharge were specific to stream type using the following stream classifications:

Type I	Salmonid spawning streams;
Type II	Salmonid rearing streams;
Type III	Streams with fish having significant use by First Nations, commercial, sport, or domestic fisheries or contributing to biological diversity;
Type IV	Streams with no fish or streams with fish having no significant use by first nations, commercial, sport or domestic fisheries or not contributing to biological diversity; and,
Type V	Other streams.

Using these stream classifications, the allowable sediment discharges standards were identified as:

Type I & V	0 mg/L above natural background levels;
Type II	< 200 mg/L above natural background levels;
Type III	< 200 mg/L above natural background levels by January 1996*;
Type IV	Specific sediment discharge standards were established for certain Yukon streams which had to be met by January 1996*.

* Interim criteria were established for 1994 and 1995

Protection criteria, such as those outlined above, are typically designed for chronic (long-term) exposures and may not adequately reflect sediment release episodes that are of high concentration but of short duration. In this chapter, specific sediment dose/response relationships are investigated to quantify the effects of sediment on aquatic resources as a function of dose (concentration and duration).

4.2. THE DOSE/RESPONSE APPROACH

One method which has been developed to address the issue of quantifying the adverse effects of TSS on fish is the ranked effects model first put forward by Newcombe and MacDonald (1991). This model compiled information from more than 70 studies on the effects of inorganic suspended sediments on freshwater fish (mainly salmonids) and invertebrates, and ranked the severity of impacts from 1 to 14 (rank effects). Regression analysis was used to correlate ranked effects with intensity (concentration x duration) of increased suspended sediment load (Newcombe and MacDonald 1991). Since the effect of elevated TSS levels on fish is a function of both the concentration of suspended sediment and the duration of the exposure, Newcombe and MacDonald (1991) developed a severity index (SI). This index provides a standardized relative measure of exposure. It is the natural logarithm of the concentration ($mg \cdot L^{-1}$) multiplied by hours of exposure (i.e., Ln $mg \cdot h \cdot L^{-1}$). This stress index provides a convenient tool for predicting effects of episodes of elevated suspended sediments of known concentration and duration.

The usefulness of the Newcombe and MacDonald (1991) ranked effects model has been questioned in the past (Gregory *et al.* 1993). The main concerns with the model are the highly variable nature of the data used to develop the model, which reduces its predictive power, and the concern that the model is unrealistically simplistic (Gregory *et al.* 1993). MacDonald and Newcombe (1993) argue the utility of the concentration-duration response model, stating that the concerns associated with model reliability are due to misinterpretation of the model's intended use.

Due to the variable nature of the available data, the regression equation developed in Newcombe and MacDonald (1991) was not intended to be used as a predictive model to precisely estimate the nature and severity of effects on aquatic ecosystems (MacDonald and Newcombe 1993). However, the ranked effects model was developed for assessing potential impacts of suspended sediment pollution episodes in coldwater ecosystems (MacDonald and Newcombe 1993).

In 1994, the ranked effects model was further refined (Newcombe 1994a). Using 140 articles on suspended sediment pollution, he developed a database of nearly 1200 datapoints concerning the effects of suspended sediments and associated effects upon marine and freshwater biota. The rank effects method was developed from a wide range of invertebrate and fish species and life stage information. The dose/response relationships of a receiving environment to sediment pollution are greatly affected by the species and life stage present in the affected area(s). Therefore, the actual effects on the aquatic ecosystem from a pollution episode will vary depending on the intensity and duration of the episode, the invertebrate community and fish assemblages and life stages present in a particular watercourse, as well as the timing of the disturbance, ambient water conditions, temperature, and the presence of disease organisms and other contaminants, and the sensitivity of habitats within the receiving environment (Newcombe and MacDonald 1991). The extensive database compiled by

Newcombe (1994a) provides a means for undertaking an extended guild and life-stage specific analysis of dose/response relationships in an effort to obtain specific relationships with more predictive power.

4.3. SPECIFIC DOSE/RESPONSE RELATIONSHIPS

Newcombe (1994a) amassed a wealth of information concerning TSS effects on fish and fish habitat. He defined the TSS dose to which the fish were exposed according to a stress index incorporating both concentration and duration of exposure. The stress index was in turn related to an index of severity of effects (SE) on a ranked effects scale ranging from minor and temporary behavioural effects at one end to large-scale mortality at the other. With such a database in place, regression analysis could be used to relate severity of effect to the dose of TSS for specific fish species or assemblages. This approach was used to describe the dose/response relationship for the effects of suspended sediments on salmonid fishes (Newcombe and MacDonald 1991), on juvenile salmon (Newcombe 1994a) and for other coldwater fishes (Newcombe 1994a) using sub-sets of the dataset which is presented in complete form in Newcombe (1994a).

The coldwater ecosystems model which was presented in Newcombe (1994a) described the severity of effects of suspended sediments in coldwater aquatic ecosystems as represented by various fishes including all life-stages of salmon and trout, invertebrates and algae. The relationship developed by Newcombe (1994a) between severity of effects and dose is represented by the equation:

1. $SE = 0.738 \, Ln \, [dose] + 2.179$ (r^2=0.638; N=120; $p<0.01$).

where: SE = severity of effects and,
dose = sediment intensity * duration ($mg \cdot hr \cdot L^{-1}$)

Newcombe (1994a) also provides a dose/response relationship for juvenile salmon which indicates that severity of effect can be described by the equation:

2. $(SE) = -0.73 + 0.866 \, Ln \, (mg \cdot hr \cdot L^{-1})$ (r^2=0.85; N=19; $p<0.01$).

The dose/response relationships for the freshwater stages of salmon species (not eggs, not fry) shows that severity of effect can be described as:

3. $(SE) = 0.886 + 0.713 \, Ln \, (mg \cdot hr \cdot L^{-1})$ (r^2=0.698; N=70; $p<0.01$).

In addition to the dose/response relationships presented in Newcombe and MacDonald (1991) for salmonid fishes and in Newcombe (1994a) for coldwater fishes and underyearling trout, Newcombe and Jensen (1995a) further expand upon dose/response relationships of aquatic resources to sediment exposure. Newcombe and Jensen (1995a) present six sediment dose/response relationships for specific fish communities exposed to elevated sediment loads. One of the important additions to the analysis presented in Newcombe and Jensen (1995a) is the linkage of grain size of sediment to the nature of ill-effect associated with sediment exposure. The dose/response relationships presented in Newcombe and Jensen (1995a) are organized according to four variables which are: taxonomic group; life stage; natural history and estimated predominant particle size range of the sediment episode. The dose/response relationships were characterized by three variables: [x], [y], and [z], where:

[x] = duration of exposure expressed as the natural log of hours;
[y] = concentration of sediment expressed as natural log of mg/L;
[z] = severity of ill effect (SE).

Since the work of Newcombe and MacDonald (1991) and Newcombe (1994a) used the Stress Index (Ln concentration · duration), the dose/response relationships presented were of the form:

SE = a + bx
where:
SE = severity of ill effects
a = intercept;
b = slope of the regression line
x = stress index value

The six dose/response relationships presented in Newcombe and Jensen (1995a) do not characterize response using the stress index, and are presented in the form:

z = a + b(Ln x) + c(Ln y)
where:
[a] = intercept
[b] = slope of x
[c] = slope of y
[x] = duration of exposure expressed as the natural log of hours;
[y] = concentration of sediment expressed as natural log of mg/L;
[z] = severity of ill effect (SE).

The six dose/response relationships presented in Newcombe and Jensen (1995a) were for:

1. All life stages (except incubating eggs) of Arctic grayling and mountain whitefish, and all species of trout and salmon for all life stages (except incubating eggs) for particles ranging in size from 0.5 to <250 microns as described by the equation:

   $z = 1.0642 + 0.6068x + 0.7384y$; $r^2(adj) = 0.6009$; n=171;

2. Adult Arctic grayling and adults of all species of salmon and trout for particles ranging in size from 0.5 to <250 microns as described by the equation:

   $z = 1.6814 + 0.4769x + 0.7565y$; $r^2(adj) = 0.6173$; n=63;

3. Underyearlings of Arctic grayling and all species of salmon and trout for particles ranging in size from 0.5 to <75 microns as described by the equation:

   $z = 0.7262 + 0.7034x + 0.7144y$; $r^2(adj) = 0.5984$; n=108;

4. Eggs and young fry of Arctic grayling and all species of salmon and trout; and, larvae and eggs of herring, perch, bass, and shad for particles ranging in size from 0.5 to <75 microns as described by the equation:

$$z = 3.7466 + 1.0946x + 0.3117y;\ r^2(adj) = 0.5516;\ n=43;$$

5. Some adult estuarian fishes (American shad, Atlantic silverside, bay anchovy, fourspine stickleback; herring; menhaden and spot) for particles ranging in size from 0.5 to <75 microns as described by the equation:

$$z = 3.4969 + 1.9647x + 0.2660y;\ r^2(adj) = 0.6200;\ n=28;\ \text{and,}$$

6. A collection of non-salmonid fishes as described in Newcombe and Jensen (1995a) as adult fishes and populations of cold, temperate and warm waters; stream and still-water habitats, including bass, bluegill, carp, species of darters, minnows, and sunfishes and other unspecified fishes for particles ranging in size from 0.5 to <75 microns as described by the equation:

$$z = 3.2547 + 0.7461x + 0.3861y;\ r^2(adj) = 0.7004;\ n=25.$$

The dose/response relationships presented above provide insight into the relationship between sediment release and adverse effects on a variety of fish communities (Newcombe and MacDonald 1991; Newcombe 1994a; Newcombe 1994b; Newcombe and Jensen 1995a). These relationships provide increased precision for the prediction of response of a particular fish species or assemblage of species based on a given dose of suspended sediment.

The overall objective of the present study was to quantify the effects of sediment on fish and fish habitat. The dose/response relationships presented by Newcombe and others (as outlined above) provide a valuable approach for the prediction of fish response to increases in sediment. The database used to determine these relationships relied heavily on the physiological response of fish to increases in sediment load; therefore, the relationships presented may not be directly applicable to the prediction of physical alteration to fish habitats due to sediment load increases and increased sedimentation. It is important to note, however, that the dose/response relationships provided by Newcombe and others would provide a realistic prediction of the suitability of macro-habitat conditions in the receiving environment during a sediment release event. That is, the dose/response relationships could be used to determine if habitats within an area affected by sediment load increases were rendered unsuitable for fish during the sediment release episode (habitat exclusion). This assessment would be particularly important if the area within a receiving environment is anticipated to provide critical habitats (e.g., spawning or overwintering) for fish during the period of sediment release, or if critical habitats for fish are present upstream of the affected area(s) and fish must pass through the receiving environment during the period of the sediment release to reach these habitats.

In the following section we attempt to extend the work of Newcombe by exploring regression relationships between TSS dose and habitat effects for Canadian fish species and life stages for which sufficient data are available. The following analysis is built upon the solid foundation of Newcombe and MacDonald (1991), Newcombe (1994a; 1994b) and Newcombe and Jensen (1995a) and uses compatible analytical techniques and data acquisition methods. The database used to develop the regressions presented below was developed by Newcombe

(1994a) with some additional data provided from the literature search. The Newcombe (1994a) database is provided as Appendix 2.

4.4. DEVELOPING THE HABITAT EFFECTS DATABASE

The first step in developing more specific dose/response criteria was to search the literature for studies reporting TSS concentrations and their effects on fish habitat. The search included government and consultants reports, research papers and other "grey" literature that would not have been available to Newcombe (1994a) when he was constructing the database. Data generated during monitoring of pipeline crossings of streams are of obvious relevance to the present project, and a special effort was made to collect as many reports of this kind as possible. One limitation to the use of this information was that, although substantial water quality monitoring information was available during pipeline crossing events, little associated biological effects information was available that corresponded with the sediment pollution episodes monitored.

Several fundamental criteria had to be satisfied for data from a report to be included in the expanded database. The report had to give at least: (1) a concentration of TSS; (2) a duration of exposure to (3) one or more identified species of fish; and, (4) a description of the effect. The severity of effect, and occasionally other data, sometimes had to be inferred from the qualitative descriptions; however, a reasonable estimate of concentration and duration had to be provided in the report for inclusion in the database.

A total of 18 reports, containing some 53 new documentations of TSS effects, were retrieved in the literature search. The new information was weighted heavily toward field data, which is appropriate for the anticipated application of the developed dose/response relationships to acute sediment release episodes.

4.5. DOSE/RESPONSE RELATIONSHIPS OF FRESHWATER HABITATS TO SEDIMENT RELEASES

The relationships which have been developed by Newcombe (1994a; Newcombe and Jensen 1995a) and which have been discussed above deal primarily with the physiological response of aquatic biota to sediment pollution. The one exception to this statement is the "coldwater ecology regression" presented in Newcombe (1994a). As mentioned above, the fish guild response relationships are important in the development of an understanding of the effects of sediment release on aquatic life; however, they do not provide insight into the effects of subsequent sedimentation on the habitats upon which fish rely.

A sub-set of the data which was considered applicable to habitat effects included information regarding changes in fish habitat preference, reductions in fish feeding habitat (as measured by reductions in invertebrate abundance or diversity), and measured physical habitat degradation. This sub-set of the Newcombe (1994a) database consisted of 75 data-points from 42 published articles on the responses of aquatic habitats to sediment pollution. An additional six articles which contained information on the ill effects of sediment release on aquatic habitats were retrieved in the literature search, that provided an additional twenty datapoints to the habitat database sub-set.

Severity of ill-effects rankings were assigned to each documented effect following the severity-of-ill-effects scale published by MacDonald and Newcombe (1993); Newcombe (1994a); Newcombe and Jensen (1995a). The nature of the observed habitat effect was assigned one of the following class effect rankings:

SE = 3	Measured change in habitat preference;
SE = 7	Moderate habitat degradation - measured by a change in the invertebrate community;
SE = 10	Moderately severe habitat degradation - as defined by measurable reductions in the productivity of habitat for extended periods (months) or over a large area (kms);
SE = 12	Severe habitat degradation - as measured by long-term (years) alterations in the ability of existing habitats to support fish or invertebrates; or ,
SE = 14	Catastrophic or total destruction of habitat in the receiving environment.

For each of the dose/response datapoints in the habitat effects database, a silt-tolerance value was assigned to the species or species assemblage which was affected by the sediment pollution event. The selection of silt-tolerance guilds was based on the recent work of Poff and Allan (1995), who evaluated 106 fish species from 23 families according to their tolerance of turbid water, as well as a range of other ecological classifications (trophic guild, stream size, habitat preferences, etc.). In Poff and Allan (1995), fishes were classified on a three-point scale as having a high, medium and low tolerance to turbidity, reproduced here as Appendix 3. Poff and Allan (1995) found that fishes from the high or medium tolerance guilds were statistically more common at sites with variable hydrological regimes (i.e., that experienced seasonal flushing flows or spates), while intolerant species were more common at hydrologically predictable sites.

Based on the classification system used by Poff and Allan (1995), species or assemblages of species in the dose/response database were assigned one of three silt-tolerance classes: (1) high; (2) medium; or (3) low tolerance. If a species in the database did not have an assigned ranking in Poff and Allan (1995), the ranking of a species with similar life history and habitat preference from the same genus was used. For macroinvertebrate communities in the database, silt tolerance rankings were assigned based on associated fish species assemblages present in the watercourse.

Since the main goal of the project was to quantify the effects of sediment release on fish and habitat, emphasis needed to be placed on sediment release events (i.e., effects of sediment pollution events rather than chronic erosion and sediment load problems). As a result, the habitat-effects database was condensed as information on chronic events (greater than 1 month in duration) were removed. The database was further condensed by the exclusion of any datapoints for which the extent of habitat modification could not be ascertained from the primary manuscripts. The database was reduced to 35 entries (Table 4.1) and was used in the following analysis to develop relationships between sediment dose and habitat effects.

TABLE 4.1

SUMMARY OF RESPONSES OF ORGANISMS AND THEIR HABITATS TO ACUTE SEDIMENT EXPOSURE

i. Common Name
ii. Habitat (f = fresh; e = estuarine)
iii. Life-History Phase (l = larvae; A = adult)
iv. Silt Tolerance

Organism i.	ii.	iii.	iv.	Exposure: Concentration and Duration mg/L	hr	Stress Index (SI): Natural log of mg.hr/L SI	SE	Nature of Ill Effect (NE): NE	Reference
benthos & silver shiner	f	A	2	1461	48	9.66	7	Slight reduction in fish numbers and alteration to habitat for benthic	Schubert, Vinikour and Gartman
invertebrates (benthic)	f	l	2	1700	2	8.13	7	Temporary changes in community structure	Fairchild and others 1987[1]
invertebrate (1)	f	l	1	29	720	9.95	7	Conditions unsuitable for intolerant taxa	M.P. Vivier, pers. comm.; from Newcombe 1994a[1]
invertebrates (2)	f	l		620	48	10.30	7	Reduction in number and species of invertebrates.	Hesse and Newcomb 1982[1]
blackfish	f	A	2	4610	8	10.50	14	93% reduction in fish biomass following sediment release	Doeg and Koehn (1994)
Macroinvertebrates	f	l	2	4610	8	10.50	8	19.4% reduction in taxa and 63.9% reduction in abundance	Doeg and Koehn (1994)
fish (2)	f	A		120	384	10.74	10	Reduction in density of fish.	Erman and Lignon 1988[1]
Centrarchids	f	A	2	144.5	720	11.55	12	Fish unable to reproduce.	Buck 1956[1]
fish (warmwater)	f	A	1	22	8760	12.17	14	Fish populations destroyed.	Menzel and others 1984[1]
Warmwater Streams	f	all	1	57	8760	13.12	10	Moderately severe habitat degradation.	Menzel and others 1984[1]
Warmwater Fish	f	A	1	66	8760	13.27	10	Habitat damage	Berkman and Rabeni 1987[1]
ecosystem	f	all	1	189	8760	14.32	12	Severe habitat degradation in warm water ecosystems.	Menzel and others 1984[1]
darters	f	A	2	2045	8760	16.70	14	Darters absent due to habitat destruction	Vaughan 1979[1]
trout (cutthroat)	f	A	3	35	2	4.25	3	Feeding ceases and fish seek cover	Cordone and Kelly 1961[1]
grayling (Arctic)	f	A	3	100	1	4.61	7	Catch rate reduced as fish change prey to tubificids	McLeay and Others 1987[1]

[1]Source: Newcombe 1994a

TABLE 4.1 (cont'd)

SUMMARY OF RESPONSES OF ORGANISMS AND THEIR HABITATS TO ACUTE SEDIMENT EXPOSURE

i.	ii.	iii.	iv.	mg/L	hr	SI	SE	NE	
herring (lake)	f	I	3	16	24	5.95	3	Change in preferred swimming depth	Swenson and Matson 1976[1]
invertebrates (macro)	f	I	3	72.5	24	7.46	7	Silt-intolerant species less abundant.	Gammon 1970[1]
brown trout	f		3	1773	4	8.87	10	Measurable reduction in spring trout pop.	Alexander and Hansen (1977)[1]
zoobenthos	f	I	3	12.5	720	9.10	7	Decrease in size of zoobenthic population.	Rosenberg and Snow 1977
Coldwater habitat	f		3	1679	7	9.40	7	Dune of deposited sediment evident on gravel bed downstream of crossing	Anderson and others (1995)[1]
salmon (1) & trout (1)	f	A	3	75	168	9.44	7	Reduced quality of rearing habitat.	Slaney Halsey and Tautz 1977[1]
zoobenthos	f	I	3	100	672	11.12	7	Standing crop reduced.	Rosenberg and Snow 1977[1]
trout (brown)	f	A	3	100	720	11.18	10	Population reduced.	Scullion and Edwards 1980[1]
trout (rainbow)	f	A	3	59	2232	11.79	10	Habitat damage: Potential impact on egg incubation via reduced porosity of gravel.	Slaney Halsey and Tautz 1977[1]
invertebrates	f	I	3	77	2400	12.13	10	Receiving stream Invertebrate density and biomass reduced.	Wagener and LaPerriere 1985[1]
trout	f	A	3	300	720	12.28	12	Decrease in the size of a trout population.	Peters 1967[1]
fauna (benthos)	f	I	3	325.5	720	12.36	10	Receiving stream: numbers of organisms per unit area reduced 75 per cent.	Tebo 1955[1]
steelhead (1)	f	A	3	1650	240	12.89	10	Loss of habitat caused by excessive sediment transport.	Coats and others 1985
invertebrates (macro-)	f	I	3	46.8	8760	12.92	10	Species diversity reduced; some species absent. Sand deposited over 17 km reach	Nuttall 1972[1]
trout (rainbow)	f	A	3	3500	1488	15.47	14	Catastrophic reduction in population size.	Herbert and Merkens 1961[1]
trout (brown)	f	A	3	1040	8760	16.02	14	Population one-seventh of expected size.	Herbert and others 1961[1]
fish (2)	f	A	3	2045	8760	16.70	12	Habitat destruction: fish populations smaller than expected.	Vaughan 1979; also Vaughan [1]
trout (brown)	f	A	3	5838	8760	17.75	14	Fish numbers one-seventh of expected.	Herbert, Alabaster, Dart[1]
mottled sculpin	f	A	3	122.5	660	11.30	12	Standing crop reduction from 109 fish/ 30 m in autumn of 1971 (precons) to 26.9 fish/ 30 m during construction in	Barton (1977) & Taylor and Roff (1986)
brook trout	f	A	3	122.5	660	11.30	12	59% reduction in standing crop	Barton (1977) & Taylor and Roff (1986)

[1]Source: Newcombe 1994a

A sub-set of the acute habitat effects database was derived which included information related to responses of intolerant habitats (class 3 Poff and Allan (1995)) to sediment effects. This sub-set of the data provided a dose/response relationship described by the equation:

6. $SE = 0.9837 + 0.7628 \ Ln \ (mg \cdot hr \cdot L^{-1})$ ($r^2adj=0.748$; $N=22$; $p<0.01$).

Similarly, sediment effects data for silt-tolerant fish species (classes 1 & 2 Poff and Allan (1995)) were used to develop a relationship between dose and response of silt-tolerant habitats. This relationship is described by the equation:

7. $SE = 0.659+ 0.818 \ Ln \ (mg \cdot hr \cdot L^{-1})$ ($r^2adj=0.384$; $N=13$; $p=0.014$).

The weaker relationship for the silt-intolerant habitat response is likely a result of the limited nature of the data available. These two regressions are presented in Figure 4.1. When plotted simultaneously, the two regressions do not appear to appreciably differ, and in fact, using a homogeneity of slope analysis, these two regressions were shown not to be significantly different (p=0.629).

As a result, the tolerant and intolerant data were pooled in order to develop a relationship between sediment dose and habitat response using the entire acute habitat effects database. An analysis of the pooled data provided a relationship (Figure 4.2) which can be described by the equation:

8. $SE = 0.943 + 0.777 \ Ln \ (mg \cdot hr \cdot L^{-1})$ ($r^2=0.659$; $N=35$; $p<0.01$).

The dose/response approach of Newcombe and MacDonald (1991) and Newcombe (1994a) defines dose as the product of TSS concentration (C in mg/L) and duration of exposure (T in hours). This definition of dose is strictly empirical and reflects the observation that the product of concentration and duration bears a closer correlation with ranked effects than does concentration alone. The inherent assumption is that brief exposures to high doses of TSS are equivalent in effect to prolonged exposure to much lower doses. Since severity of effect is determined based on a linear relationship with dose ($Ln \ C \cdot T$) of the form $SE = a + b \ (Ln \ C \cdot T)$, the biological receptor response (SE) is assumed to respond to an effective dose in which concentration and duration are equally as important (i.e., the Effective Dose = C^nT; where $n = 1$).

However, it has been proven in much of the literature related to the response of biological receptors to toxic agents, that the relationship between concentration and duration is often more complex. That is, a high concentrations for a very short time can cause a higher or lower response than can a low concentration for a longer time (Zelt 1995). In essence, by assuming a linear response (as measured by SE) to dose (as a function of $Ln \ C \cdot T$) we assume that a unit increase in concentration (in mg/L) is equal to a unit increase in time (in hours). This assumption may or may not be a valid one.

FIGURE 4.1

RESPONSES OF ORGANISMS AND THEIR HABITATS TO SEDIMENT EXPOSURE

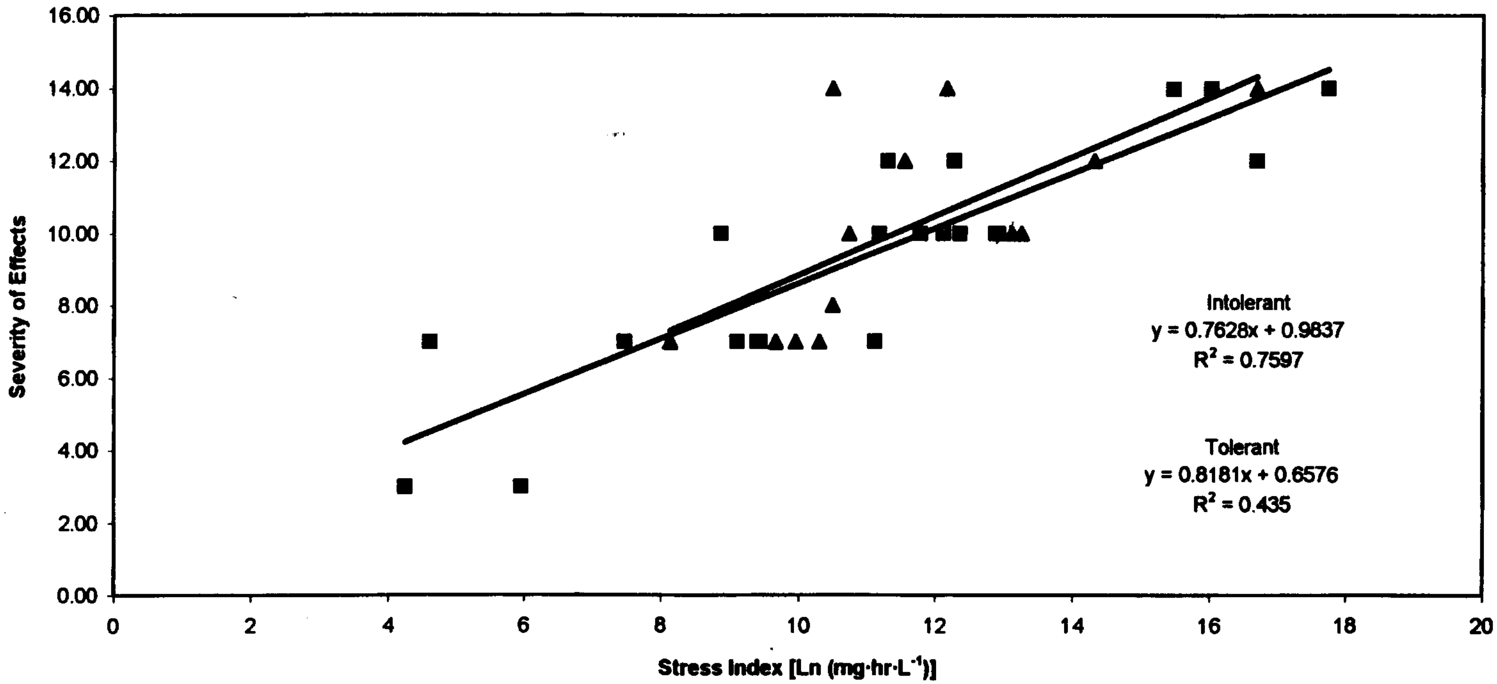
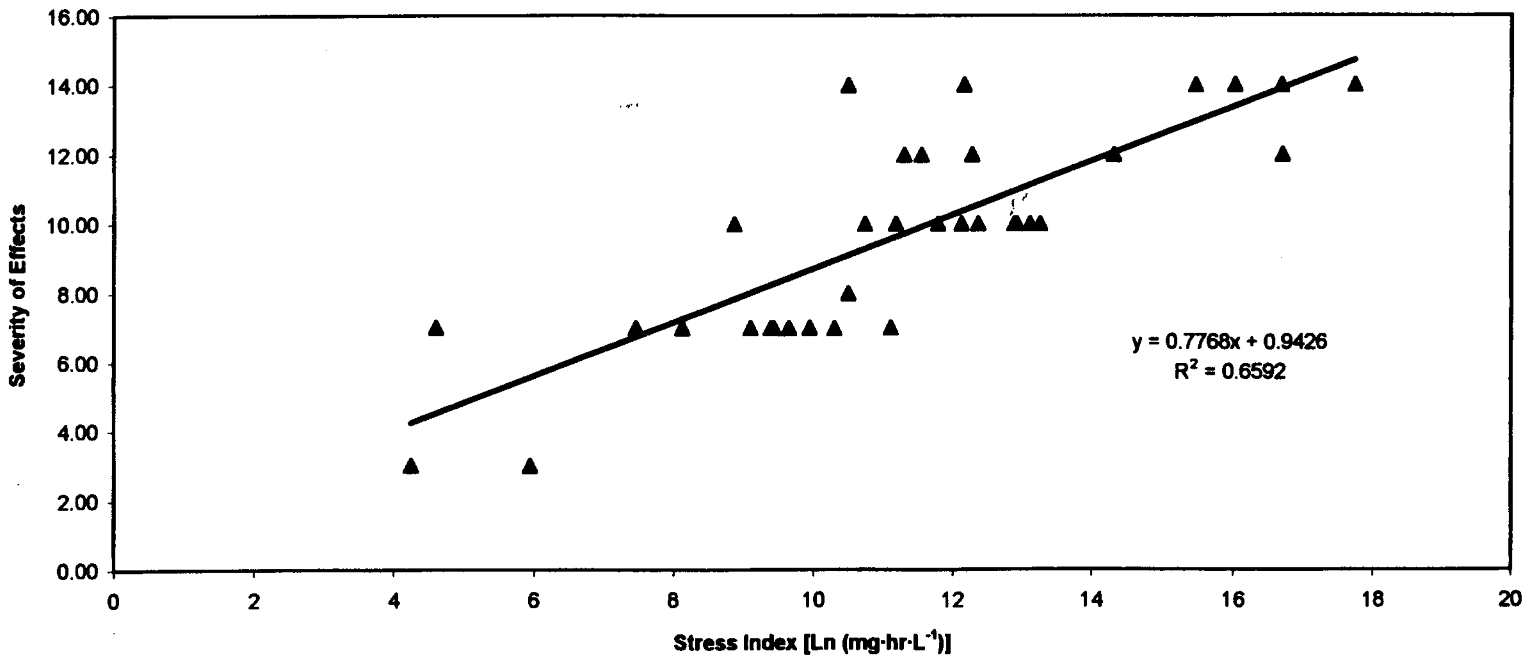


FIGURE 4.2

RESPONSE OF ORGANISMS AND THEIR HABITATS TO SEDIMENT RELEASE
(Low, Moderate and Highly Tolerant Organisms Combined)



In an effort to address the potential for non-linearity in the relationship between concentration and duration in determining the effective dose of sediment (i.e., Effective Dose $=C^n \cdot T$; where $n \neq 1$), Newcombe and Jensen (1995a) used multiple regression analysis to develop severity of effect relationships based on concentration and duration:

$z = a + b(\text{Ln } x) + c(\text{Ln } y)$

where:

[a] = intercept
[b] = slope of x
[c] = slope of y
[x] = duration of exposure expressed as the natural log of hours;
[y] = concentration of sediment expressed as natural log of mg/L;
[z] = severity of ill effect (SE).

This approach, in effect, allows for different factors (slopes) to be assigned separately to the variables of concentration and duration.

In order to explore the relationship between concentration and duration in influencing habitat change, the habitat effects database was analyzed using multiple regression analyses. This analysis identified a relationship between sediment exposure and habitat effects which can be described by the equation:

9. $z = 0.032 + 1.008 \text{ Ln}(X) + 0.978 \text{ Ln}(Y)$; $r^2(adj) = 0.993$; $n=35$; $p<0.001$.

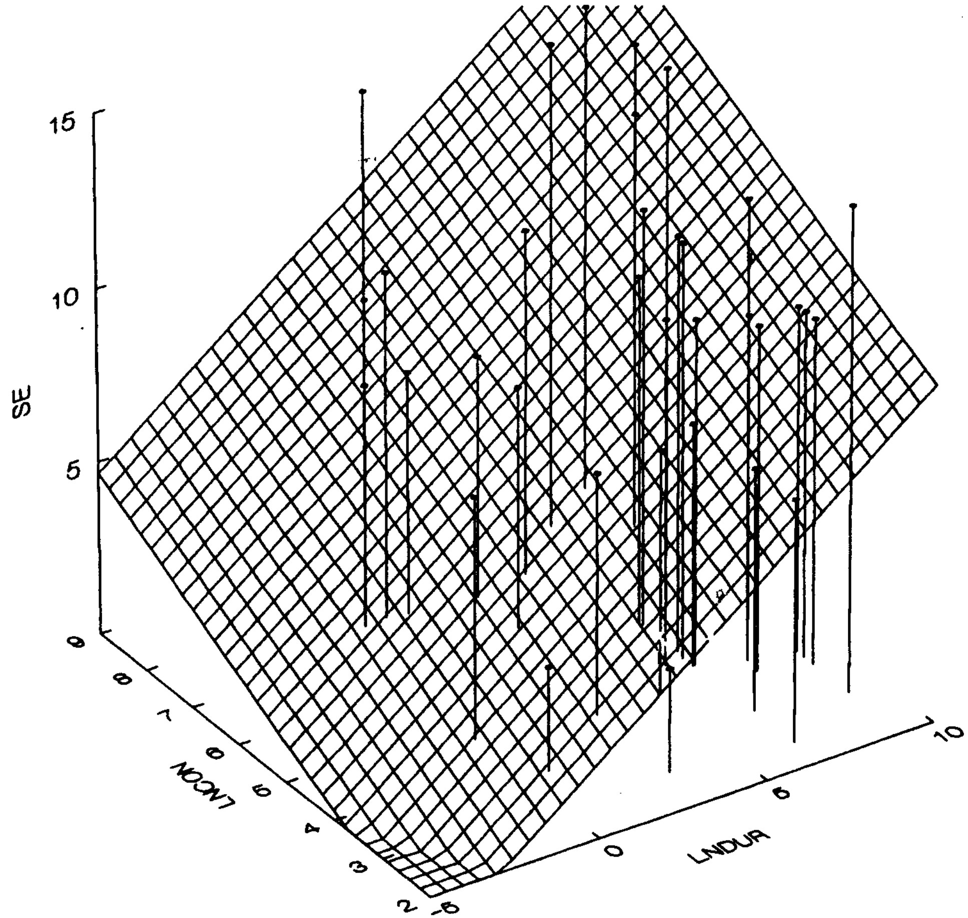
Statistics for the multiple regression relationship presented are summarized in Table 4.2. The high adjusted r^2 for this relationship ($r^2(adj) = 0.993$) indicates the good fit of this relationship as compared to any of the previously identified treatments of the acute habitat effects dataset. The increased strength is the result of enabling separate slope coefficients to be applied to the natural logs of concentration and duration in the regression. This indicates that concentration and duration affect the extent of habitat alteration in dissimilar ways or in other words, that the effective dose of sediment is a function of a non-linear relationship between the two predictive variables (i.e., Effective Dose $=C^n \cdot T$; where $n \neq 1$).

TABLE 4.2
STATISTICS FOR THE MULTIPLE REGRESSION RELATIONSHIP (EQUATION 9)

Variable	Coefficient	Std. Error	Std Coef	Tolerance	T	P (2Tailed)
Constant	0.032	0.180	0.000		0.177	0.860
Ln Con.	0.978	0.025	0.564	0.973	39.871	0.000
Ln Duration	1.008	0.015	0.920	0.973	65.061	0.000

Figure 4.3 illustrates the multiple regression relationship between Ln Concentration, Ln Duration and habitat effect. This figure illustrates the more dominant role which the duration of exposure plays in determining the extent of the habitat effect. The "T" statistic for each slope in the regression (Table 4.2) is an expression of the importance of each variable with respect to the relationship derived. The higher score attributed to duration indicates its importance in determination of habitat effects (i.e., Effective Dose = $C^n \cdot T$; where $n < 1$).

FIGURE 4.3
DOSE RESPONSE FOR FISH HABITAT EFFECTS AS A FUNCTION OF SEDIMENT CONCENTRATION AND DURATION OF EXPOSURE



From our analysis it would appear that the duration of the sediment release episode is an important factor in the relationship between sediment exposure and habitat effects. From an ecological perspective, this would indicate that an important mitigative measures associated with minimizing the effects of sediment release on aquatic habitats would be to minimize the duration of the disturbance (i.e., the duration of instream activity).

A comparison of severity of ill-effects scores using the simple linear regression (equation 8) and the multiple regression (equation 9) are presented in Table 4.3. The numbers for concentration and duration were generated at random within ranges anticipated to be encountered during sediment release events; that is, a concentration range of 0-3000 mg/L for acute exposure durations (<96 h).

The two equations show a relative consistency within SE scores, with equation 9 providing more conservative (i.e., higher SE scores) for any given sediment release event.

4.6. CONFOUNDING FACTORS

The dose/response relationships presented in this chapter make generalizations about the anticipated level of effects to the aquatic environment which may result from a sediment release episode. Since these are generalizations, the actual effects which are realized by a sediment release episode may be more or less severe based on a number of confounding factors.

Characteristics of Suspended Particles

The potential for adverse effects on fish and their habitats associated with sediment release is a function of increasing particle size (Newcombe and Jensen 1995b). Instream excavation suspends coarse-grain particles which might normally be too large to be entrained and transported by the flow within the watercourse under normal conditions. As a result, the effects of particle size on the severity of the effects caused by instream construction may be of special concern since these types of sediment pollution events may subject fish and habitats to particle sizes to which they may not normally be exposed. More information relating dose-response relationships between specific fish guilds or habitat types as a function of particle size range is required in order to develop a better understanding of this confounding factor.

The angularity or mineralogy of suspended particles may play a important role in the potential for physiological or toxicity effects (Newcombe and Jensen 1995a). The angularity of a particle may be of particular importance with respect to gill abrasion of fish within the receiving environment, and may also influence the rate of infiltration of particles into the stream bed. Meanwhile, the mineralogy of the particle may be important since the particle itself may have some potential chemical activity at the cellular level (Newcombe and Jensen 1995a). In addition, the potential for contaminants adsorbed to sediment particles is also a concern, since suspension of contaminated river sediments could make certain compounds available to fish which could have more dramatic effects than those which might be caused by the release of sediments alone.

TABLE 4.3

COMPARISON OF SEVERITY OF EFFECTS SCORES (SE) USING SIMPLE LINEAR REGRESSION AND MULTIPLE REGRESSION EQUATIONS

Concentration[1] (mg/L)	Duration[1] (mg/L)	SE Equation 8[2]	SE Equation 9[3]
271.8	95.1	8.8	10.4
146.0	4.3	6.0	6.7
137.6	23.3	7.2	8.3
228.7	38.6	8.0	9.3
336.2	20.3	7.8	9.0
109.1	40.4	7.5	8.6
28.1	73.7	6.9	7.9
127.5	93.2	8.2	9.6
389.0	92.5	9.1	10.7
440.6	5.4	7.0	8.0
195.8	94.4	8.6	10.1
154.2	86.9	8.3	9.7
86.2	81.2	7.8	9.1
797.7	8.6	7.8	9.0
862.8	79.9	9.6	11.3
168.4	25.6	7.4	8.6
155.7	38.0	7.7	8.9
69.1	26.6	6.8	7.8
2528.5	60.6	10.2	12.1
1807.8	39.9	9.6	11.4
617.5	82.1	9.4	11.0
2657.8	92.7	10.6	12.6
369.1	38.6	8.4	9.8

[1] Randomly generated
[2] SE = 0.943 + 0.777Ln(dose mg h /L)
[3] SE = 0.032 + 1.008(LnX) + 0.978 (LnY)

Temperature of the Receiving Environment

The temperature of the water can have an impact on the severity of the effects caused by a sediment release event. As discussed in Chapter 3, the oxygen holding capacity of water and the metabolic and respiratory rates of fish are influenced by water temperature. As a result, ill-effects of sediment exposure may be greater in seasonably warm waters than would be expected for the same fishes in seasonably cold water (Newcombe and Jensen 1995a).

Ultra-sensitivity

The severity of effects which are caused by sediment release may be a function of the levels of stress acting on the system at the time of, or before, the sediment release episode. Therefore, as discussed in Chapter 3, the timing of sediment release is of critical importance.

4.7. SUMMARY

There are a number of existing criteria which have been used to identify acceptable levels of suspended sediment within a watercourse. These criteria have been based on observations of fish populations under chronic exposure conditions, and therefore, may not be appropriate for use in developing acceptable criteria for acute sediment release events. Through work undertaken by Newcombe and others, a dose/response approach has been used to develop relationships between sediment exposure and effect on the aquatic environment.

A number of relationships have been developed which relate sediment dose to the response of fish guilds or the habitats which they use. The dose/response relationships presented in this report include the results of analyses conducted by Newcombe and MacDonald (1991), Newcombe (1994a), MacDonald and Newcombe (1993) and Newcombe and Jensen (1995a). For more information regarding the development and application of these dose/response relationships, the reader is directed to these original studies.

Dose/response relationships were developed for fish habitat using the approach developed by Newcombe and others. Separate relationships were developed for the response of silt-tolerant and silt-intolerant habitats to sediment release. A comparison of these relationships determined that there was no significant difference in response, and that pooling of the data improved overall predictive capabilities.

The use of multiple regression analysis enabled the development of a better predictive tool for the assessment of sediment effects on habitat, since this approach allowed separate coefficients (slopes) to be attributed to the two predictive variables of sediment concentration and duration of exposure. The relationship developed between sediment release and fish habitat response is described by the equation:

$$z = 0.032 + 0.978 \text{ Ln (Concentration)} + 1.008 \text{ Ln(Duration)}$$

This relationship had a very good fit with the dataset used for its development (adjusted r^2= 0.993); however, it has not yet been field tested.

The response of biological receptors to environmental stresses is complex. Many factors may influence the actual severity of effects which are caused by a sediment release episode, including: characteristics of the particles suspended; temperature of the water; and, the existing stress level within of the receiving environment. Although many factors may influence the response of aquatic systems to sediment release, the dose/response relationships which have been developed contribute insight into the effects of sediments on fish and their habitats and provide a foundation by which these impacts can be quantified.

5.0. SEDIMENT TRANSPORT MODELLING

In Chapter 4, the specific sediment dose/response relationships for fish habitats and guilds was discussed. These relationships describe the severity of ill-effects as a function of sediment dose in a predictive relationship. In many cases, sediment dose is determined based on actual field monitoring data which are gathered during the sediment release episode; however, it would be beneficial to have the ability to predict the characteristics of potential sediment release episodes based on sediment transport models. Sediment transport models would be of use to resource managers for estimating the amount of sediment added to the natural stream sediment load, for determining the spatial area of the watercourse which may be affected by elevated suspended sediments, and in the identification of areas which may be altered as a result of sediment deposition. In this chapter, several sediment transport models in current use are evaluated with respect to their applicability to instream activities such as a water crossing.

Sediment processes have an impact on the aquatic community through a number of mechanisms, namely:

- suspension of sediment material due to instream disturbance,
- transport of sediment,
- deposition of sediment, and
- re-suspension (scour) of deposited materials.

Sediment processes are quite complex in nature and consequently are difficult to predict using numerical models. There has, however, been a great deal of sediment engineering research conducted to gain a better understanding of the specific river/sediment processes occurring in a river reach. The concepts of tractive force (Shields 1936), incipient motion, transport capacity (Münning 1895; Strickler 1923 and Einstein 1950), continuity of sediment mass (Exner 1931), active bed, rate of replenishment (Gessler 1970) have been extensively studied with empirical and physically based relationships established to predict these phenomena. The difficulty associated with modelling these processes lies in the complex inter-relationships which exist amongst these various processes. There are few numerical models available which account for all of the important processes and their inter-dependence in a logical manner. Models capable of simulating river sediment scour, transport and deposition require physical, hydrological, and sediment data to calibrate and simulate impacts of river sediment conditions. These data often include the following:

- physical data including bathymetry (i.e., cross-sectional bed and bank elevation data), bed and bank hydraulic roughness, thickness of bed sediment layer defining the active (erodible) sediment layer;
- hydrologic data including flow conditions representative of the construction period;
- sediment data including description of the grain-size distribution of the active bed sediment layer along the reach, estimates of total suspended solids and grain-size distribution of the total suspended solids at the upstream boundary; and,

- hydraulic data including downstream water levels for flow conditions to be simulated - usually specified in terms of a rating curve.

The amount and type of information that is normally collected at pipeline crossings is often quite limited. While it may be feasible to collect representative static information, such as physical data (i.e., cross sections, slope, bed roughness, etc.), the time and resources available will often constrain the collection of sediment information (TSS, grain-size distributions of bed and suspended materials) along the reach and flow information (velocity, depth) for a representative range of hydrological conditions. As with the simulation of all stream processes, the more information which is available for the calibration and verification of existing conditions, the more accurate will be the prediction of short and longer term impacts on downstream aquatic organisms and habitat.

The remainder of this chapter presents an evaluation of several existing sediment scour, transport and deposition estimation methods in the context of their applicability to pipeline crossing studies, followed by a conceptual model of sediment transport, that is tailored to the information requirements and data limitations of pipeline crossing evaluations. The conceptual model is designed for *a priori* assessments but also includes capabilities for calibration to monitoring data collected during construction, in order to permit the model to be evaluated and model parameters to be refined over time.

The scope of work completed under this contract includes: (1) an evaluation of existing methods; and, (2) development of a new conceptual model framework which incorporates estimation of sediment loading due to construction activities and simulation of downstream sediment transport, deposition and re-suspension.

5.1. EVALUATION OF EXISTING METHODS

5.1.1. Sediment Loading

Two important factors associated with a pipeline crossing include the concentration of the sediment which will be suspended in the watercourse at the location of the crossing and the distance that the suspended sediment will be transported downstream. An accurate prediction of the elevated suspended solids concentrations at the location of the crossing brought about by the disturbance of the bed material during construction is very difficult to achieve.

Trow Consulting Engineers Ltd. (1994) developed a simple empirical method for predicting the average concentration of total suspended solids generated by crossing construction. This equation is reported to be applicable for non-cohesive solids coarser than medium silt (i.e., >0.04 mm). The equation for predicting the average concentration of TSS generated by the excavation is:

$$TSS = \frac{V_t \times R_r \times U_w \times 10^3}{V_w} \tag{4-1}$$

where, TSS = average increase in TSS (mg/L)
V_t = volume of trench excavated per unit time (m^3/time)
R_r = recovery ratio (dimensionless)

V_w = flow past construction area (m^3/time)
U_w = dry unit weight of trench material (kg/m^3)

The calibration factor in this equation is the empirical recovery ratio constant (R_f), for which no generally applicable guidance is given. There appears to be very little research or results from practical studies available to assist in the estimation of the quantity, size and rate of material generated by pipeline construction activities. The estimation of elevated suspended sediment levels from disturbance of the bed during construction is critical to the subsequent prediction downstream transport, deposition and re-suspension, and is necessary to evaluate downstream impacts.

5.1.2. Sediment Transport, Deposition, and Re-suspension

With an estimate of the elevated suspended sediment concentrations at the construction location, the next step is to be able to predict the distance over which the material may be transported and deposited, and the nature of the deposition within this zone of influence.

Trow Consulting Engineers Ltd. (1994) has developed a simple empirical method for predicting the length of instream transport of elevated sediment concentration. This equation is reported to be applicable for non-cohesive solids coarser than medium silt (i.e., >0.04 mm). This equation is:

$$L = \frac{D \times U_m}{V_s \times C} \qquad (4\text{-}2)$$

where,
L = distance downstream of excavation where settlement is expected (m)
D = average depth of flow in the area of deposition (m)
U_m = mean flow velocity of the stream (m/s)
V_s = soil particle settling velocity (m/s)
C = coefficient to account for turbulence (typically 0.6-1)

There are a number of limitations to the general application of this equation. Equation 4-2 provides an estimate on the length of the settlement zone, but can not predict distribution or amount of settling within the zone of "settlement" which may be critical to the assessment of potential habitat alteration. Also, the equation assumes a prismatic channel having a constant velocity. The settling velocity of a particle must incorporate the tendency for particles to be supported or elevated as a result of turbulent flow. As well, currents within a channel vary across and along the channel, making the prediction of sediment zones and concentrations quite complex. Equation 4.2 incorporates an empirical calibration coefficient (C). There does not appear to be any generally applicable guidance available for estimating the value of C, making this modelling approach difficult to use for *a priori* assessments. The approach should be used with caution and investigators should include a program to collect calibration data during construction, and to calibrate the model and verify the results.

Numerical sediment transport models for streams are widely available (e.g., HEC6 - USACE 1991, MOBED - Krishnappen 1981, 1983, 1986, ONE-D-SED - Morse *et al.* 1991, and FETRA - Onishi 1981), and have been widely applied. They simulate the erosion, transport and deposition based on the hydraulic characteristics of the stream. Many sediment transport models incorporate hydraulic simulation sub-models, which supply the necessary hydraulic information to the sediment transport sub-model.

Sediment transport is the fundamental process governing the zone of influence. Many models such as HEC-6 determine transport capacity by considering the potential of the stream to carry sediments of various grain sizes coupled with the fraction of each grain size present in the bed to yield sediment as well as the quantity of suspended material present from upstream. Deposition is considered to occur when the in-flowing sediment load is greater than the transport capacity. The rate at which sediment is deposited is controlled by the particle settling velocities of the grains comprising the sediment layer. This basic principle has been considered in the Trow model but only for uniform (prismatic) channel conditions.

The actual prediction of sediment transport is quite complex; depending on the quality of calibration data, more sophisticated physically based prediction methods may be required. For example, four basic sediment properties which affect the rate of sediment transport are the size, shape factor, specific gravity and fall velocity of the particles. The HEC-6 model attempts to account for these factors in predicting transport capacity. Specific gravities for sand, silt and clay can be input separately; an equation which considers the length of the material along each axis is used to compute the shape factor; and Toffaleti (1996) equations are used to determine the fall velocity of a particle.

Typically, different model formulations are used for non-cohesive (sand sized and larger) and cohesive (silt and clay) sediments. In HEC-6 for example, there are 12 relationships which can be used to predict the transport of sand and gravel in a stream. These relationships for non-cohesive sediment transport are typically simulated by a sediment carrying capacity approach and have been developed by Ackers and White (1973); Yang (1973); Colby (1964); Toffaleti (1969); Meyer-Peter (1948); and Müller (1943).

A widely used formulation for non-cohesive sediment developed by Ackers and White (1973) is described here briefly. The formulae are based on three dimensionless parameters, the mobility number F_{gr}, the transport parameter G_{gr}, and the dimensionless grain diameter D_{gr}, which are defined as follows:

$$F_{gr} = \frac{v_*^n}{\sqrt{gD(s-1)}}\left[\frac{V}{\sqrt{32}\log(10y/D)}\right]^{1-n} \qquad (4\text{-}3)$$

$$D_{gr} = D\left[\frac{g(s-1)}{\nu^2}\right]^{1/3} \qquad (4\text{-}4)$$

$$G_{gr} = C\left(\frac{F_{gr}}{A} - 1\right)^m \qquad (4\text{-}5)$$

where,

	v_*	=	shear velocity given by $v_* = \sqrt{gRS}$
	g	=	acceleration due to gravity
	R	=	hydraulic radius
	S	=	slope of the river
	n	=	transition exponent dependent on sediment size

D	=	Sediment diameter (D_{35} for graded sediments)
s	=	specific gravity of sediment particles
V	=	mean velocity of flow
v	=	kinematic viscosity of fluid
y	=	mean depth of flow

The coefficients C, A, M and n are functions of D_{gr}, determined as follows:

When $D_{gr} > 60$ (coarse sediment),

n	=	0
A	=	0.17
m	=	1.50
C	=	0.025

When $1 \leq D_{gr} < 60$,

n	=	$1.0 - 0.56\log_{10}(D_{gr})$
A	=	$0.23/\sqrt{D_{gr}} + 0.14$
m	=	$9.66/D_{gr} + 1.34$
$\log_{10}C$	=	$2.86\log_{10} D_{gr} - (\log_{10} D_{gr})^2 - 3.53$

The average TSS concentration or carrying capacity (C_{av}) can be calculated as follows:

$$C_{av} = \frac{G_{gr}D}{y(v_*/V)^n} \tag{4-6}$$

When the concentration in the stream is less than C_{av}, re-suspension will occur and when the concentration in the stream exceeds C_{av}, deposition will occur. The advantage of the Ackers and White (1973) formulation is that it requires no empirical parameters and is specified in terms of flow parameters which are easily measured.

An equation used in HEC-6 for cohesive sediments (i.e., silt and clay) deposition was developed in a flume under conditions having slow aggregation rates and suspended sediment load concentrations less than 300 mg/l, and is defined as follows:

$$\frac{C}{C_O} = e^{(-kt)} \tag{4-7}$$

where,	C	=	concentration at the end of a time period
	C_0	=	concentration at the beginning of time period
	t	=	time defined as the reach length/flow velocity
	k	=	$(V_S P_r)/(2.3\ D)$
	Vs	=	settling velocity of particles
	Pr	=	probability that a floc will stick to bed (1-tb/td)
	D	=	water depth
	tb	=	bed shear stress

td = critical shear stress for deposition

Another formulation for cohesive sediments was developed by Partheniades (1965) and Krone (1962) for estimating re-suspension (S_R) and settling (S_D). This is expressed as follows:

$$S_R = M\left(\frac{\tau_b}{\tau_{cR}} - 1\right) \quad (4\text{-}8)$$

$$S_D = WC\left(1 - \frac{\tau_b}{\tau_{cD}}\right) \quad (4\text{-}9)$$

where, M = erodibility coefficient for the sediment
W = sediment fall velocity
C = suspended sediment concentration
τ_b = bed shear stress, calculated as a function of flow velocity
τ_{cR} = critical shear stress for sediment re-suspension
τ_{cD} = critical shear stress for sediment deposition

The sediment fall velocity (W) can be calculated from:

$$W = K' C^{4/3} \quad (4\text{-}10)$$

where, K' = empirical constant, dependent on sediment type

M, τ_{cR} and τ_{cD} depend on the sediment type and are generally determined by field or laboratory tests (Onishi 1981). This requirement limits the applicability of these formulations for pipeline crossing studies; however, recent studies have derived the coefficients for specific sediment types and have revised the formulations. For example Burban (1990) have developed the following equation for estimating the settling velocities of medium grained (10-100 υm) cohesive sediment:

$$v_s = B_1(mG) - 0.85 d_m^{-[0.8+0.5\log(mg - B_2)]} \quad (4\text{-}11)$$

$$G = 0.0015(v_a)^2 \quad (4\text{-}12)$$

where, v_s = settling velocity
B_1 = empirical cohesive sediment constant (9.6×10^{-4})
G = fluid shear stress
d_m = sediment diameter
m = concentration of solids
B_2 = empirical cohesive sediment exponent (7.5×10^{-4})
v_a = advective velocity

Some sediment re-suspension models (e.g., IPX - Velleux 1995) account for the increase in critical shear stresses as freshly deposited cohesive sediments age. In general, the critical shear stress for re-suspension of cohesive sediments will stabilize in the order of seven days after deposition.

Environmental Management Associates (1993) implemented a two-dimensional (lateral and longitudinal) dispersion model (MULTI) to simulate TSS concentrations in the Sukunka River downstream of a pipeline crossing. The model was not implemented prior to construction, but rather after construction to generate a more complete picture, both temporally and spatially, of TSS concentrations during construction. This information was required to assess compliance with a TSS criteria that was determined based on the physiological stress effects threshold for a given time period using the dose/response relationship provided in Newcombe and MacDonald (1991). The study had the benefit of being able to calibrate to information collected during construction. This study is therefore not directly applicable to an *a priori* simulation of TSS levels during construction of a pipeline crossing; however, the study does provide some insight into what would be applicable to a pre-construction (*a priori*) simulation. MULTI (HydroQual and Gore & Storrie 1988) is a computerized model which incorporates an analytical solution to lateral and longitudinal mixing in river systems. Settling was simulated using a first-order decay process, which is analogous to using a constant settling velocity, provided average depths are not highly variable. MULTI can simulate a time-series of TSS concentrations, under steady state flow conditions. Data collected for calibration included depth, velocity and TSS concentration profiles at four transects downstream of the crossing. In order to circumvent the difficulty in estimating the mass loading of TSS to the river from the construction, monitoring data from the first transect (100 m downstream) was used to define input conditions. The calibrated model was able to provide a good representation of measured TSS concentrations at the three downstream transects. Three parameters needed to be set to calibrate the model; a lateral mixing zone coefficient (dimensionless), a longitudinal dispersion rate (cm^2/s), and a settling rate (1/day). The model was calibrated using a settling rate of zero, indicating that no significant settling was occurring within 2 km downstream of the crossing (the furthest downstream transect). Application of this type of model prior to construction would be more difficult. Lateral mixing could be eliminated by simulating laterally averaged TSS concentrations. Longitudinal dispersion can be adequately estimated from literature values. Estimation of the mass loading of TSS from construction activities and specification of representative settling rates are more difficult, and suffer from the same limitations as the Trow model discussed previously: no objective means for estimating values for total load exists.

5.2. CONCEPTUAL MODEL DESIGN

A conceptual sediment transport modelling system for pipeline crossings is outlined in the following section. The modelling system consists of two major components, the first of which is a methodology for estimating the mass loading rate and composition of sediment resulting from construction. The loading methodology generates the sediment load input for the second major component, a sediment transport model which predicts the concentrations of TSS, the amount and distribution of settled sediment, and possibly the potential for subsequent re-suspension of the settled sediment.

The working model (yet to be developed) should be structured to include the capability for calibration to data collected during construction, thereby improving the understanding of transport model parameter and loading relationships. In addition, incorporation of continuous simulation capability is a feature which should be incorporated into the sediment transport model for both pre- and post-construction simulations.

The data requirements for the modelling system must be practical and be sensitive to the human and capital resources available to study the impacts of the pipeline crossing. Data which are typically collected for pipeline crossings and which would be required for the modelling system are discussed briefly. The individual components of the conceptual model are discussed in more detail in the remainder of this section.

5.2.1. Stream Crossing Data

Data commonly collected for a stream crossing evaluation prior to construction includes; depth and velocity transects in the vicinity of the crossing, bed sediment composition, and background TSS concentrations (Goodchild and Metikosh 1994). It is assumed that any additional data required to calibrate a sediment transport model for pipeline crossings would have to fit within the scope of existing data collection programs (i.e., not prohibitively affect the cost of data collection). This information should be collected during base flow conditions as well as higher flow conditions experienced following a significant rainfall or snow-melt event.

Suspended sediment concentrations and grain-size distribution, and additional flow information are typically collected during construction of the crossing. Sediment deposition is also monitored during construction of some crossings (e.g., EMA 1992, 1993, 1994). This information should be collected at the same time the flow, velocity and depth information is obtained in a manner which would facilitate the calibration of the modelling system after construction has taken place. Data collection guidelines would be developed as part of the modelling system, which would also fit with the typical scope of information collected during construction of pipeline crossings.

5.2.2. Estimation of Sediment Load

The preceding literature review and our discussions with relevant regulatory agencies failed to identify any studies dealing specifically with the issue of sediment loading associated with pipeline crossings, other than the Trow model reviewed in Sections 5.1.1 and 5.1.2. Although the rates and quantities of excavated sediment can be calculated based on the requirements of trench size and stable angle of repose for the native material, the amount of suspended sediment generated versus that removed from the stream can not be directly determined. Estimation of sediment loading from the construction is required in order to evaluate downstream TSS concentrations and sediment deposition. A methodology is needed for estimating sediment loading rates, total loads, and sediment composition resulting from the construction of pipeline crossings which accounts for the specific characteristics of the crossing.

A useful model could be constructed by combining applicable physically based relationships used in generalized sediment scour, deposition and transport models such as HEC-6. Appropriate assumptions can be made in applying the various relationships to render a practical modelling approach. This type of a model would offer the significant advantage that the component processes would be fundamentally expressed in terms of relationships which have been adequately studied and previously found to exist. While this approach might be recommended from a strictly scientific viewpoint, it is a major undertaking and is not recommended from a cost perspective. As an alternative, an empirical approach is suggested. A large body of relevant monitoring information from past pipeline crossing is readily available. This database could be compiled and analyzed to attempt to develop statistical relationships for load generation based on the characteristics of the stream crossing. Obvious characteristics which may affect sediment loadings, include:

- Watercrossing technique (e.g., open cut, dam and pump, flume);
- Size of excavated trench;
- The excavation method (e.g., backhoe, sauerman, clamshell, suction dredge);
- Stream velocity;
- Stream depth;
- Substrata composition; and,
- Flow turbulence (qualitatively evaluated).

Statistical techniques (e.g., cluster analysis, multiple regression) could be used to attempt to relate these characteristics (and possibly others) to sediment generation characteristics (i.e., total quantity, loading rates and grain-size distributions). The objective would be to develop predictive relationships and/or distributions of sediment generation characteristics based on readily available site characteristic information, and the excavation method. Where possible, relationships of sediment generation should be analyzed during specific phases of the construction (i.e., trenching, pulling the pipe, and back-filling).

5.2.3. Sediment Transport and Deposition

The main characteristics of a sediment transport model for pipeline crossings would include prediction of TSS concentrations and the amount of sediment deposited as a function of distance downstream of the crossing. Inclusion of the capability to simulate time-variable TSS concentrations could be included for post-construction evaluations, as well as for pre-construction simulations where sufficient information was available.

A one-dimensional model is recommended that would utilize measured or estimated flow and velocity information. Transport would include advection and possibly longitudinal dispersion. Settling algorithms and parameters from a range of sediment transport models, such as those reviewed in Section 5.1.2, should be evaluated to attempt to provide formulations, based on the hydraulic and sediment characteristics of the stream. Simple Stokes settling rates are not sufficient since they fail to account for turbulence or processes such as flocculation and siltation, and are not applicable to finer-grained particles.

All models require estimates of parameters (physically based or empirical) of the transport characteristics of the site-specific sediment. Laboratory experiments designed to measure sediment transport characteristics to calibrate a numerical model (e.g., Krishnappen and Engel 1995) can cost up to $10 000 or more. This level of expenditure may be feasible only for larger or particularly sensitive pipeline crossings. For the majority of crossings where all necessary information can not be collected within the scope of the pipeline crossing studies, specific guidance needs to be provided on estimating these parameters for different hydraulic and sediment characteristics. In other words, only formulations which provide sufficient guidance to parameterize the sediment transport model to site-specific characteristics should be selected for the pipeline water crossing sediment model.

5.2.4. Sediment Re-suspension

The main sediment re-suspension issues are: how long will the deposited sediment from the crossing remain in the bed; and, possibly, the rate of downstream movement of bed sediment. It is likely that algorithms to predict the re-suspension of deposited sediments could be included; however, data requirements and resources required to predict downstream movement of the bed sediment is beyond the scope of the proposed modelling system.

Re-suspension could be predicted from critical shear stress (a function of sediment composition) based equations and estimated flows for the period of interest following construction of the crossing. The flow conditions could be evaluated to determine if the shear stresses exceed the critical shear stress required for re-suspension. The main hydraulic information required for simulation of re-suspension would be velocities associated with different flows. If the review of existing pipeline crossings indicated that this information was not commonly available, a recommendation to exclude re-suspension from the modelling system would have to be made.

5.3. OUTLINE FOR MODEL DEVELOPMENT AND TESTING

Future work which would be needed in order to develop a workable sediment transport model for pipeline applications would involve the development of a working simulation model from the conceptual model outlined in Section 5.2. The two main components are the estimation of sediment loading, and simulation of transport, deposition and re-suspension.

Development of methods for sediment loading estimation due to construction activities would involve the compilation of existing pipeline crossing data and statistical analysis of this data to develop relationships between crossing characteristics and downstream sediment loadings. The data needed could be largely obtained from existing sediment monitoring studies during pipeline installation. Statistical techniques, such as cluster analysis and multiple regression could then be used to attempt to develop predictive equations of load generation based on site characteristics of the crossing (flow, velocity, depth, channel shape, sediment characteristics, etc.), and characteristics of the construction methods (construction method, duration, amount of material excavated, etc.). The resulting methodology would allow estimation of loadings from readily available site-specific and construction information.

The development of the sediment transport sub-model could involve three separate phases: (1) development of a numerical transport framework to simulate hydraulic characteristics of the stream and advective and dispersive transport of sediment; (2) development of routines to predict settling rates within the transport framework; and, (3) development of routines to predict re-suspension of the freshly deposited sediment within the transport framework. Development of the deposition and re-suspension routines would need to utilize pipeline crossing data to test different algorithms to determine which were applicable to pipeline crossings, under what conditions, and to help develop guidance for parameterizing the algorithms.

From the wide range of generalized sediment transport models, and a sub-set which are potentially applicable to the pipeline crossings would need to be identified. Criteria to determine the suitability of a model should include;

- Input data requirements compatible with information available for pipeline crossings;
- Ability to adequately parameterize the model within the scope of information collected for pipeline crossings;
- Spatial and temporal resolution consistent with the information requirements of pipeline crossings; and,
- Models which minimize the use of empirical constants.

The sub-set of sediment transport models could then be tested against data from previous pipeline crossings to identify a final sub-set of models for use. The final set of models could then be calibrated to pipeline crossing data to help develop guidance for conditions under which specific sub-models would be applicable, and guidance for setting model parameters under a range of hydraulic and sediment conditions.

The program would need to guide the user through the process of estimating suspended sediment loading, including identification of data requirements, data entry, displaying steady state or time variable load estimates and interfacing with the sediment transport model. The sediment transport model component of the program could take information from the load estimator, along with other site-specific information, and predict the sediment transport characteristics using the appropriate transport sub-model.

The integrated pipeline crossing sediment model should be geared specifically to the information requirements of pipeline crossings. The program should be designed to facilitate the modification and/or addition of sediment transport sub-models, and to incorporate refinements to load estimation algorithms as more information becomes available. A range of features should be incorporated into the program including; integrated data management, on-line help, output processing and graphics, and on-line assistance with setting model parameter options.

5.4. SUMMARY

Sediment processes are quite complex in nature and are difficult to predict using numerical models. There has been a great deal of sediment engineering research conducted to gain a better understanding of the specific river/sediment processes.

There are few numerical models available which account for all of the important processes required for simulating sediment loads downstream of a pipeline crossing. Models capable of simulating river sediment scour, transport and deposition require a great deal of information to calibrate and simulate impacts of river sediment conditions. The amount and type of information that is available for pipeline crossings is often quite limited.

In an attempt to provide the predictive capabilities desired using the limited data normally available, Trow (1994) developed a system to predict sediment transport downstream from water crossings. The first component within the Trow system is a simple empirical method for predicting the average concentration of total suspended solids generated by crossing construction. The calibration factor in the sediment load generation equation is the empirical recovery ratio constant (R_f), for which no generally applicable guidance is given. The next component in the Trow model is an empirical method for predicting the length of instream transport of elevated sediment concentration. This component does not allow prediction of distribution or amount of deposition within the zone of "settlement" and assumes a prismatic channel having a constant velocity, both of which are considered critical limitations to the assessment of potential habitat alteration. Finally, there is also no applicable guidance available for estimating the empirical calibration coefficient (C) in the settlement component making this modelling approach difficult to use for *a priori* assessments.

Environmental Management Associates (1993) implemented a two-dimensional (lateral and longitudinal) dispersion model (MULTI by HydroQual and Gore & Storrie 1988) to simulate TSS concentrations downstream of a pipeline crossing. The model was implemented following the completion of construction to generate a complete picture of TSS concentrations during construction. This model would generally be applicable for *a posteriori* assessment of sediment transport and deposition using sediment monitoring data from the construction period.

A conceptual model framework was presented which outlines each model component necessary to predict suspended sediment conditions during and after instream construction activities. Future work which would help provide a comprehensive sediment transport model would include a compilation of existing pipeline crossing data, actual development of statistically based loadings models, and actual development of the numerical transport, deposition and re-suspension model.

6.0. RECOVERY

The transport of sediments in lotic systems has been discussed in Chapter 5. The effects of sediment transport and deposition on aquatic communities and their habitats has also been discussed (Chapters 3 & 4). This section of the report deals with the recovery of lotic systems following a sediment-induced disturbance.

The first section of this chapter discusses the recovery of fish following sediment stress. It explores the physiological processes related to fish recovery and discusses the information from the available literature with respect to the recovery of fish (as individuals) from sediment episodes.

The next two sections of the chapter examine the recovery of aquatic ecosystems and aquatic habitats following a sediment release event. Aquatic system recovery is defined as the return of the physical and ecological processes within a watercourse to pre-disturbance or control conditions following a disturbance caused by a sediment event. As the definition implies, recovery must consider physical and ecological conditions, since biological recovery is dependent largely on the return of physical habitat condition.

6.1. RECOVERY OF FISH FROM SEDIMENT EXPOSURE STRESS

Recovery from the effects of elevated sediment load episodes is greatly influenced by the extent of sediment dose, mass of material added to the stream bed, type of material, the hydrologic/geophysical characteristics of the stream, species affected and the life stages present, and the availability of undamaged areas as refugia and as a source of recolonization. Most of the available information is focused on recovery from indirect effects such as habitat loss. Little information concerning the recovery from direct effects (i.e., physiological responses and tissue damage) is available.

The literature review conducted by Newcombe (1994a) indicates that behavioural effects upon fish tend to be transitory and do not persist long after the concentrations of suspended sediments approach background levels. Recovery from physiological effects is dependent on not only the magnitude of exposure, but also on the general condition of the fish plus the type of resulting damage (effect). Some physiological responses can occur in the absence of physical damage. An example is impaired growth resulting from an inhibition of feeding. Recovery can be expected to be quick once suspended sediment concentrations decline and fish resume feeding, assuming that there has not been an associated loss in habitat or food supply.

Recovery may be longer when physical damage to fish has occurred. Generally, blood parameters such as plasma glucose and percent hematocrit will return to normal levels within 10 hours after the stress has stopped (McLeay 1977 cf Noggle 1978, Swift and Lloyd 1974 cf Noggle 1978). The physiological cause of the stress may however, influence the time to recovery. For example, elevated hematocrit is an indicator of hypoxia. An hypoxic condition resulting from gill dysfunction and damage would presumably require a longer recovery period than what would occur from exposure to low dissolved oxygen in the water column.

Information concerning the recovery from sediment-induced physical damage is limited. Goldes (1983 cf Newcombe 1994a) indicated that the cell hyperplasia and necrosis observed in damaged gill tissue was absent 58 days after cessation of exposure. Even less information was uncovered concerning recovery of fish from secondary pathogenic infections which have resulted from abrasion of dermal and epithelial surfaces. The ability of the fish to recovery from these conditions will likely depend on the severity of the infection and the general health of the fish.

6.2. RECOVERY OF AQUATIC ECOSYSTEMS FOLLOWING SEDIMENT EPISODES

Aquatic communities respond to sediment stress through emigration from affected areas, reduced growth, reduced recruitment and mortality. A review article by Rosenberg and Snow (1975) indicates that the recovery period of stream and river biota can vary from a few days to not at all. Increased concentrations of suspended sediments and increased loadings of sediment are known to cause fish and macroinvertebrates to emigrate from the affected area. Embryonic and larval life stages of fish are the most susceptible to sediment effects. The sensitivity of these life stages is increased by the inability to leave the receiving environment.

6.2.1. Invertebrate Recolonization

The initial response of benthic invertebrates to increases in sediment load has been shown to be increased drift under experimental conditions (Gammon 1970, White and Gammon 1976, Rosenberg and Wiens 1978). In this way, benthic invertebrates can avoid areas of high sediment loads by emigrating from the source of the disturbance (Hynes 1973, Young 1986). Additionally, certain taxa have been shown to be more inclined to actively emigrate from a disturbance (Anderson *et al.* 1995; Rosenberg and Wiens 1975, Young 1986).

Invertebrate drift is an important behavioural adaptation which allows sensitive invertebrate taxa to emigrate from an area under unfavourable conditions. However, drift is also a critical element in the recolonization of areas which have been disturbed. Barton (1977) suggests that invertebrate fauna disturbed during instream construction quickly recolonize denuded areas by drift from upstream areas. Williams and Hynes (1976) describe four mechanisms of benthic recolonization. These mechanisms are drift from upstream areas which can be active or passive, active drift from downstream areas, vertical drift from the hyporheos of insect larvae and non-insect adult and immature stages, and colonization from aerial sources via oviposition (Williams and Hynes 1976). Of these four recolonization mechanisms, drift from upstream has been shown to be most important for the recolonization of disturbed areas (Williams and Hynes 1976, Young 1986).

Recolonization of the impacted area by macroinvertebrates can be rapid and complete within days (Rosenberg and Snow 1975). However, the rate of recolonization is dependent on the amount of sedimentation which has occurred. Schubert *et al.* (1985) found that benthic recolonization of an area affected by 12 hours of trenching activities took two to seven months. Likewise, Lamberti *et al.* (1991) found that it took close to one year before the macroinvertebrate communities were fully re-established in a 500 metre section of stream disrupted by a landslide. The ability of a stream benthic ecosystem to recover following a disturbance is dependent on the nature of the disturbance, the recovery of vegetation in disturbed areas, the flushing effects of spate periods, and the ability of undisturbed areas to replenish denuded zones (Young 1986).

6.2.2. Fish Community Recovery

Recolonization of impacted areas by fish appears to require a longer time period than that required by macroinvertebrates. The reason for the longer time period is unclear but is likely related to habitat degradation. It appears that although fish may immigrate into the area, recruitment can remain impaired. Schubert *et al.* (1985) found that the densities of the dominant fish species (silver shiner *Notropis photogenis*) remained significantly reduced from pre-sediment numbers one year after a sediment event. This condition was continued despite the fact that benthic recolonization was complete within a two to seven month period. Recolonization also appears to be species specific. Novak (1988) observed that the resident population of rainbow trout within an affected stream had increased to levels greater than the pre-sediment densities, while the resident population of brown trout never did recover.

The accumulation of sediment within critical areas utilized for spawning and egg incubation is likely one of the major factors influencing fish recruitment. The residency of accumulated sediments is influenced by stream morphology and flow. Periods of high flow (i.e., spring runoff) can dislodge accumulated sediment and therefore return the substrata to pre-event conditions (Dehoney and Mancini 1984). In low gradient streams the time required to remove accumulated sediments can take more than one season. Alexander and Henson (1988) found that approximately six seasons were required before a stream reverted back to a normal gross channel morphology, bed type and water velocities. Although all of these parameters were ultimately returned to pre-event conditions, the resident brook trout population remained significantly impaired due to a degradation of spawning and nursery habitat, and the production of invertebrate trout food.

6.3. RECOVERY OF AQUATIC HABITATS FOLLOWING SEDIMENT EPISODES

The previous sections in this chapter provide insight into the rates and mechanisms of recovery for fish and aquatic invertebrates following a disturbance caused by a sediment release event. Intuitively, population recovery is directly linked with the recovery of the physical habitats within the watercourse. This section of the report discusses the factors which influence the rate of recovery of physical stream habitats following sedimentation: in particular, the factors which effect sediment re-suspension and transport from the affected area.

6.3.1. Sediment Accumulation

In gravel-bed streams, deposition of sediments occurs through the upper, poorly graded, coarse pavement layer into underlying substrata (Reiser *et al.* 1985). It should be noted that the term "pavement" is used here to refer to the surficial-most layer of the stream bed. This term does not necessarily indicate stream bed armouring, as this layer can be very dynamic under certain flow conditions (Leopold and Rosgen 1990). The fine particles transported in suspension deposit within the interstitial spaces of the pavement layer by the effects of gravity settling and by sieving of the inter-gravel flow entering the stream bed. Once the fine sediment has been deposited in the gravel bed, minimal upward or horizontal movement of this material takes place (Einstein 1968).

Einstein (1968) found that the rate of inter-gravel sediment accumulation was dependent on the concentration of the sediment load. In addition, the amount of material which intrudes into the gravel bed has been shown to be highly dependent on the grain-size distribution of the transported sediment as well as that of the gravel bed. If the suspended sediment load is composed of very fine material, the gravel pores tend to fill from the bottom to the top of the pavement layer. If the suspended particles are larger in size, angular or platelet in shape, a film can develop within the substrata which will tend to limit the intrusion of additional sediments into the interstitial spaces of the stream bed (Beschta and Jackson 1979). Beschta and Johnson (1979) concluded that the finer the suspended sediment, the greater the potential was to fill interstitial voids.

The shape of the stream bed substrata may also affect sediment deposition. Under low flow conditions, rounded stream bed substrata tend to accumulate more sediment than angular substrata, whereas, during high flows, the reverse is true (Meehan and Swanston 1977). This may be due to the reduced turbulence levels at the gravel bed in rounded stream beds during low flows, while at higher discharges a flow separation zone can develop behind angular materials causing greater sediment deposition (Reiser *et al.* 1985).

6.3.2. Sediment Removal

Once sediment input into a system has been reduced, fine sediments can be flushed from the substrata to a depth of about 1 cm (Beschta and Jackson 1979, O'Brien 1984). However, flushing of sediments deposited deeper in the substrata requires mobilization of the stream bed. This indicates that sediment deposited surficially during a sediment episode may become "flushed" under normal hydrologic conditions; however, sediments which accumulate deeper in the substrata are "trapped" until discharge conditions (or other factors) are sufficient to displace the stream bed pavement. Therefore, sediments which are deposited within a stream bed may often remain in place until a natural flow event occurs which is sufficient to displace the stream bed material and "flush" sediments out.

A stream bed having a gravel or cobble surface underlain by finer non-cohesive material such as silts and sands is considered to be "armoured". This condition reflects a limited supply of finer sediment material to be scoured and transported. In an equilibrium condition, the armour layer forms as a result of fines being transported away more rapidly than they are replaced by the in-flowing sediment load. Gessler (1970) has developed a probabilistic relationship to determine the stability of the sediment particles in the bed surface. Fundamentally, it makes use of the Shield's tractive force relationship relating the bed shear stress to the critical shear stress.

6.3.3 Factors Affecting Rate of Physical Habitat Recovery

There are many factors which influence the rate at which sediments are flushed from the system. The most important factors governing the rate of flushing are discussed below.

6.3.3.1 Depth

The magnitude of the discharge required to flush sediments of a certain size will depend upon the depth of the area to be flushed. Stream flow changes generally influence water velocities and areas of riffle more than area of pool (Reiser and Bjornn 1979). In general, higher flows are required to remove surface sediments from pools than riffle areas.

6.3.3.2 Discharge

Discharge is likely the most important parameter in the flushing of sediments from habitats, and therefore, in the determination of recovery rates for aquatic systems from sediment episodes. Bjornn *et al.* (1977) demonstrates that the amount of coarse and fine sediments capable of being transported through a given reach of stream is a function of flow (Figure 6.1).

6.3.3.3 Substrata and Sediment Type

As previously described, the size and shape of stream bed substrates and transported sediment can affect the rate of deposition of sediments. These factors are also important to the rate at which sediments are flushed from the system. Streams with coarse substrata (such as gravel or cobble) can trap sediments which accumulate in interstitial spaces and may require flows sufficient to disturb the stream bed substrata before sediments can be suspended. However, depending on the characteristics of the watercourse, the bed surface materials may move frequently. Leopold and Rosgen (1990) documented evidence of bed surface movement at discharges equal to, or less than, bankfull width (1-2 year return period).

In streams which have "armoured" stream beds, sediments can be trapped for extended periods since this type of stream bed requires higher discharges to disturb the armoured veneer. Bjornn *et al.* (1977) identified the critical discharges needed for transporting coarse and fine sediments across riffles, out of pools and out of riffles after dislodging armour layers, and out of a substrate after moving boulders. These relative discharges for sediment transport for a given section of stream are provided in Figure 6.1.

6.3.3.4 Duration of Flushing Flows

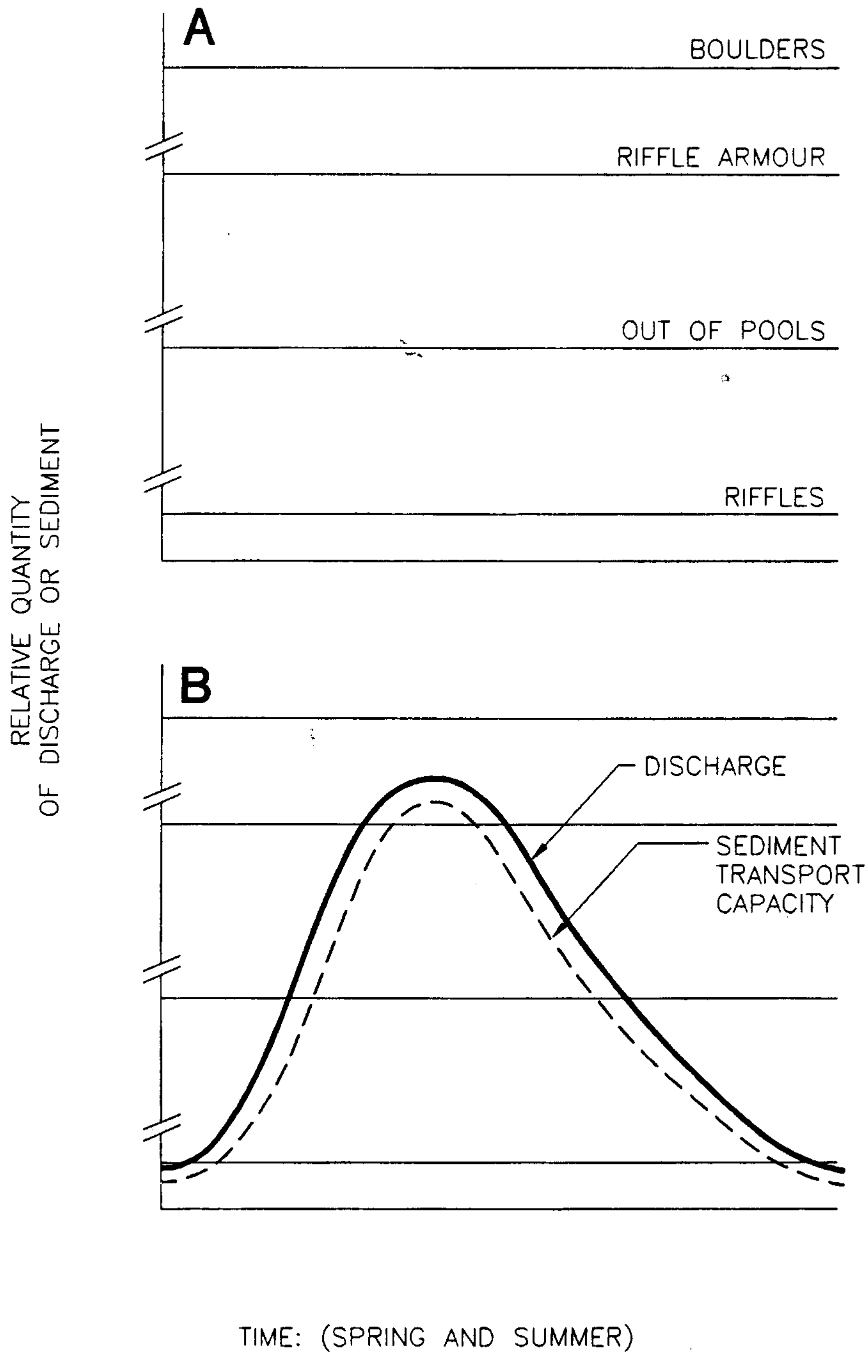
In many cases, the gravel bed must be mobilized in order to release fine sediments for transport. However, once the bed begins to mobilize, most of the fine material is entrained quickly by the moving water. When flushing flows cease, the bed stops moving and the fine sediments will again settle quickly into the gravel. Consequently, with the exception of clay particles, flushing must continue until the fine material from the uppermost portion of the reach travels through the entire section of stream and are deposited into areas which are not sensitive to sedimentation. Reiser *et al.* (1985) report that, under most conditions of interest, a sediment particle travel time is at least 70% of the water travel time. As a result, a particle travel time of about 1.5 times the water travel time would appear to be required for adequate flushing flow duration. The quantity, duration and frequency of flushing flows has received considerable attention in the instream flow needs related literature. For more information on this subject, the reader is directed to the review by Reiser *et al.* (1985).

6.3.3.5 Stream Gradient

The gradient of a stream is also an important factor in determining the re-suspension rate of deposited sediments. The relationships between discharge, grain size and channel bed slopes are illustrated in Figure 6.2. Figure 6.2 provides an estimate of the unit discharge in a stream that is required to mobilize the stream bed and initiate transport. This figure illustrates that for a certain unit discharge, the median grain size of the sediment material which can be mobilized increases substantially with increased stream bed slope.

RELATIVE CRITICAL DISCHARGES AND SEDIMENT TRANSPORT CAPACITIES

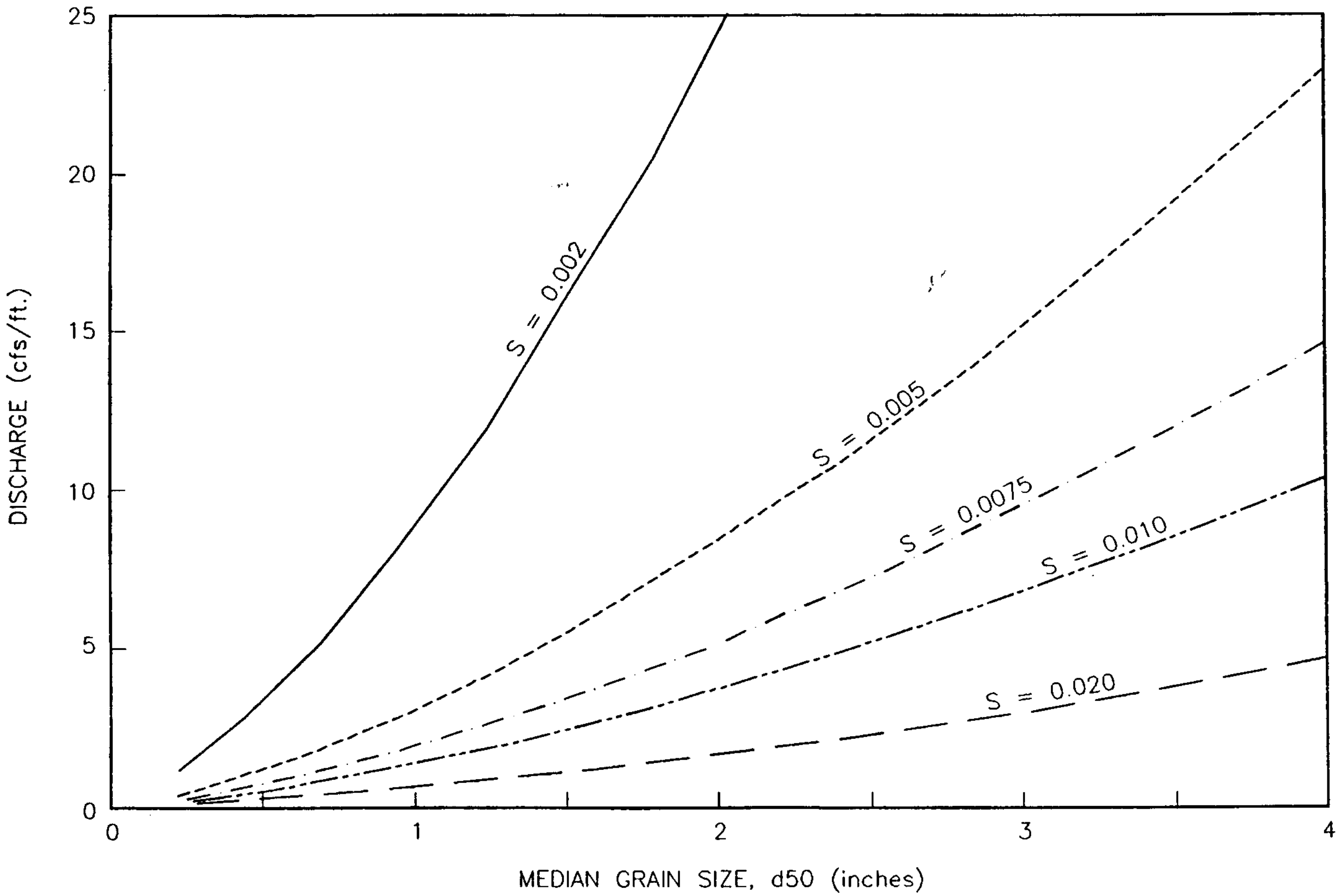
Figure 6.1



SOURCE: BJORNN et al 1977

962-2308\CDST.dwg

962-2308\CUDIS.dwg



CRITICAL UNIT DISCHARGE FOR BED MOBILIZATION AS A FUNCTION OF GRAIN SIZE AND CHANNEL SLOPE

Figure 6.2

6.4. SUMMARY

There is a dearth of information regarding the processes and time required for self-healing of fish to sediment induced stress. Therefore, it is difficult to make any conclusions regarding the duration of recovery times for fish. This is unfortunate, since issues such as the potential for cumulative effects of repeated sediment release episodes or the effects of work stoppages and "clear water" intervals in the assessment of overall impact of instream construction are dependent upon a more comprehensive understanding of duration and factors related to fish recovery.

The literature suggests that the recovery period of aquatic ecosystems with respect to community abundance and diversity can be extremely variable. Short recovery times are normally associated with events which cause increased emigration or drift, while longer recovery periods are more likely associated with sediment release events which cause physical alterations to habitat quality or quantity.

The amount of sediment deposition and gravel bed intrusion related to a sediment release event is highly dependent on the grain-size distribution and shape of the suspended material and the stream bed. Instream excavation activities normally suspend particles which are larger in size than those normally present in the sediment load of a watercourse, since the particles do not have to be delivered by the erosional processes in the watershed, and particle entrainment from the stream bed by the flow is not required. Due to the relatively coarse nature of the sediments, instream construction activities would tend to cause high rates of sedimentation; however, inter-gravel intrusion by sediments is likely to be lower than would be expected by smaller-sized materials (Breschta and Jackson 1979).

The rate of sediment removal, and hence aquatic habitat recovery, is dependent on a number of physical habitat properties of the watercourse. The sediment transport capabilities of a stream are largely a function of stream velocity. Stream velocity, in turn, is dependent on stream discharge, channel configuration (water depth), stream gradient, and channel roughness (stream bed composition). Therefore, the duration of deposited sediment residency is a complex function of how the above factors relate to determine sediment re-suspension and transport. There is not a sediment re-suspension and transport model available that can be used based on readily collectable information. As a result, more work is required in order to develop a practical re-suspension and transport model which will predict the recovery period of stream habitats following sediment release.

There is, however, some literature available which can provide an indication of the likely extent of sediment-induced habitat impairment. It has been suggested by Klein (1984) that the removal of sediment accumulated on the surface of stream beds downstream of construction will require the occurrence of floods ranging from the two to ten year return period, based on observations by Fox (1974). Klein (1984) also suggests that the removal of coarser accumulations, deep interstitial sediments or vegetated sediment bars would require floods with magnitudes equivalent to a 50- to 200-year event.

Based on all of the information available, it is anticipated that minor accumulations of surficially deposited sediments downstream of instream construction would normally be removed by the stream during normal, high flow events such as a large spate or spring freshet. Larger accumulations of surficial sediments, especially coarse-grained sand slugs, may require larger flood events, but in most cases should be removed within a year in areas which experience a spring freshet. Materials which filter into the inter-gravel medium may remain until flows are encountered which can move the stream bed material itself. Work by Leopold and Rosgen (1990) suggest that some stream bed movement occurs in floods equal to, or less than, bankfull stage which is equivalent to a 1.5 to 2 year flood event (Rosgen pers. comm.). However, deeply deposited (> 5 cm) interstitial sediments, or deposited sediments which become vegetated, may require floods of much higher magnitude (in the range of 50- to 200-year return period) in order to be swept downstream.

Additional studies examining habitat recovery times would provide further insight into the real impacts on habitat caused by sediment release and the duration of habitat impairment. Sediment accumulation and flushing can be monitoring using established methodologies (see Chapter 8), and studies which involve monitoring of sediment accumulation, re-suspension and transport would provide valuable information for effects assessment and for the development of an applicable sediment transport model.

7.0. CONCEPT SYNTHESIS

In order to make thoughtful management decisions regarding the potential effects of sediment pollution episodes, resource managers must make an assessment regarding the likelihood of harmful alteration, disturbance or destruction (HADD) of habitat. In essence, resource managers must assess the risk of HADD which can be associated with the sediment-release event. The objective of this chapter is to discuss each of the attributes which should be considered when assessing sediment-induced aquatic impact and to describe how these attributes can be evaluated in an effort to make an assessment of HADD risk.

Based on the sediment effects literature review, there are three main factors to consider when assessing the level of risk of HADD associated with sediment release episodes. These factors are:

1. the level of exposure;
2. the sensitivity of exposed habitats; and,
3. the length of time habitats are likely to be impaired.

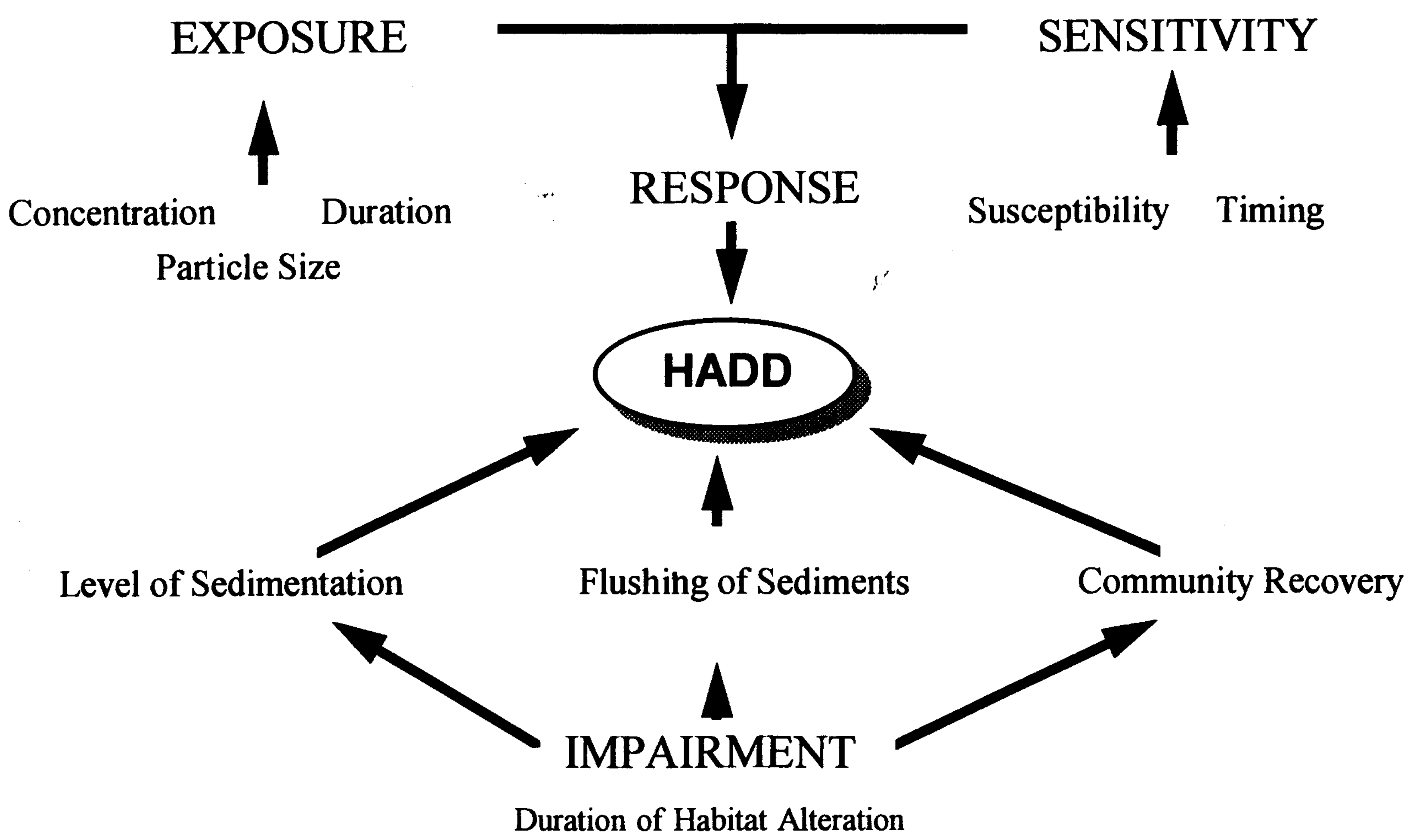
All of the factors which must be considered in the risk assessment are schematically represented in Figure 7.1. Since each of the factors must be evaluated, some of the considerations in this evaluation are discussed briefly below.

7.1. LEVEL OF EXPOSURE

Since it is the level of sedimentation which is of most concern with regard to habitat alteration, the most useful information for assessing level of exposure would include some quantification of the level of sediment deposition in the watercourse. The best information would provide some assessment regarding the amount of deposition and the downstream extent of the impacted area. This information could be collected using established methods (as outlined in Chapter 8), or could be determined from suspended sediment monitoring data using *a posteriori* models to simulate sediment deposition characteristics (e.g., the MULTI model developed by HydroQual and Gore and Storrie 1988).

In the absence of sufficient information regarding sediment deposition, or in cases where the main concern is associated with suspended sediment-induced stress on fish, the level of exposure can be categorized based on suspended sediment information. A discussion of methods for determining sediment release duration and average concentration is presented in Chapter 8. The level of exposure should incorporate the concentration of suspended sediment and the duration of the sediment release episode, and the anticipated response which is likely to result from the exposure. The severity of ill-effects level (SE of 1-14) can be determined using the most appropriate regression equation from Chapter 4. In many situations, the habitat response model presented in Chapter 4 (Equation 9) will be the most appropriate tool for assessing level of exposure from a habitat alteration perspective.

FIGURE 7.1 RISK OF HADD



As discussed in Chapter 4, the severity of effects relationships which have been developed by Newcombe and Jensen (1995a) are not directly applicable to habitat alteration and the habitat response model presented in this report has not yet been field tested. Therefore, these sediment response relationships should be applied with caution.

7.2. SENSITIVITY OF THE RECEIVING ENVIRONMENT

Considerations regarding the sensitivity of the receiving environment should include the susceptibility to alteration of the habitats within the receiving environment, and the timing of the sediment release. Habitats which are sensitive to sedimentation, such as invertebrate production riffles, known spawning areas or likely overwintering areas, should be identified and correlated with the areas of likely sediment deposition.

In addition to overall sensitivity of the watercourse and the sensitivity of the habitats it supports, a related consideration is the species and life stages which are present during the period of sediment release. As discussed in Chapter 2, certain life stages are especially sensitive to increases in sediment load (such as developing eggs and larvae, or overwintering fish); as a result, the presence of these life stages during construction would increase the sensitivity of the watercourse to disturbance.

An additional related consideration regarding construction timing sensitivity is the flow conditions within the watercourse during the sediment release episode. Watercourse discharge influences sediment concentration, transport and deposition as well as the extent of habitat present and the ability of resident biota to avoid areas of elevated sediment.

7.3. DURATION OF HABITAT IMPAIRMENT

The duration of habitat impairment is one of the most critical consideration in the assessment of HADD risk since habitat alteration will only affect the aquatic community if the altered habitat would have been used during the period of impairment. Logically, the level of concern associated with habitat alteration increases as the duration of impairment increases. The duration of impairment is considered to be the length of time before deposited sediments are flushed from the watercourse into a non-sensitive area such as a lake and should be viewed as the number of life history stages which are impacted during the period in which the habitat is in an altered state.

7.4. SUMMARY

The assessment of risk associated with sediment release should consider level of exposure, the nature of the habitats and communities affected and the duration of likely impairment caused. The severity of effects approach which have been developed by Newcombe and others are not easily applied to the prediction of habitat change and attributing justifiable numbers to abstract concepts such as system sensitivity is difficult at best. Resource managers need to apply expert judgement to ensure that models and assumptions are not applied blindly and that model results do not violate the most important management tool, which is common sense.

As a result, effects monitoring data should be used to identify the potential for habitat alteration whenever possible. This information might include sediment deposition and flushing information, and/or information on changes and recovery of the biological community (Chapter 8).

8.0. MONITORING SEDIMENT LOADS AND THE EFFECTS OF SEDIMENT RELEASE

As previously discussed, the assessment of sediment exposure effects in natural aquatic systems is a complex issue, with many of the assessment techniques still in the developmental process. This uncertainty in assessment technology underscores the importance of detailed, standardized monitoring programs to quantify the effects of sediment release episodes, test the predictions of the current approaches, and allow for the refinement of promising techniques. In this chapter we discuss key considerations in the development of a sediment sampling program, effects monitoring and in the analysis of the monitoring data collected.

8.1. SEDIMENT LOAD MONITORING

8.1.1. Sample Site Selection

In order to effectively characterize the receiving environment during sediment release, a series of transects should be established along a designated length of the watercourse to be crossed. Ideally, the selection of the sampling transect locations is based on results of sediment transport modelling (Chapter 5). The number of sampling transects which should be established downstream from construction will be a function of the anticipated zone of influence (Goodchild and Metikosh 1994). As discussed in Chapter 5, an effective *a priori* model for the description of sediment transport during sediment release is not available. However, with some additional guidance regarding assignment of specific coefficients, the system developed by Trow may be suitable for providing an order of magnitude-type prediction of the initial settling zone and may be suitable for use in identifying appropriate areas for establishing sampling transects. More analysis of available data is required to test the Trow model for use in this context.

In the absence of appropriate sediment transport modelling information, criteria for selecting water quality sampling sites should be based on the size and configuration of the stream or river being crossed. For feedback monitoring, sampling transects should be selected just upstream of the crossing and at several sites downstream.

Control Transect

A sampling transect should be established upstream of the crossing to provide "control" information regarding background levels of sediment load in the watercourse during construction. The upstream site should be located far enough upstream that it is not influenced by construction activity.

Downstream Transects

Downstream sites should be selected by assessing a combination of factors including stream configuration, water depth, current velocity and turbulence, site access, and worker safety. Downstream transects should include sampling within an "initial dilution zone" where sediment generated by instream activity would not be fully mixed with the stream flow and sedimentation has not occurred. Sampling in the initial dilution zone is important in order to determine the maximum concentrations of the suspended sediment which were generated by instream construction activities. Sampling within the initial dilution zone is also important since this area is likely to experience the highest level of sedimentation, and hence, has the highest potential for HADD.

The preferred locations for the first downstream transect is as close to the construction activity as possible, without compromising safety considerations. A maximum distance of three average wetted stream widths downstream of the crossing, to a maximum of 100 m downstream of construction, is considered the optimal location for the first downstream transect (H. Klassen, DFO, pers. comm.).

Additional transects will be required further downstream for determining the dispersion effects on the sediment plume and the extent of the area influenced by sediment release. One method for placement of transect locations is to use multiples of five times the preferred distance to the first transect (three average wetted widths). Normally, two additional downstream transects would be included in the monitoring program. For example, for a watercourse that is 20 m in average wetted width, transects would be established within 60 m of construction, and 300 m and 600 m downstream of instream construction activities.

In some circumstances, suspended sediment levels may still be substantially elevated above background levels at the third downstream transect. In these situations, addition transect(s) should be established further downstream in an effort to determine the area of influence. In addition, the presence of critical habitats within the area of influence may justify the inclusion of additional sampling transects.

Sampling Stations

A transect should contain from two to ten sample sites at regular intervals across the stream, depending on the wetted width of the stream. For streams up to 30 m wide, a minimum of two sample sites (1/3 and 2/3 across the stream) is recommended. For streams wider than 30 m, an additional sample site should be added for each additional 10 m of width. Sample site selection should also consider physical characteristics of the watercourse such as islands, braided channels, mixing characteristics and fish habitats. For small watercourses where it has been determined that sediment-laden water is completely diluted/mixed at the second and third transects, one sample location mid-stream is normally sufficient.

At each sampling station, the number of samples collected will be determined by the quality assurance goals set for the project and depth of the stream channel. In deep watercourses (>1.5 m), samples are frequently taken at mid channel and near bottom (0.2 · depth). This will allow some distinction between washload sediments and the coarser bedload sediments. This distinction is important for assessing the potential for habitat alteration and for calibrating sediment transport models. In watercourses of intermediate depth (0.5 to 1.5 m) a depth-integrated sample may be more appropriate. A depth-integrated sampler obtains a composite sample taken over the entire depth of the water column. In shallow watercourses (<0.5 m) a single grab sample from mid-channel depth may provide sufficient information. A component of the QA/QC program for the monitoring study must include some provision for replicate sampling at sampling stations, due to the inherent variability in TSS sampling results.

8.1.2. Frequency of Sampling

The frequency of sampling at each transect along a watercourse will vary depending on logistical constraints such as access, the location of the transect in proximity to construction, and the instream construction activities being conducted. The transect located in closest proximity downstream from construction (T1) should be sampled most frequently since sediment load increases as a result of construction would presumably be highest at this transect.

Through discussions with representatives from DFO, the following recommendations are provided regarding the frequency of sampling at suspended sediment monitoring transects during instream construction activities. However, the sampling program outlined may not be appropriate for all watercourses; less intensive surveys may be suitable at watercourses with lower sensitivity.

Upstream Control Transect

A control transect established upstream from construction activities should be monitored to determine the background turbidity levels within the watercourse. The frequency of sampling at this station will be dependent on the natural sediment levels of the stream and the expected variance within background levels. Upstream water quality should be measured approximately every six hours, starting one hour before commencement of preparation and construction activities. More frequent sampling may be required at the control transect if variability in background suspended sediment load is detected.

Pre-Construction

All downstream sites should be monitored shortly (one hour) before preparation work and commencement of instream activities.

During Preparation and Construction

The sampling sites at the first downstream transect should be measured hourly. Hourly sampling may be reduced to every three hours when turbidity levels return to background control conditions. During construction activities that have the potential to generate significant volumes of suspended sediments, additional sediment monitoring samples (every 15 minutes) are recommended at sites on the first downstream transect. Sampling at 15 minute frequency should continue until any sediment pulse has passed, or until there is no potential for a sediment pulse to pass those sites. In addition to the sample frequency suggested above, should distinct suspended sediment plumes be detected at times not represented by the above, monitoring personnel must include supplementary samples to document the start, peak and passing of plumes.

Sites at the second and third downstream transects may not warrant the same sampling intensity. Sampling every three hours may be sufficient, with more frequent sampling every hour during periods when a suspended sediment plume reaches the site. The time-of-travel for the sediment to reach each of the downstream transects can be estimated using river velocity measurements and field observations. As with the first downstream transect, supplementary samples should be included if distinct changes in suspended sediment plumes are detected at times not represented by the above to document the start, peak and passing of the plumes.

Post-Construction

The sampling frequency undertaken during instream construction activities should continue until background turbidity levels return to the control levels, and there is no potential for a sediment plume to pass a site. If background levels are not reached within four hours post construction, sampling should be conducted every three hours at all downstream sites until background levels are reached.

At the end of each working day, following the completion of instream activities, sampling should continue until the river velocity through the study area would indicate that there will be no further potential of high sediment pulses passing through the sites, and background turbidity measurements are reached at sites at the first downstream transect.

8.1.3. Measurements of Suspended Sediment Load

There are at least three recognized methods for measuring the suspended solid load of water (Lind 1979). The method used to determine the suspended sediment level is dependent upon the timeliness with which the results are required, the nature of the suspended solids and the question(s) being asked (Perry *et al.* 1985).

Turbidity in water is caused by suspended matter, such as clay, silt, finely divided organic and inorganic matter, soluble coloured organic compounds and plankton. It is measured using the reduction of transmission of light through the water either by absorption or by scatter (Lind 1979). Suspended solids load is the measure of the weight of filterable solids in a unit weight of water. The two are not directly related due to the differing light scattering and absorbing properties (e.g., size, shape and refractive index of the particulates) of different suspended materials (Lind 1979).

For many years, the standard method for determining turbidity has been based on the Jackson candle turbidimeter with the measurement standard termed a Jackson Turbidity Unit (JTU). This instrument is limited in its ability to measure low turbidities and the results are not directly correlated with suspended material load. Water colour also affects JTU readings and must be accounted for by subtracting the background turbidity of the water without silt (Lind 1979). JTU's can be correlated, using a calibration curve, directly to the concentration of suspended solids in the water providing the material in suspension is relatively uniform (Lind 1979).

In recent years, the Jackson candle turbidimeter has been replaced by a nephelometric method. A field turbidimeter can produce immediate measurement of the turbidity - or light extinction properties - of a river *in situ*. Nephelometry is another measure of light extinction which measures the light which is scattered at a 90° angle by suspended particles (Lind 1979). There is not an exact correlation between Nephelometry Turbidity Units (NTU's) and JTU's; however, for suspensions of clay < 50 NTU, the relationship is *approximately* 1 JTU = 2 NTU (Lind 1979).

The most accurate measure of the suspended solids load is to measure the solids in the water directly. This can be done by filtering a known quantity of water and weighing the filtered solids after drying at 105°C. This method can be time consuming and can not be done *in situ*. It is, however, the only direct measure of the suspended solids load.

Turbidity (using nephelometry) can be used as a proxy for suspended sediment levels since it can be correlated with suspended sediment levels and can be measured in real time. Therefore, the monitoring of suspended solids load during instream construction activities should involve a combination of turbidity measurement using a field turbidity meter and total suspended solids measurement in the laboratory. Turbidity measurements should be conducted for all water samples collected using a meter which has sufficient precision (e.g., Hach Model 2100A turbidimeter).

Turbidity and suspended sediment are usually specifically related to both the parent geology and basin type, and therefore are not readily transferable between river systems. Due to the site-specific nature of TSS-turbidity relationships, it is necessary to derive an empirical relationship between these two measures for all monitoring programs. A sub-sample of the water samples collected and tested for turbidity should be selected for TSS measurement based on the results of the turbidity analysis. The sub-sample selected for TSS analysis should contain the entire range of turbidities in order to establish the site-specific relationship between turbidity and TSS. For the samples that are analyzed for TSS concentration, the TSS results should be regressed against the respective turbidity measurements to define a relationship (usually linear) between turbidity and TSS. In this way, TSS concentrations may be predicted for samples which were only measured for turbidity.

8.1.4. Other Monitoring Parameters

In addition to monitoring of suspended sediment load during construction, it may be important to monitor other water quality parameters. Monitoring of additional parameters is especially important when the monitoring program is linked to habitat compensation agreements (H. Klassen, DFO, pers. comm.).

Additional water quality parameters that may be incorporated into monitoring programs include measurements of dissolved oxygen concentration (especially in watercourses with low flow and accumulated organic sediment), and air and water temperature. Other parameters which are important to measure during sediment monitoring programs include stream discharge and settleable solids.

Estimation of Discharge

At each sampling transect, daily measurements of water depth and velocity should also be conducted. Methods to be used should follow techniques outlined in Terzi (1981). Briefly, this involves establishing a tagline across the watercourse and dividing the channel width into 20 equal sections and recording the depth and water velocity at 60% of channel depth within each section. If water depth is $\geq$ 0.75 m, current velocity is measured at both 20% and 80% of total water depth.

Measure of Settleable Solids

As discussed in Chapter 3, settleable solids are that fraction of the sediment load which can more easily drop from suspension and deposit on the stream bed. The amount of settleable matter in the sediment load is of particularly important when considering the potential for harmful alteration to fish habitat.

Settleable solids are measured with an Imhoff cone. The concentration of settleable solids is a determination of the quantity of material that can be deposited from solution in a one-hour period. Settleable matter can be reported as either volume (millilitres per litre) or weight (milligrams per litre) basis (APHA 1981). This test is inexpensive and simple to do in the field.

It is recommended that the level of settleable solids be measured during sediment monitoring programs. Settleable solids measurement should be conducted in parallel with the measurement of turbidity so that the relationship between concentration and settleable solids can be developed on a site-specific basis. The purpose of quantifying the levels of settleable solids would be to associate the level of habitat disturbance with settleable solids so that the influence of the proportion of larger particles on habitat alteration can be assessed.

8.2. MONITORING DATA ANALYSIS

8.2.1. Defining the Sediment Release Event

The dose-response approach of Newcombe and others provides a solid foundation upon which to predict potential detrimental effects of TSS. However, the database which was compiled and first presented in Newcombe (1994a) is composed primarily of dose/response relationships resulting from sediment exposures which were relatively uniform in nature. In reality, the sediment concentrations encountered downstream from instream excavations are considerably more complicated and this complexity creates difficulties in model application.

Characterizing an instream construction event is difficult since construction does not produce uniformly high TSS concentrations downstream. For example, pipeline water crossings are marked by discrete, relatively brief periods of high TSS concentrations during each of the principal activities involved in the crossing, specifically excavation, pipe laying, and back-filling. When construction stops, at night, for equipment repair or during periods of inclement weather, TSS concentrations downstream may decline dramatically, once the stream bed at the crossing site is no longer being disturbed. Some residual increase in TSS concentrations may persist during breaks in construction, however, as newly exposed surfaces are eroded or settled material is resuspended. Therefore, defining the sediment release episode associated with instream construction can be a difficult problem.

Because TSS concentrations vary so widely during a stream crossing, and in practice will only be measured at intervals, there are a number of options for defining the sediment release event, depending on whether the crossing is taken as one event or a series of events in close succession. As an illustration, Figure 8.1 displays contrived data intended to represent TSS concentrations produced by a stream crossing accomplished in rather less than two days. The example assumes TSS samples have been collected at a downstream site at regular hourly intervals from the onset of construction to its completion; real data are unlikely to be so complete or so regular. For the moment, work stoppages at night have been ignored. While these data are fictitious, they are more or less typical of the concentrations and temporal patterns observed at real stream crossings.

The data in Figure 8.1 contain three distinct peaks of TSS concentration, interrupted by brief interludes when concentrations return to background levels (10 mg/L). Abrupt peaks of TSS like these might be produced by activities such as excavation, pipe laying, and back-filling. Because TSS was measured hourly, and the exact duration of the crossing is known, there are at least three ways of defining the sediment release event. Due to its ease in calculation, the Stress Index approach has been used to illustrate the differences in data handling approaches for the purposes of this demonstration.

The first manner by which the sediment release episode could be defined is a simple computation of Stress Index for each hourly TSS measurement, by taking the natural logarithm of the concentration. This is tantamount to performing a log-transformation of the data, and leads to the results plotted in Figure 8.1. The Stress Index for the crossing could then be calculated as the mean of the 40 individual measurements, leading in this example to SI = 5.52. Clearly, this option is unsatisfactory because it does not consider the overall effect of the entire sediment release event and produces 40 separate estimates of dose, yet there is no reason to assume that the measurements are on separate events.

Second, the Stress Index for the entire crossing could be estimated as the product of duration (40 h) and the mean TSS concentration (see Section 8.6.2 for further discussion on characterizing sediment concentration) for the whole period (990 mg/L); in our example the estimate would be SI = 10.59. This option does produce a reasonable definition of the sediment release episode, assumes that the entire construction period consists of one event, and that the mean TSS concentration is a good estimator of the TSS stress to which downstream organisms are exposed. By assuming a constant TSS concentration, this method produces a stress index comparable with those supporting the Newcombe (1994a) database. The stress index by this approach is much greater than that by the first method, and it does not require the untenable assumption that the crossing consists of 40 independent events, each of one hour's duration.

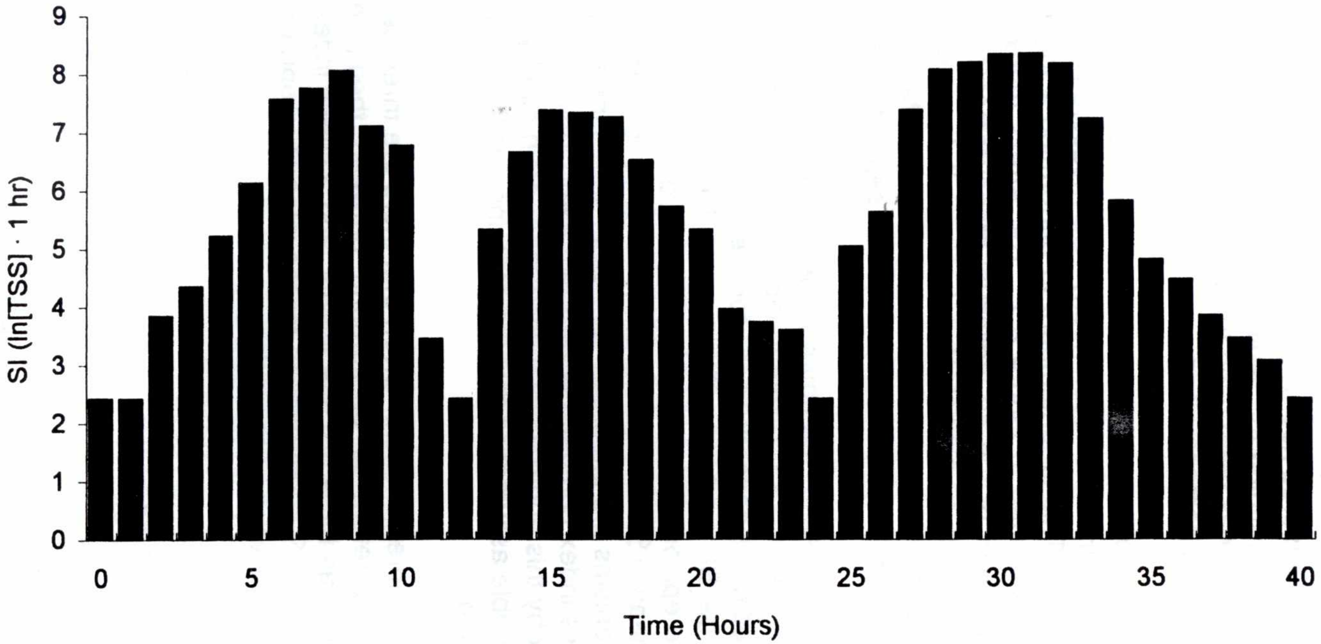
The third option is more complex. Given that there are three peaks in TSS concentration, and that concentrations return to background between them, the construction period could arguably be viewed as three discrete events, and a stress index could be calculated for each, based on the mean TSS concentration for the interval. Applying this approach to the example data produces the following SI estimates:

Period	Stress Index
2-11 h	9.22
13-23 h	8.81
25-40 h	10.03

Notwithstanding the brief duration of these events, the stress index values are surprisingly high. Indeed, the stress index for the last 15 h alone is equivalent, within the accuracy of the Newcombe model, to that calculated for the entire construction period. The discrepant estimates of TSS dose arise because of the logarithmic transformation included in the Stress

FIGURE 8.1

STRESS INDEX FROM A STREAM CROSSING
(Contrived Data)



Index. Longer periods of measurement naturally lead to higher SI values; but because concentration-time products are log-transformed, a unit increase in the Stress Index requires a relatively larger increase in concentration (or duration) at the high end of the scale than at the lower end.

The Stress Index for the entire 40-h period might also be less than expected because the effect of longer time is diluted by the inclusion of low TSS concentrations in the average. One way to get around this problem, and perhaps establish a more valid basis for comparison, is to delete low TSS concentrations from the data. This simplification can be independently justified on biological grounds because low TSS concentrations would have minimal biological effects, especially within the typically short time frame of a pipeline crossing. Indeed, Newcombe and Jensen (1995b) endorse the removal of intervals of clear water from the dataset. To test the effect of low-turbidity periods on the stress index, the overall index was recalculated after deleting all TSS measurements < 100 mg/L. This manipulation reduced the event duration to 26 h, and produced a Stress Index of 10.57, virtually identical to the index without deletions (10.59). Index values for individual events (9.21, 8.80 and 10.02), were also marginally less than those calculated from the unedited data. It is evident from these examples that any augmentation of the Stress Index consequent to deleting low TSS concentrations (and thus raising the mean concentration) is entirely offset by the reduction in estimated duration of the event.

One further manipulation is worth exploring. Notwithstanding that shortening the event duration depresses the Stress Index, higher estimates might still be obtained for individual events if only the periods with highest concentration were included in the calculation. This possibility was tested with the example data by considering only the peak concentrations for each event. The pared data contained only 5, 4 and 6 observations. Rather than increasing, the Stress Index was slightly reduced in the "peaks-only" data (SI = 9.14, 8.54, 9.90); again the negative effect of shorter duration more than offset the positive effect of excluding relatively low TSS concentrations. To test this result, the example data were extensively manipulated by substituting higher TSS concentrations in the peak period. In every test the Stress Index for the entire event exceeded that for the peak period alone.

In conclusion, Stress Index values calculated for selected sub-sets of data for a particular event will typically be less than values for the entire event, for any TSS concentrations that might reasonably be expected downstream from instream construction activities. Calculating SI for the entire construction period, and for individual events within it (delimited by periods of background TSS concentrations) both appear to be valid for use with the dose-response model, but not shorter periods. The remaining question then, is which should be used in practice.

From the perspectives of ecological effects and stream protection, it is the sum effect of all disturbances which is of critical interest. It is possible that three brief periods of turbidity, with SI = 9.22, 8.81 and 10.03 represent a greater threat to aquatic biota than a single, longer event with SI = 10.59, especially given that the three smaller events occurred in close succession (i.e., without time for recovery between them). However, at present there is no manner by which the cumulative nature of small events can be assessed. On the other hand, the stress index for the entire period will always be the larger number, and may in practice exceed some threshold criteria (such as physiological effects or on-set of mortality) while individual events may not. Hence, both the former and the latter values could, arguably, be used in assessments of effects of construction on watercourses.

Since both perspectives have validity from an ecological point of view, how the data are analyzed should be based on site-specific circumstances. For example, if instream construction activities produce increased sediment loads for a specific period without extended periods of work shut down, then the episode should be viewed as a single event. However, if instream construction is protracted in nature with long periods when sediment loads return to near background levels, then it would be more appropriate to consider the sediment release as a series of increased sediment episodes. In most cases, pipeline construction events such as pipe installation and back-filling follow immediately upon the completion of the previous construction operation. Therefore, it is more realistic to consider the pipeline crossing as one pollution event rather than a series of smaller episodes. If instream construction operations are considered to be a single sediment release episode, then a single value to characterize the concentration of suspended sediments will need to be provided.

8.2.2. Calculation of the Sediment Dose

Calculating TSS dose from events like stream crossings is an important consideration which poses a series of interesting problems. Since instream construction activities do not create uniformly high TSS concentrations throughout the construction period, it is difficult to assign a single concentration of sediment which accurately describes the sediment release. However, in order to make an assessment of the effects associated with a sediment release, a sediment concentration value must be determined.

There are numerous methods by which the "central tendency" of a dataset can be determined, the most often used of which is the arithmetic mean. The arithmetic mean best characterizes the central tendency in a dataset that has a symmetrical distribution. Since the suspended sediment concentrations during instream construction activities do not tend to be symmetrical in nature, there has been considerable discussion regarding the use of this statistic to characterize sediment release. Some of the statistics which have been offered as a replacement statistic for sediment release characterization include:

- Median or middle measurement in the dataset,
- Mode or the most frequently occurring measurement in the dataset,
- Geometric mean,
- Harmonic mean,
- Root mean square,
- Weighted average.

The geometric mean (GMy) is the n-th root of the product of the n data. It can be computed as the antilogarithm of the arithmetic mean of the logarithms of the data.

GMy = antilog $1/n \sum \text{Log } Y$

Where: N = number of sampling intervals; and,
Y = Concentration of suspended sediment.

It is useful for specific functions, such as in the calculation of the average of ratios, databases exhibiting exponential distribution, and in averaging percent change (Zar 1984).

The harmonic mean (Hy) is the reciprocal of the arithmetic mean of the reciprocals of the data. It is occasionally used when dealing with averaging of rates (Zar 1984).

$$1/Hy = 1/n \sum 1/Y$$

The geometric and harmonic means are appropriately calculated for ratio scale data only (Zar 1984). Unless the individual items in a dataset do not vary, the geometric mean is always less than the arithmetic mean and the harmonic mean is always less than the geometric mean (Sokal and Rohlf 1981).

Newcombe and Jensen (1995b) endorse the use of the root-mean-square (RMS) value for assigning a sediment concentration to a sediment release episode. The RMS value can be calculated using the equation:

$$\text{RMS} = \sqrt{\sum Y^2 / n}$$

The root-mean-square was recommended for sediment release characterization since it is often used for determining a mean value for data with high fluctuations (Newcombe pers. comm.). In general, this statistic is used for datasets which exhibit large, fairly regular fluctuations and may or may not be appropriate to sediment monitoring data which exhibit either short spikes of high concentration or large, very sporadic fluctuations.

Weighted averages are often applied to datasets which may differ in their reliability, based on different sample sizes or for other reasons (Sokal and Rohlf 1981). For example, weighted means are often applied to determine the mean of a group of average values where the weight of each average is "weighted" by the sample sizes from which they were derived. The weighted average can be calculated as follows:

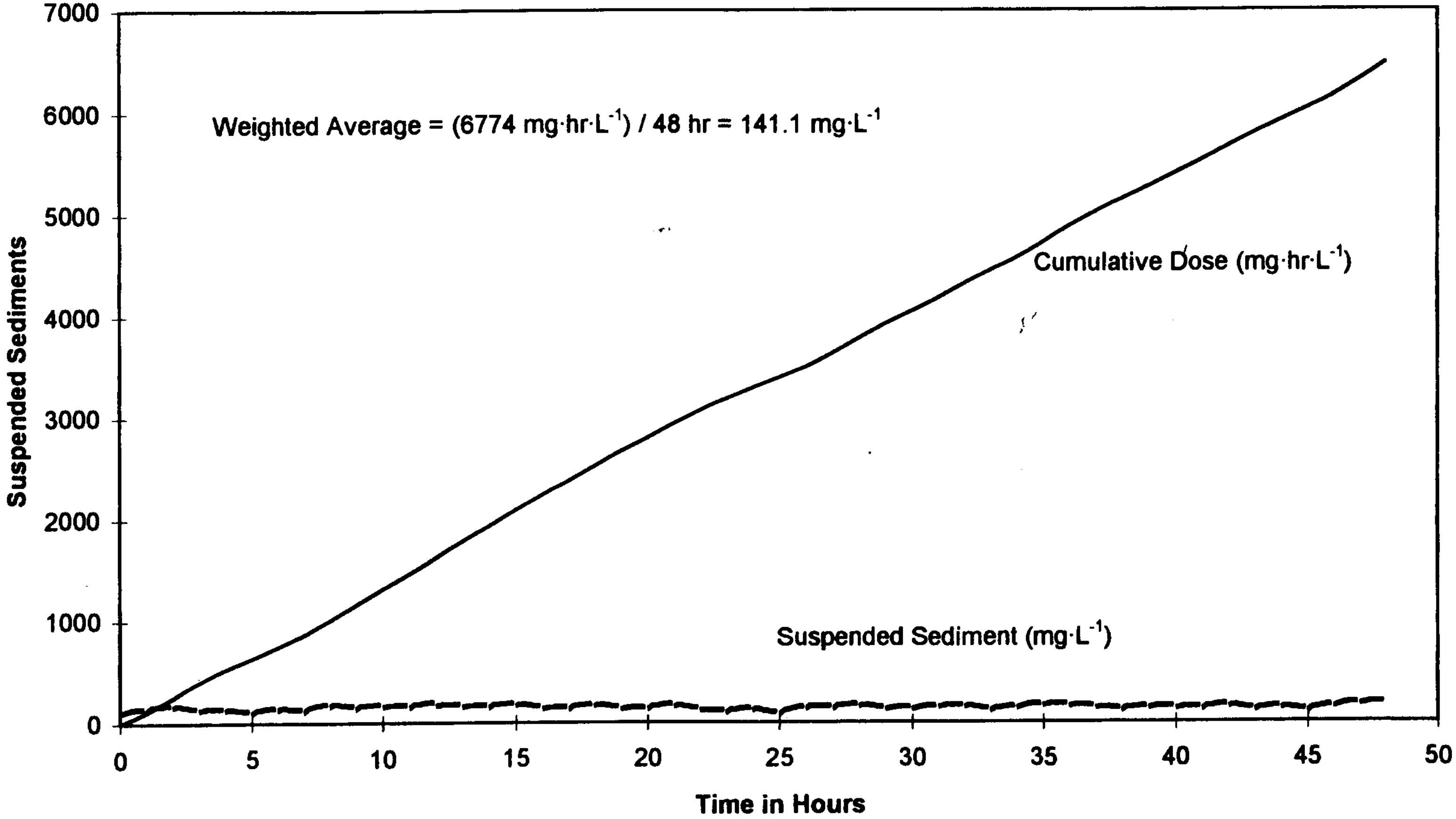
$$Y_w = \frac{\sum w_i y_i}{\sum w_i}$$

With respect to sediment monitoring data, it can be argued that the average suspended sediment concentrations should be "weighted" by the duration of time the receiving environment experienced that level of TSS.

For sediment monitoring data, the weighted average concentration of sediment would be determined by calculating the cumulative dose of sediment divided by the total duration of the entire sampling program. Cumulative dose is calculated as the sum of the mean concentration during an interval, multiplied by the duration of that interval. Figure 8.2 illustrates the relationship between concentration and cumulative dose, using a set of random numbers. The weighted average would then be calculated as the cumulative dose divided by the overall duration of the sediment release episode.

FIGURE 8.2

RELATIONSHIP BETWEEN CONCENTRATION (TSS IN mg·L^{-1}) AND CUMULATIVE SEDIMENT DOSE (mg·hr·L^{-1})



In order to illustrate how each of these statistics differ with respect to the treatment of sediment monitoring data, each of the statistics were calculated using several datasets, obtained from sediment monitoring during pipeline water crossings (Table 8.1). The different treatments for determining central tendency in sediment monitoring data are presented in Table 8.2.

Depending on the dataset, there can be very large differences in the statistic used to characterize the average concentration of suspended sediment. Based on the results of the analyses presented in Table 8.2, several generalizations regarding the different statistical treatments can be made. As expected, the geometric mean and harmonic mean of the sediment concentrations were always lower than the arithmetic mean. This, in conjunction with the fact that these statistics are better suited to analyses involving ratios, scaled data or population data which exhibits exponential distribution, may make these statistics less appropriate for characterizing sediment release episodes than some of the others discussed below.

The median value, with some exceptions, tended to provide a lower estimate of average concentration when compared to the arithmetic mean. Since the median is simply the middle data value of the dataset, it does not consider the range or distribution within the data, and therefore is not a suitable measure for characterizing a sediment release episode.

The root-mean-square method of characterizing the sediment load generally tended to provide the highest value of the statistics used. Since the calculation requires that data are squared, the root-mean-square approach increases the influence of the high peaks and decreases the importance of periods of low concentration. This method provides a conservative description of the concentration during a sediment release event; however, since no importance is placed on the duration of these peaks, this approach may over estimate the sediment concentration.

The weighted average approach is the only statistic tested which considers the duration of each monitoring interval. Since the duration of each monitoring interval is not always uniform (Section 8.2), this is a valuable advantage of this approach. This approach places more importance on the duration in which the receiving environment is subjected to a particular sediment concentration, and as such, does not over emphasize periods when numerous samples were taken. For these reasons, the weighted average method is the recommended approach for characterizing the concentration during sediment release episodes.

8.3. ESTABLISHING SEDIMENT EFFECTS CRITERIA

Since the dose/response approach considers both concentration and duration, it provides a better working model for assessing acute exposures to sediment than water quality criteria consisting of permissible concentrations alone. However, there are limitations to the dose/ response relationships, which are of significant practical importance. Foremost among these is the lack of a lower bound on concentration in the dose-response models. According to the models presented by Newcombe and MacDonald (1991), MacDonald and Newcombe (1993); Newcombe (1994a); and Newcombe and Jensen (1995a), any increase in TSS above zero is potentially harmful if it lasts long enough. For example, a seven-day exposure (168 hrs) to a TSS concentration well below background levels in virtually all watercourses (1 mg/L), would exceed the threshold for sub-lethal effects in all of the models presented by Newcombe and

TABLE 8.1

SEDIMENT MONITORING DATA FOR THREE SEDIMENT RELEASE EVENTS

Open Cut			Repair Work			Dam and Pump		
Time	TSS	Dose	Time	TSS	Dose	Hours	TSS	Dose
1	1000	0	2.8	84.4		0.0	134.6	
4	3050	6075	5.3	93.4	229.7	1.0	82.8	108.7
8	2900	17975	6.8	64.4	341.5	2.0	73.4	186.8
12	2500	28775	22.2	75.0	1416.8	35.4	87.2	2873.2
16	2240	38255	23.7	54.0	1513.5	36.4	80.1	2956.8
20	1980	46695	25.2	76.4	1611.3	37.5	89.9	3041.7
24	1720	54095	25.5	59.5	1634.0	49.6	159.8	4558.2
28	1460	60455	25.7	65.2	1644.4	50.6	113.5	4694.9
32	1200	65775	28.7	61.4	1834.1	51.6	82.9	4793.1
36	1100	70375	30.2	79.9	1940.0	52.6	79.7	4874.3
40	60	72695	31.2	71.4	2015.7	53.6	74.6	4951.5
44	40	72895	45.7	62.0	2983.5	105.9	331.0	15561.2
48	30	73035	47.7	70.6	3116.1	106.8	92.0	15744.5
52	20	73135	49.1	54.7	3204.9	107.9	76.0	15839.7
56	20	73215	50.3	58.7	3275.7			
60	53	73361	51.7	51.2	3349.0			
64	85	73637	52.3	57.0	3385.0			
68	118	74043	70.5	51.4	4369.0			
72	150	74579	72.3	45.2	4457.6			
76	200	75279	73.2	42.5	4494.2			
80	15	75709	74.9	79.8	4601.2			
84	500	76739	76.0	89.3	4692.7			
88	1000	79739	77.7	72.0	4827.1			
92	1500	84739	78.8	94.1	4924.0			
96	2000	91739	79.7	69.8	4992.3			
100	2500	100739	93.6	33.2	5709.2			
104	3050	111839	95.1	49.6	5771.3			
108	250	118439						
112	20	118979						
116	15	119049						
120	10	119099						
124	10	119139						
128	7	119173						

Time = Time in hours from commencement of in-stream activity
TSS = Concentration of TSS in mg/L (Average across a transect)
Dose = Cumulative Dose of sediment in (mghr /L)

TABLE 8.2

DIFFERENT TREATMENTS FOR ESTIMATING CENTRAL TENDENCY IN TSS DATA

Random	TSS	Dose	% Diff.
average	136.6	6558.4	-0.40
median	137.7	6610.3	0.39
Harmonic	133.1	6388.6	-2.98
geomean	134.9	6473.8	-1.68
rms	138.4	6641.7	0.87
Wt.Avg	137.2	6584.6	0.00

Theoretical	TSS	Dose	% Diff.
average	965.6	38624.4	-2.41
median	275.0	11000.0	-72.21
Harmonic	50.4	2016.3	-94.91
geomean	245.2	9808.0	-75.22
rms	1591.4	63654.8	60.83
Wt. Avg	989.5	39580.0	0.00

Open Cut	TSS	Dose	% Diff
average	933.4	118544.9	-0.53
median	250.0	31750.0	-73.36
Harmonic	43.0	5464.9	-95.41
geomean	233.1	29603.3	-75.16
rms	1401.8	178033.4	49.39
Wt. Avg	931.0	119173.0	0.00

Repair	TSS	Dose	% Diff
average	64.41	6043.98	3.55
median	63.25	5934.65	1.68
Harmonic	60.18	5647.00	-3.25
geomean	61.65	5785.17	-0.88
rms	66.35	6225.42	6.66
Wt. Avg	60.43	5836.68	0.00

Dam and Pump	TSS	Dose	% Diff
average	111.2	12005.0	-24.21
median	85.0	9174.3	-42.08
Harmonic	94.4	10184.2	-35.70
geomean	98.2	10596.6	-33.10
rms	129.1	13935.8	-12.02
Wt. Avg	146.8	15839.7	0.00

Jensen (1995a). As a result, if the dose/response approach is to be used for establishing suspended sediment criteria, a method of assessment must be developed which will overcome this apparent deficiency in the approach as described.

Newcombe and Jensen (1995a) provide a method by which threshold criteria can be assigned for periods of various duration within the instream construction period. The predicted severity of ill-effects tables provided in Newcombe and Jensen (1995a) provide the predicted severity of effects which may be associated with a wide range of duration and exposure combinations. These tables provide a means by which sediment criteria can be assigned in a justifiable manner for the protection of aquatic habitat.

A severity of effects level of 7 is associated with a class effect which involves moderate levels of habitat degradation. This is the lowest severity of effects level at which habitat alteration is attributed and as such represents the threshold of habitat alteration. Using this approach, any sediment release episodes which do not exceed the severity of effects level of 7 would not be expected to have caused a habitat alteration. Any sediment release episode which exceeds this criterion would have the potential to cause some form of habitat change. Following the severity of ill-effects scale provided by Newcombe and Jensen (1995a), sediment releases which exceeded SE levels of 10 would have the potential to cause moderately severe habitat degradation, while severe habitat degradation potential would be attributed to events causing SE levels of 12 or greater.

Another strength of this approach is that the tables presented in Newcombe and Jensen (1995a) provide guidance with respect to confidence in predictions; since, extrapolations outside of the dataset and confidence intervals on predictions are indicated as shaded sections within the tables. When assessing the likely effects of sediment release episodes, the use of extrapolated portions of the tables should be made with caution and there should be some consideration of confidence intervals on all predictions.

8.4. EFFECTS MONITORING

As with any model, predictions based on the Newcombe and Jensen (1995a) dose/response relationships should be made with caution, and any predictions of habitat alteration should be supported with information collected in the field. In the following sections, some of the most important methods for monitoring effects of sediment release are discussed.

8.4.1. Measure of Sediment Deposition

An evaluation of the substrate composition downstream of instream construction activities is a logical way to assess the deposition of sediments as a result of sediment release, the physical recovery of habitats following a disturbance, and to obtain additional information which would be useful in sediment transport model calibration. Many techniques have been developed for the assessment of substrate composition. The utility of each technique is contingent upon its application both before and after instream construction, or the availability of appropriate "control" sites in suitable habitats outside of the area of influence. Many of the available techniques and advantage and disadvantages of each are summarized below.

Substrate Sampling

One of the most frequently used methods for assessing substrate composition is to remove a small portion of the stream bed for size-distribution analysis and determination of percent of fine material. The collection of stream bed samples is generally accomplished using one of two techniques which are grab sampling (McNeil and Ahnell 1964; Targart 1976; Reiser and Wesche 1977) and freeze-core sampling (Ryan 1970, Walkotten 1976, Everest *et al.* 1980, Golder 1995).

The grab sampling technique normally employs a metal tube which is manually forced into the substrata to a specified depth. The material contained in the tube is removed and analyzed for particle-size distribution. Typical sample tube diameters include 15 to 30.5 cm; the tube diameter selected should be two to three times larger than the diameter of the largest particle visible in the stream bed (Shirazi and Seim 1979). The disadvantages of grab sampling techniques, as reported by Everest *et al.* (1981), Platts *et al.* (1983) and Reiser *et al.* (1985), are that:

- the core tube often pushes larger particles sizes out of the way and therefore there is the potential for sample bias;
- core materials are completely mixed so that no interpretation of stratification within samples can be made;
- suspended sediments in the core are lost;
- particle sizes larger than the core can not be collected; and,
- the sampler may not be inserted to a specified depth if there are large sediment particles or compacted substrate.

Freeze-core sampling entails the driving of a hollow (single or multi-tube) probe into the substrate and injecting the probe with a cryogenic medium. After a specified period, the probe is removed, and with it, the frozen core of substrata which adheres to it. The material which adheres to the probe is then analyzed for particle-size distribution. There are a number of cryogenic medium which can be used in this sampling techniques, including liquid CO_2, and liquid N_2. The disadvantages of freeze-core sampling techniques, as reported by Everest *et al.* (1981), Platts *et al.* (1983) and Reiser *et al.* (1985), are that:

- the freeze-core probes are difficult to drive into substrate containing many particles over 10 cm in diameter;
- the freeze-core technique is equipment-intensive and requires CO_2 bottles, hoses, manifolds, probes and sample extractor (tripod with come-along); as a result, this technique is normally limited to easily accessible areas; and,
- depending on the size of the substrate being sampled and the variability between samples, a large number of freeze-core samples may be required in order to allow for statistically valid comparisons between sampling sites.

Substrate samples collected using either the grab or freeze-core technique are analyzed using either volumetric displacement or gravimetric analysis and a series (12-16) of sieves with sieve sizes ranging from 100 mm to 0.06 mm.

Sediment Traps

A second approach for assessing sediment deposition is through the quantification of fine materials within the inter-gravel environment using sediment traps. Mahoney and Erman (1984), Carling (1984), Meehan and Swanston (1977) and Reiser (1983) all described methods which could be applied for the measurement of inter-gravel sediment accumulation. Many different types of sediment traps have been described including buried cans (Meehan and Swanston 1977), solid and screened cylinders (EMA 1993), and modified Whitlock-Vibert boxes (Reiser 1983).

Regardless of the type of sediment trap used, clean washed gravel or marbles are used to fill the trap and the trap is normally buried flush with the surface of the stream bed. The traps should be installed before instream construction occurs and are installed along transects at pre-determined locations up- and downstream of the construction activities. The traps are left in the gravel for a specified time and then removed for particle-size analysis and determination of fine material accumulation.

Sediment traps provide a useful technique for determining the accumulation of fine materials in the stream bed which has substantial ecological merit. By removing the traps immediately after construction activities, the increased rates of sedimentation can be assessed by comparison with upstream controls; or, the traps can be left in-place for longer periods in order to document the flushing of accumulated sediments over time.

Visual Analyses

Several visual (ocular) assessment techniques have been developed which can aid in the assessment of substrate composition. These are described below.

The substrate classification method involves the establishment of a transect across the watercourse. The substrate at one foot intervals is then classified by major size classes using the categories provided in Government of Canada (1987), and Howes and Kenk (1988). Post-construction substrate composition can then be compared to substrate composition documented before instream construction was conducted.

The level of embeddedness is another useful visual assessment technique. As defined by Stowell *et al.* (1983), embeddedness is a rating of the degree of fine sediment cover on larger particles sizes such as gravel, cobble or boulder. One manner to evaluate embeddedness uses a rating system based on percentages. Platts *et al.* (1983) recommends the following rating system:

Rating	Description
1	75% of surface covered with sediments
2	50-75% of surface covered with sediments
3	25-50% of surface covered with sediments
4	0-5% of surface covered with sediments

Embeddedness taken at specified intervals across a transect before and after instream construction can provide useful documentation of sedimentation as a result of sediment release. The embeddedness ratings can also be taken in concert with other methods of visual substrate classification.

Pebble count techniques provide an objective method of substrate characterization for assessment of sedimentation following a sediment pollution episode (Newcombe and Jensen 1995a). This technique involves the sampling of about 100 randomly selected grains on the surface of a stream bed (Kondolf 1995). Kondolf and Li (1992) suggest that the pebble count method is recognized as a better alternative to characterize substrate than any of the visual estimation methods.

Survey Techniques

Several standard survey techniques also provide useful assessments of sediment deposition. Cross-sectional profiling involves measuring of bed elevations at specified intervals across permanent transects as referenced to an established benchmark. This technique provides an excellent method for documenting channel aggradation or degradation (Platts *et al.* 1983) and has been used in the past to assess temporal changes and recovery in a stream bed following sediment release episodes (Anderson *et al.* 1995).

Other survey type methods, such as pre- and-post mapping of sediment accumulation or pre- and post-photo transect interpretation also provide useful approaches for documentation of changes in substrate composition related to sediment release episodes.

Direct Measures of Stream Bed Porosity

Inter-gravel standpipes can be used to measure important parameters which are related to sediment deposition and salmonid spawning habitat suitability including gravel permeability, inter-gravel velocity, and inter-gravel dissolved oxygen (Reiser *et al.* 1985). Standpipes, which are open at both ends, are driven into the stream bed and afford an access portal for measuring the above mentioned parameters in the inter-gravel environment (Reiser *et al.* 1985). In this way, important parameters which are directly relevant to the biological effects of sedimentation can be documented.

The selection of the most appropriate sediment deposition monitoring program (if any) is dependent on the issues and concerns of a specific monitoring program. In addition, practical considerations such as access, equipment required and cost must also be evaluated.

8.4.2. Biological Monitoring

The only true way to monitor the effects of sediment release on fish and their habitats is through sampling of aquatic communities. Impacts to fish and harmful alteration of habitat should cause measurable effects to the aquatic communities as indicated by reduction is biodiversity, reductions in sensitive taxa, or reductions in abundance.

Due to the wide variety of aquatic community types and the associated range of bio-monitoring assessments available, it is beyond the scope of this document to develop specific biological monitoring programs. However, as with sediment deposition monitoring, pre- and post-disturbance information and/or suitable data from control sites are essential for assessment of effects related to sediment release events.

For more information regarding the biological assessment of the effects on instream disturbances, the reader is directed to a number of studies including Anderson *et al.* (1995); McKinnon and Hnytka (1988); Schubert *et al.* (1985); Stowell *et al.* (1983); Tsui and McCart (1981); Vinikour and Schubert (1987); and Young (1986).

8.5. SUMMARY

Suspended sediment monitoring should include a series of downstream transects to delineate the extent of increased suspended sediments and an upstream control transect to document natural (background) levels. Sediment monitoring transects consist of a series of sampling stations, the number of which is dependent on the width of the watercourse and the extent of lateral mixing of the sediments.

The frequency of sampling is highly dependent on the nature of the instream activity and the associated sediment plume. Sampling should extend from before instream construction commences until the point where background levels are re-established following the completion of construction. Monitoring of suspended sediments can be accomplished through measurement of turbidity, as long as a site-specific relationship between total suspended sediment and turbidity is developed. Additional parameters for monitoring may include dissolved oxygen, temperature, discharge, and concentration of settleable solids.

In the analysis of suspended sediment monitoring data, the construction period and associated suspended sediment information can be characterized using several different approaches. Several of these approaches are valid and the manner in which the data are analyzed should be determined based on site specific conditions regarding the actual duration of construction and work stoppages which may have taken place. A number of techniques are also presented for providing a single concentration to represent the sediment release episode. The weighted average approach is the recommended statistic since it considers the length of the time interval at a given concentration; however, other statistics may also be appropriate.

In an effort to provide some guidance regarding when alternate mitigation options might be implemented during construction, sediment exposure criteria were recommended. It is suggested that the predicted severity of ill-effects tables provided in Newcombe and Jensen (1995b) be used to identify when exposure levels are approaching levels which might be expected to cause habitat damage. These exposure levels are based on a severity of ill-effects level of 7.

The use of suspended sediment monitoring data, in conjunction with physical and biological effects information provides a foundation upon which informed management decisions can be made. Through the collection of these types of information, a greater insight will be developed and a comprehensive understanding of the impacts of sediment release on fish and their habitats will be obtained.

9.0. FUTURE DIRECTION

The literature review and investigation into the effects of sediment on fish and evaluation of current techniques has identified a number of specific information gaps which could be filled through undertaking certain research studies. Some of these studies have been identified below:

9.1. QUANTIFYING THE EFFECTS OF VARYING GRAIN SIZE

Newcombe (1994a) has identified the importance of grain size and shape on the effects to fish caused by suspended sediments. Since sedimentation is the principal mechanism for habitat alteration associated with instream activity, grain size is of particular importance. The influence of particle size in habitat alteration is also of significant importance in relation to instream activity since excavations instream will often expose watercourses to particle sizes to which they are not normally exposed. Future studies might focus on determining the influence of the dominant size of particles suspended on the realized effects on fish and fish habitat associates with a sediment release event.

9.2. PREDICTING SEDIMENT LOAD

One of the main problems with the conceptual sediment transport model presented is that there is little information regarding the sediment load generated during instream construction. A critical issue is the determination of how much material is suspended versus that recovered and placed on the stream bank. In addition, it is often reported that site-specific conditions, construction methods and hydrotechnical factors dictate the sediment loads and suspended sediment concentrations which result from instream construction activities. An important investigation might include the development of the relationship describing the resultant sediment loads and TSS concentrations at the location of the stream crossing as a function of region, soil types, flow regime, geotechnical conditions, stream properties and construction methodology.

9.3. SEDIMENT RE-SUSPENSION AND SYSTEM RECOVERY

Development of a numerical transport framework to simulate hydraulic characteristics of the stream and the scour/re-suspension, deposition and transport of sediment in a stream would be a beneficial addition to the present tools available. This work would provide a better foundation for the determination of likely effects of a proposed sediment release and the likely duration of system recovery.

9.4. DEVELOPING THE SEDIMENT TRANSPORT MODEL

Once more detailed information is available regarding sediment load issues, a comprehensive sediment transport model could be developed. The sediment transport model should include a user interface to handle model input and output, and to control the model. This interface for the modelling system could be created in a graphical environment.

9.5. DEVELOPMENT OF BETTER HABITAT EFFECTS RELATIONSHIPS

The main problem with the development of habitat response relationships to sediment release is the lack of available information which contains quantifiable effects to fish habitat as a result of sediment release. Important studies to overcome this information deficiency would include quantification of habitat effects using *in-situ* methodologies. Studies of this type should focus on evaluating the effects of instream construction on a variety of fish habitats as a function of concentration, construction duration, and dominant particle size. A study of this type would also provide some opportunity for the evaluation of the effectiveness of construction mitigation measures for minimizing aquatic impact.

In addition, the study may also aid in the development of a better understanding of the linkages between habitat alteration and community effects. Another benefit of such a study might be the development of methods to determine effects of multiple stressors and determination of relevant importance of acclimatization of aquatic biota.

Once more detailed information is available regarding the response of aquatic habitats to sediment load increase, an analysis of the data may allow the development of better relationships. Since the studies would allow for the testing of specific hypotheses, more robust analytical tecnniques would be available than are available for the meta-analysis techniques conducted to date.

Through carefully designed studies and detailed investigations and analyses, better tools, with more predictive power may be developed and a better understanding obtained regarding the effects of sediment on fish and their habitats.

10.0 MANUSCRIPT SUMMARY

The first goal of the Policy for the Management of Fish Habitat in Canada is habitat conservation, the guiding principle of which is no net loss of the productive capacity of habitats. The suspension and subsequent transport of fine-grained materials associated with in-stream construction operations within a natural watercourse can have impacts on the aquatic biota living within the system, and on the habitats upon which they rely. A review of the literature was undertaken in order to assess the potential effects of sediment pollution-related episodes on aquatic environments to aid resource managers in making decisions with respect to the effects of sediment releases on fish and fish habitat.

Increased concentrations of suspended sediments can have direct effects on fish behaviour, fish physiology and fish populations. Behavioural changes are generally considered benign and transitory; typical responses include an increased frequency of the cough reflex, avoidance of suspended sediments, a reduction in feeding and temporary disruption of territoriality. Physiological changes can be measured in fish as a response to the increased stress of suspended sediments; typical responses include impaired growth, histological changes to gill tissue, alterations in blood chemistry, and an overall decrease in health, resistance to parasitism and disease. The primary mechanisms of alteration to fish populations are through increased egg mortality, reduced egg hatch, a reduction in the successful emergence of larvae, and the sediment-induced death of juvenile and adult fish.

The potential effects of suspended sediments on aquatic organisms can be substantial; however, it is generally the potential for alteration of aquatic habitats due to sedimentation which poses the greatest risk to fish populations. The assessment of risk of habitat alteration associated with sediment release should consider level of exposure, the nature of the habitats and communities affected, and the likely duration of impairment. Sediment loads can alter the composition of the stream bed, the inter-gravel movement of water, as well as the gross morphology of streams. When sediments are deposited on the stream bed they fill in the interstitial spaces. This process can effect spawning and nursery habitat of fish, particularly that of salmonids species. It can also cause changes in invertebrate communities, thereby altering food supplies for fish.

In an effort to identify acceptable levels of suspended sediment within a watercourse, a number of existing criteria have been developed. These criteria have been based on observations of fish populations under chronic exposure conditions, and therefore, may not be appropriate for use in developing acceptable criteria for acute sediment-release events. Multiple regression analysis was used to develop an acute sediment dose/habitat effect relationship. The relationship developed between sediment release and fish habitat response is described by the equation:

$$\text{Severity of Habitat Effects} = 0.032 + 0.978 \text{ Ln (Concentration)} + 1.008 \text{ Ln (Duration)}$$

The response of biological receptors to environmental stresses is complex. Many factors may influence the actual severity of effects which are caused by a sediment release episode, including: characteristics of the particles suspended; temperature of the water; and, the existing stress level within the receiving environment. Although many factors may influence the response of aquatic systems to sediment release, the dose/response relationship contributes insight into the effects of sediments on fish and their habitats, and provides a foundation by which these impacts can be quantified.

A conceptual model framework is presented which outlines each model component necessary to predict sediment transport conditions during and after in-stream construction activities. Future work which would help provide a comprehensive sediment transport model would include a compilation of existing pipeline crossing data, actual development of statistically based loadings models, and actual development of the numerical transport, deposition and resuspension model.

A critical factor in the determination of the extent of habitat alteration is the timing of sediment release and the duration of habitat impairment. If the period of impairment does not overlap with the timing of habitat use, then no biological consequence is anticipated. The rate of sediment removal, and hence aquatic habitat recovery, is dependent on a number of physical habitat properties of the watercourse. The sediment transport capabilities of a stream are largely a function of stream discharge, channel configuration (water depth), stream gradient, and channel roughness (streambed composition). Therefore, the duration of deposited sediment residency is dependent on the interaction between these factors in determining sediment resuspension and transport. Additional studies examining habitat recovery times would provide further insight into the real impacts on habitat caused by sediment release and the duration of habitat impairment. Sediment accumulation and flushing can be monitored using established methodologies. Studies which involve monitoring of sediment accumulation, resuspension and transport would provide valuable information for effects assessment and for the development of an applicable sediment transport model.

Effects monitoring data should be used to identify the potential for habitat alteration whenever possible. This information may include sediment deposition and flushing information, and/or information on changes and recovery of the biological community. The use of suspended sediment monitoring data, in conjunction with physical and biological effects information, provides a foundation upon which informed management decisions can be made. Through the collection of these forms of information, a greater insight will be developed, and a comprehensive understanding of the impacts of sediment release on fish and their habitats will be obtained.

11.0. LITERATURE CITED

Ackers, P., and W.R. White. 1973. Sediment transport: new approach and analysis. Journal of the Hydraulics Division, ASCE, Vol. 99, No. HY11, pp. 2041-2060.

Alabaster, J.S. and R. Lloyd. 1982. Finely divided solids. Pages 1-20 In J.S. Alabaster and R. Lloyd editors. Water quality criteria for freshwater fish, 2nd edition. Butterworth, London.

Alexander, G.R. and E.A. Hansen. 1988. Decline and recovery of a brook trout stream following an experimental addition of sand sediment. Michigan Department of Natural Resources Fisheries Division. Fisheries Research Report No. 1943.

Alexander, G.R. and E.A. Hansen. 1986. Sand bed load in a brook trout stream. North American J. Fisheries Management. 6: 9-23.

Alexander, G.R. and E.A. Hansen. 1983. Sand sediment in a Michigan Trout Stream, Part II: Effects of reducing sand bedload on a trout population. North American J. Fisheries Management. 3: 365-372.

American Public Health Association (APHA) 1981. Standard Methods for the Examination of Water and Wastewater. Fifteenth Edition. 1134 pp.

Anderson, N.H. and D.M. Lehmkuhl. 1967. Catastrophic drift of insects in a woodland stream. Ecology 49: 198-206.

Anderson, P.G., T.J. Chandler, C. Fraikin. 1995. Assessment of impacts of pipeline construction on a stream ecosystem in the North Bay shortcut. Prepared by BAR Environmental, Guelph, Ontario for the Environmental Affairs Dept., TransCanada PipeLines and the Ontario Ministry of Natural Resources. 86 pp.

Auld, A.H. and J.R. Schubel. 1974. Effects of suspended sediment on fish eggs and larvae. Special Report 40, Reference 74-12, Chesapeake Bay Institute, John Hopkins University, Baltimore, Maryland.

Auld, A.H. and J.R. Schubel. 1978. Effects of suspended sediment on fish eggs and larvae. A laboratory assessment. Estuarine and Coastal Marine Science. 6:153-164.

Barton, B.A. 1977. Short-term effects of highway construction on the limnology of a small stream in southern Ontario. Freshwater Biology 7 99-108.

Barton, J.R., D.A. White, P.V. Winger, and E.J. Peters. 1972. The effects of highway construction on the fish habitat in the Weber River, near Henefer, Utah. Eng. Res. Centre. Colorado, Bur. Reclamm. Rept. No. REC-ERD-72-17, June 1972. pp 17-28.

Berg, L. and T.G. Northcote. 1985. Changes in territorial, gill-flaring, and feeding behaviour in juvenile coho salmon (*Oncorhynchus kisutch*) following short-term pulses of suspended sediment. *Can J Fish Aquat Sci.* 42:1410-7

Beschta, R.L. and W.L. Jackson. 1979. The intrusion of fine sediments into a stable gravel bed. J. Fisheries Research Board of Canada. 36(2): 204-210.

Bisson, P.A. and R.E. Bilby. 1982. Avoidance of suspended sediment by juvenile coho salmon. North American J. Fisheries Management, 4:371-374.

Bjornn, T.C., M.A. Brusven, M.P. Molnau, J.H. Milligan, R.A. Klamt, E. Chacho and C. Schaye. 1977. Transport of granitic sediment in streams and its effects on insects and fish. Office of Water Research and Technology, U.S. Department of the Interior. Washington, D.C. 20240. Research Technical Completion Report, Project B-036-IDA. 43 pages.

Bode, R.W. 1988. Methods for rapid biological assessment of streams. Stream Biomonitoring Unit, Bureau of Monitoring and Assessment. Division of Water, NYS Department of Environmental Conservation. February, 1988.

Brown, R.S. 1994. Spawning and overwintering movements and habitat use by cutthroat trout (*Oncorhynchus clarki*) in the Ram River, Alberta. M.Sc. Thesis, University of Alberta. 126 pp.

Brown, R.S., S.S. Stanislawski, and W.C. Mackay. Effects of frazil ice on fish. In T.D. Prowse (ed) Proceedings of the Workshop on Environmental Aspects of River Ice. Saskatoon, Saskatchewan. August 8-20, 1993. pp 261-278.

Buck, D.H. 1956. Effects of turbidity on fish and fishing. transactions of the 1956 North American Wildlife Conference, 21:249-261.

Burban, P.Y. 1990. Settling speeds of flocs in freshwater and seawater. J. Of Geophysical research. Vol. 95. 1990.

Bustard, D.R. and D.W. Narver. 1975. Aspects of winter ecology of juvenile coho salmon (Oncorhynchus kisutch) and steelhead head trout (Salmo gairdneri). J. Fisheries Research Board of Canada 32:667-680.

Butler, R.L. 1982. A trout stream in winter. Trout 23:36-39.

Calkins, D.J. 1989. Winter habitats of Atlantic salmon, brook trout, brown trout and rainbow trout: a literature review. U.S. Forest Service, Department of Agriculture. Special Report 89-34.

Campbell, H.J. 1954. The effects of siltation from gold dredging on the survival of rainbow trout and eyed eggs in Powder River. Fisheries Bulletin, Oregon State Game Commission, Portland, Oregon. 3 pp.

Canadian Council of Ministers of the Environment. 1994. Canadian water quality guidelines, Chapter 3: Freshwater and aquatic life. Task Force on Water Quality Guidelines, Environment Canada, Ottawa, Ontario.

Carling, P.A. 1984. Deposition of fine and coarse sand in an open-work gravel bed. Can. J. Fish. Aquat. Sci. 41:263-270.

Chapman, D.W. and T.C. Bjornn. 1969. Distribution of salmonids in streams, with special reference to food and feeding. Institute of Fisheries, University of British Columbia. pages 153-176.

Chisholm, I.M., W.A. Hubert, and T.A. Wesche. 1987. Winter stream conditions and use of habitat by brook trout in high-elevation Wyoming streams. Trans. Am. Fish. Soc. 116:176-184.

Cerven, D.R. 1973. Overwinter mortality of trout in Temple Fork of the Logan River, Utah State University. M.Sc. Thesis

Clapp, D.F., R.D. Clark, Jr and J.S. Diana. 1990. Range, activity, and habitat of large, free-ranging brown trout in a Michigan (USA) stream. Trans. Amer. Fish. Soc. 119:1022-1034.

Colby, B.R. 1964. Practical computations of bed-material. Proceedings, ASCE, Vol. 90, No. HY2.

Cooper, A.C. 1965. The effect of transported stream sediments on the survival of sockeye and pink salmon eggs and alevin. Int. Pac. Salmon Fish. Comm. Bull. 18 (71 pp)

Cordone, A.J. and D.W. Kelley. 1961. The influences of inorganic sediment on the aquatic life of streams. California Fish and Game 47: 189-228.

Cunjak, R.A. 1988. Physiological consequences of overwintering in streams: the cost of acclimatization? Can. J. Fish. Aquat. Sci. 45:443-452.

Cunjak, R.A. 1995. Behaviour and microhabitat of young Atlantic salmon (Salmo salar) during winter. Can. J. Fish. Aquat. Sci. 45:2156-60.

Cunjak, R.A. 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity (in press). Can. J. Fish. Aquat. Sci. 53 (Supplement 1).

Cunjak, R.A. and R.G. Randall. 1993. Instream movements of young Atlantic salmon (*Salmo salar*) during winter and early spring, pp. 43-51. In R.J. Gibson and R.E. Cutting (ed.). Production of Juvenile Atlantic Salmon, *Salmo salar*, in Natural Waters. Can. Spec. Publ. Fish. Aquat. Sci. 118. cited from Cunjak 1996.

Cunjak, R.A. and G. Power. 1986. Seasonal changes in the physiology of brook trout, Salvelinus fontinalis (Mitchell), in a sub-Arctic river system. J. Fish. Biol. 29:279-288.

Cunjak, R.A., R.A. Curry, and G. Power. 1987. Seasonal energy budget of brook trout in streams: implications of a possible deficit in early winter. Trans. Amer. Fish. Soc.116:817-828.

Dance, K.W. 1978. Macroinvertebrates diversity in two streams as affected by agricultural land use. Paper presented at the annual meeting of the N. Am. Benthological Society, Winnipeg, MN.

Dehoney, B. and E. Mancini. 1981. Aquatic biological impacts of instream right-of-way and construction and characteristics of invertebrate community recovery.

Department of Fisheries and Oceans. 1983. The Yukon placer authorization and supporting documents: Applicable to placer mining in the Yukon Territory. June, 1993. Ottawa.

Department of Fisheries and Oceans. 1986. Policy for the management of fish habitat. Ottawa, Ontario. DFO/4486. 28 pp.

Department of Fisheries and Oceans. 1994. Draft decision framework for the determination and authorization of harmful alteration, disruption or destruction of fish habitat. Prepared for DFO, Marine Environment and Habitat Directorate, Ottawa, Ontario, by: ESSA Technologies, Richmond Hill, Ontario. 24 pp.

Department of Fisheries and Oceans. 1995a. Fish habitat conservation and protection, what the law requires. The Directive of the Issuance of Subsection 35(2) Authorizations. Ottawa, Ontario. DFO/5077. 6 pp.

Department of Fisheries and Oceans. 1995b. Fish habitat conservation and protection, Guidelines for attaining no net loss. Ottawa, Ontario. DFO/4961. 8 pp.

Einstein, H.A. 1950. The bed-load function for sediment transportation in open channel flows. United States Department of Agriculture, Soil Conservation Service, Washington, D.C. Soil Conserv. Serv., Tech, Bull. No. 1026. September 1950

Einstein, H.A. 1964. Channel sedimentation, Part II, Section 17, Handbook of Applied Hydrology, V.T. Chow, ed. New York, NY.

Einstein, H.A. 1968. Deposition of suspended particles on a gravel bed. Proc. of ASCE. J. Hydraul. Div., Vol. 94, No. HY5, pp 1197-1205.

Elliott, J.M. 1967a. Invertebrate drift in a Dartmoor Stream. Archs. Hydrobiol. 63: 202-237.

Elliott, J.M. 1967b. The life histories and drifting of the Plecoptera and Ephemeroptera in a Dartmoor streams. J. Anim. Ecol. 36: 343-362.

Elwood, J.W. and T.F. Waters. 1969. Effects of floods on food consumption and production rates of a stream brook trout population. Trans. Amer. Fish. Soc. 99:253-267.

Environmental Management Associates (E.M.A.) 1992. Sediment monitoring during the crossing of the Red Deer River. Prepared for NOVA Gas Transmission Ltd.

Environmental Management Associates (E.M.A.) 1992. Total suspended sediments and sedimentation at the Pembina River pipeline crossing. Prepared for NOVA Gas Transmission Ltd.

Environmental Management Associates (E.M.A.) 1993. Total suspended sediments and sedimentation downstream of the Red Deer River pipeline crossing, Nevis Lateral Loop. Prepared for NOVA Gas Transmission Ltd.

Environmental Management Associates (E.M.A.) 1993. Report on suspended sediment monitoring for pipeline crossings of the Sukunka River and Rocky Creek. Talisman Energy Inc. 128 pp.

Environmental Management Associates (E.M.A.) 1994. Sediment monitoring during the crossing of York/Lyons Creek. Prepared for NOVA Gas Transmission Ltd.

European Inland Fisheries Advisory Commission. 1964. Water quality criteria for European freshwater fish: Report on finely divided solids and inland fisheries, J. Air and Water Pollution, 9(3): 151-168.

Everest, F.H., F.B. Lotspeich, and W.R. Meehan. 1981. New perspectives on sampling, analysis and interpretation of spawning gravel quality. *In* N. Armantrout (ed), Acquisition and utilization of aquatic habitat inventory information, pp. 325-353. West Div. Amer. Fish. Soc.

Everest, F.H., C.E. McLemore, and J.F. Ward. 1980. An improved tri-tube cryogenic sampler. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, PNW-350.

Exner, F.M. 1931. Zur dynamik der dewegungsformen auf der erodoberfläche. (On the dynamics of various forms of movement on the earth's surface). Ergebnisse der Kosmischen Physik, Vienna, Vol. 1 (1931). p. 373.

Fox, H.L. 1974. Effects of urbanization on the Patuxent River, with special emphasis on sediment transport, storage and migration. Ph.D. J. Hopkins Univ. Baltimore., MD.

Fudge R.J.P., and R.A. Bodaly. 1984. Postimpoundment winter sedimentation and survival of lake whitefish (*Coregonus clupeaformis*) eggs in southern Indian Lake, Manitoba. *Can J Fish Aquat Sci.* 41:701-5.

Gailani, J., C.K. Ziegler and W. Lick. 1991. Transport of suspended solids in the lower Fox River. J. Great Lakes Res. 17(4): 479-494.

Gardner, M.B. 1981. Effects of turbidity on feeding rates and selectivity of bluegills. *Transactions of the American Fisheries Society.* 110:446-50.

Gammon, J.R. 1970. The effect of inorganic sediment on stream biota. U.S. E.P.A. Water Quality Office, Pollution Control Research Service. 141 pp.

Gessler, J. 1970. Beginning and ceasing of sediment motion. Proceedings of the Institute of River Mechanics, Colorado State University, Fort Collins, Colorado, 15-26 June 1970.

Gessler, J. 1971. Beginning and ceasing of motion. Chapter 7: River Mechanics, H.W. Shen, ed., Water Resources Publs., Fort Collins, CO.

Golder Associates Ltd. 1995. Sediment monitoring study of Dogpound Creek pipeline crossing. Submitted to NOVA Gas Transmission Line Inc. Report No. 952-2328. September 1995. 17 pp. plus Tables, Figures and Appendices.

Goldes, S.A. 1983. Histological and ultrastructural effects of the inert clay kaolin on the gills of rainbow trout (Salmo gairdneri Richardson). M.Sc. Thesis, University of Guelph, Guelph, Ontario, 103 p. (cf Newcombe 1994a).

Goodchild, G.A. and S. Metikosh. 1994. Fisheries-related information requirements for pipeline water crossings. Can. Manuscr. Rep. Fish. Aquat. Sci. 2235: 17 p.

Government of Canada. 1987. The Canadian system of soil classification. Agriculture Canada Expert Committee on Soil Survey. Research Branch, Agriculture Canada. Publication Number 1646. 164 pp.

Government of Canada. 1974. The system of soil classification for Canada. Information Division. Canada Department of Agriculture, Ottawa, Ontario, Canada. 255 pp.

Gregory, R.S., J.A. Servizi, and D.W. Martens. 1993. Comment: Utility of the stress index for predicting suspended sediment effects. North American J. Fisheries Management. 13(4):868-873.

Griffith, J.S. and R.W. Smith. 1993. Use of winter concealment cover by juvenile cutthroat and brown trout in the south fork of the Snake River, Idaho. North American Journal of Fisheries Management 13:823-830.

Hall, J.D. and R.L. Lantz. 1969. Effects of logging on the habitat of coho salmon and cutthroat trout in coastal streams. *In* T.G. Northcote (ed) Symposium on salmon and trout in streams. Inst. Fish., Univ. Brit. Columbia. pp. 355-375.

Hartman, G.F. 1965. Role of behaviour in the ecology and interaction of underyearling coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gardneri*). Journal of the Fisheries Research Board of Canada. 22:1035-1081.

Hausle, D.A. and D.W. Coble. 1976. Influence of sand in redds on survival and emergence of brook trout. Trans. Amer. Fish. Soc. 1:57-63.

Heggenes, J., T.G. Northcote, and P. Armin. 1991. Seasonal habitat selection and preferences by cutthroat trout (Oncorhynchus clarki) in a small, coastal stream. Can. J. Fish. Aquat. Sci. 48:1364-1370.

Heggenes, J. and S. J. Saltveit. 1990. Seasonal and spatial microhabitat selection and segregation in young Atlantic salmon, Salmo salar L., and brown trout, Salmo trutta L. , in a Norwegian river. J. Fish Biol. 36:707-720.

Herbert, D.W.M. and J.C. Merkens. 1961. The effect of suspended mineral solids on the survival of trout. *Int J Air Wat Poll.* 5(1):46-55.

Hillman, T.W., J.S. Griffith. and W.S. Platts. 1987. Summer and winter habitat selection by juvenile chinook salmon in a highly sedimented Idaho stream. Transactions of the American Fisheries Society 116(2):185-195.

Hlohowsky, J.I. and T.E. Wissing. 1987. Seasonal changes in low oxygen tolerance of fantail, Etheostoma flabellare, rainbow , Etheostoma caeruleum, and greenside, Etheostoma blennioides, darters. Environmental Biology of Fishes 18(4):277-284.

Hollis, E.H., J.G. Boone, C.R. DeRose, and J. Murphy. 1964. A literature review of the effects of turbidity and siltation on aquatic life. Maryland Department of Chesapeake Bay Affairs, Annapolis Mayland, 26 pp.

Howes, D.E. and E. Kenk. 1988. Terrain classification system for British Columbia: A system for the classification of surficial materials, landforms and geological processes of British Columbia. Recreational Fisheries Branch, Ministry of Environment, and, Surveys and Resource Mapping Branch, Ministry of Crown Lands, Province of British Columbia. 90 pp.

Hunt, R.L. 1969. Overwintering survival of wild fingerling brook trout in Lawrence Creek Wisconsin. Journal of the Fisheries Research Board of Canada 26:1473-1483.

Hydroqual Consultants Inc., and Gore & Storrie Ltd. 1989. Stochastic River Quality Model: Manual Version 2.0. Produced for Alberta Environment Planning Division, Edmonton.

Hynes, H.B.N. 1973. The effects of sediment on the biota in running water. Proc. 9th Can. Hydrol. Symp. Fluvial Processes and Sedimentation. Univ. of Alberta. Inland Waters Directorate, Dept. Environ. pp 652-663.

Kerr, S.J. 1995. Silt, turbidity and suspended sediments in the aquatic environment: An annotated bibliography and literature review. Southern Region Science and Technology Transfer Unit. Technical Report TR-008.

Klein, R.D. 1984. Effects of sediment pollution upon the aquatic environment. Dated 30 November 1984. MD. Unpublished Manuscript.

Kondolf, G.M. 1995. Discussion. "Use of pebble counts to evaluate fine sediment increase in stream channels by John P. Potyondy and Terry Hardy." Water Resources Bulletin 31(3):537-538.

Kondolf, G.M., M.J. Sale, and M.G. Wolman. 1993. Modification of fluvial gravel size by spawning salmonids. Water Resources Research. 29(7):2265-2274.

Kondolf, G.M. and M.G. Wolman. 1993. The sizes of salmonid spawning gravels. Water Resources Research 29(7):2275-2285.

Kondolf, G.M. and S. Li. 1992. The pebble count technique for quantifying surface bed material size in instream flow studies. Rivers 3(2):80-87.

Koski. 1966. The survival of coho salmon from egg deposition to emergence in three Oregon coastal streams. M.Sc. Thesis. Oregon State University.

Krishnappan, B.G. 1981. User's manual: Unsteady, non-uniform, mobile boundary flow model - MOBED. Environment Canada, Hydraulics Division, National Water Research Institute. 119 pp.

Krishnappan, B.G. 1983. MOBED users manual update I. Environment Canada, Hydraulics Division, National Water Research Institute. 75 pp.

Krishnappan, B.G. 1986. MOBED users manual update II. Environment Canada, Hydraulics Division, National Water Research Institute. 103 pp.

Krishnappen, B.G. and P. Engel. 1995. Critical shear stress for erosion and deposition of fine suspended sediments in the Fraser River. NWRI Contribution No. 94-60.

Krone, R.B. 1962. Flume studies of the transport of sediment in estuarial shoaling processes. Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Lamberti, G.A., S.V. Gregory., L.R. Ashkenas., R.C. Wildman. and K.M.S. Moore. 1991. Stream ecosystem recovery following a catastrophic debris flow. Can. J. Fish. Aquat. Sci.48:196-208.

Lenat, D.R., D.L. Penrose, and K.W. Eagleson. 1981. Variable effects of sediment addition on stream benthos. Hydrobiologia 79: 187-194.

Leonard, P.M. and D.J. Orth. Use of habitat guilds of fishes to determine instream flow requirements. North American Journal of Fisheries Management. 8 (4) :399-409.

Leopald, L.B. and Rosgen, D. 1990.

Leopold, L.B. , M.G. Wolman and J.P. Miller. 1964. Fluvial processes in goemorphology. W.H. Freeman and Company.

Leopold, L.B. 1970. A reverence for rivers. Geology 5: 429-430.

Lind, O.T. 1979. Handbook of common methods in limnology. 2nd Edition. C.V. Mosby Company, Toronto.

Lisle, T.E. and J. Lewis. 1992. Effects of sediment transport on survival of salmonid embryos in a natural stream: a simulation approach. Can. J. Fish. Aquat. Sci. 49: 2337-2344.

Lloyd, D.S. 1987. Turbidity as a water quality standard for salmonid habitats in Alaska. North American J. Fisheries Management. 7: 34-65.

MacDonald, D.D. and C.P. Newcombe. 1993. Utility of the stress index for predicting suspended sediment effects: Response to comment. North American J. Fisheries Management. 13(4): 873-876.

Mahoney, D. and D.C. Erman. 1984. An index of stored fine sediment in gravel bedded streams. Water Resources Bulletin, Vol. 20, No. 3, pp 342-348.

Marcus, M.D., M.K. Young, L.E. Noel, and B.A. Mullan. 1990. Salmonid-habitat relationships in the western United States: a review and indexed bibliography. United States Department of Agriculture. General Technical Report RM-188.

McKinnon, G.A. and F.N. Hnytka. 1988. The effects of winter pipeline construction on the fishes and fish habitat of Hodgson Creek, N.W.T. Central and Arctic Region, Department of Fisheries and Oceans, Winnipeg, Manitoba. Canadian Technical Report of Fisheries and Aquatic Sciences No. 1598.

McLeay, D.J. 1977. Development of a blood sugar bioassay for rapidly measuring stressful levels of pulpmill effluent to salmonid fish. J. Fish. Res. Board. Can. 34:477-485. (cf Noggle 1978).

McLeay, D.J., I.K. Birtwell, G.F. Hartman, and G.L. Ennis. 1987. Responses of Arctic grayling (*Thymallus arcticus*) to acute and prolonged exposure to Yukon placer mining sediment. Can. J. Fish. Aquat. Sci. 44: 658-673.

McMahon, T.E. and G.F. Hartman. 1989. Influence of cover complexity and current velocity on winter habitat use by juvenile coho salmon (*Oncorhynchus kistuch*). Can. J. Fish. Aquat. Sci. 46:1551-1557. cited in Cunjak 1996.

McNeil, W.J. and W.H. Ahnell. 1964. Success of pink salmon spawning relative to size of spawning bed materials. U.S. Fish and Wildlife; Fish. Bull. 63(3):575-588.

Meehan, W.R. and D.G. Swanston. 1977. Effects of gravel morphology on fine sediment accumulation and survival of incubating salmon eggs. USDA Forest Service Research Paper, PNW-220, Portland Oregon.

Mende J. 1989. River and stream investigations: Portneuf River assessment.. Idaho Dept of Fish and Game and Idaho State University. Poccatello, Idaho. F-711-R-12 Sub.3, J4. pp 1-72.

Meyer-Peter, E., and R. Müller. 1948. Formulas for bed-load transport. International Association of Hydraulic Research, 2nd Meeting, Stockholm.

Modde, T., D.R. Young, and D.L. Archer. 1991. Evaluation of factors influencing population characteristics and habitat utilization of trout in the Flaming Borge tailwater. 1987-1989. Division of Wildlife Resources, Utah Department of Natural Resources. Publication No. 91-10. 192 pages. ABST

Morse, B, R.D. Townsend and M. Sydor. 1991. Mathematical modelling of riverbed dynamics - a Canadian case study. Can. J. Civ. Eng. 18:772-780.

Müller, R. 1943. Theoretische Grundlagen der Fluss und Wildbachverbaumgen (Theoretical principles for regulation of rivers and torrents). Eidgenössische Technische, Hochaschule, Zürich, Milleilungen der Versuchsanstalt für Wasserbau und Erdbau. No. 4.

Münning, R. 1895. On the flow of open water in open channels and pipes. Transactions, Institutions of Civil Engineers of Ireland, Vol. 20, pp. 161-207, Dublin, 1891, Supplement. Vol. 24, pp 179-207.

Newcombe, C.P., and J.O.T. Jensen. 1995a. Channel sediment and fisheries: a synthesis for quantitative assessment of risk and impact. Habitat Protection Branch. British Columbia Ministry of Environment, Lands and Parks, Victoria, British Columbia. Canada. 51 pp.

Newcombe, C.P., and J.O.T. Jensen. 1995b. Suspended Sediment Pollution: A fisheries field guide for assessment of risk and impact. Draft September 1995.

Newcombe, C.P. 1994a. Suspended sediments in aquatic ecosystems: ill effects as a function of concentration and duration of exposure. Habitat Protection Branch, British Columbia Ministry of Environment, Lands and Parks. Victoria, British Columbia, Canada, 298 pages.

Newcombe, C.P. 1994b. Suspended sediments pollution: Dose/response Characteristics of Various Fishes. Habitat Protection Branch. British Columbia Ministry of Environment, Lands and Parks. Victoria, British Columbia, Canada. DRAFT 20 pages + Appendices.

Newcombe, C.P. and D.D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management 11:72-82.

Nickelson, T.E., J.D. Rodgers, S.L. Johnson, and M.F. Solazzi. 1992. Seasonal changes in habitat use by juvenile coho salmon (Oncorhynchus kisutch) in Oregon coastal streams. Can. J. of Fisheries and Aquat. Sci. 49:783-789.

Noggle, C.C. 1978. Behavioural, physiological and lethal effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management 11:72-82.

Novak, M.A. 1988. Impacts of a fire-flood event on physical and biological characteristics of a small mountain stream. Montana State University.

O'Brien, J.S. 1984. Hydraulic and sediment transport investigations, Tampa River, Dinosaur National Monument. WRFSL Rept. 83-8.

Olmsted, L.L. and D.G. Cloutman. 1974. Repopulation after a fish kill in Mud Creek. Trans. Amer. Fish. Society 103, 79-87.

Onishi, Y. 1981. Sediment - contaminant transport model. Journal of the Hydraulics Division, A.S.C.E. 107: 1089-1107.

Ontario Ministry of the Environment 1984. Water Management: Goals, policies, objectives and implementation procedures of the Ministry of Environment. Queen's Printer of Ontario, Toronto, Ontario, 70 pp.

Panthenaides, E. 1965. Erosion and deposition of cohesive soils. Journal of the Hydraulics Division. ASCE, March 1965. pp. 755-771.

Perry, J.A., D.J. Schaeffer, and E.E. Herricks. 1985. Innovative designs for water quality monitoring: Are we asking the questions before the data are collected? In Boyle, T.P. ed. New approaches to monitoring aquatic ecosystems. ASTM 1985.

Peterson, N.P. 1982. Immigration of juvenile coho salmon (*Oncorhynchus kisutch*) into riverine ponds. Canadian Journal of the Fisheries and Aquatic Sciences 39:1308-1310.

Phillips, R.W., R.L. Lantz, E.W. Claire and J.R. Moring. 1975. Some effects on gravel mixtures on emergence of coho salmon and steelhead trout fry. *Transactions of the American Fisheries Society*. 3:461-6.

Platts, W.S., W.F. Megahan, and G.W. Minshall. 1983. Methods for evaluating streams, riparian and biotic conditions. USDA. Gen. Tech. Rept. INT-138., Ogden, Utah. 70 pp.

Poff, N.L. and J.D. Allan. 1995. Functional organization of stream fish assemblages in relation to hydrological variability. Ecology 76(2), pp. 606-627.

Porter, T.R., D.M. Rosenberg and D.K. McGowan. 1974. Winter studies of the effects of highway crossing on the fish and benthos of the Martin River, NWT. Resource Management Branch, Central Region, Environment Canada, Fisheries and Marine Service. CEN/T-74-3. pp.1-50.

Power, G. and J.R. Colman. 1967. Winter rotenoning as a means of collecting and studying trout in an ice and snow covered Canadian stream. Trans. Am. Fish. Soc. 96:222-223.

Prowse, T.D. 1993. Proceedings of the workshop on environmental aspects of river ice. August 18-20, 1993. Saskatoon, Saskatchewan. Nat. Hydrology and Research Institute. Saskatoon, Saskatchewan. NHRI Symposium No. 12, 390 pp.

Prowse, T.D. and N.C. Gridley. 1993. Environmental aspects of river ice. 155 pp.

Redding, J.M. and C.B. Schreck. 1980. Chronic turbidity and stress in juvenile coho salmon and steelhead trout. Report PNW-1705-16, Pacific Northwest Forest and Range Experiment Station, U.S. Forest Service, Corvallis, Oregon.

Reiser, D.W. 1983. Development and testing of an intergravel sampling device for quantifying fine sediments in streams. Preliminary Research Proposal.

Reiser, D.W. and T.C. Bjornn. 1979. Habitat requirements of anadromous salmonids. *In* W.R. Meehan (ed). Influence of Forest and Rangeland Management on Anadromous Fish and Habitat in Western N. America. Gen. Tech. Rept. PNW-96., Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon.

Reiser, D.W., J.M. Peters and S.K. Running. 1989. Development and application of an intergravel sampling devise for quantifying sediments in streams. Prepared for Pacific Gas and Electric Company by EA Engineering, Science, and Technology Inc.

Reiser, D.W., M.P. Ramey and T.R. Lambert. 1985. Review of flushing flow requirements in regulated streams. San Ramon, California. Pacific Gas and Electric Company, Dept. of Engineering Research. Z19-5-120-84. pp.1-97 + App.

Reiser, D.W. and T.A. Wesche. 1977. Determination of physical and hydraulic preferences of brown and brook trout in the selection of spawning locations. Water Resources Service. No. 64. Water Resour. Res. Inst. Univ. of Wyoming, 100 pp.

Riera, M., M.T. Prats, L. Palacios, J. Pesquero, and J. Planas. 1993. Seasonal adaptations in oxygen transport in brown trout (Salmo trutta fario). Comparative Biochemistry and Physiology 106(4):695-700.

Rimmer, D.M., U. Paim, and R.L. Saunders. 1983. Autumnal habitat shift of juvenile Atlantic salmon (Salmo salar) in a small river. Canadian Journal of Fisheries and Aquatic Sciences 40:671-680.

Root, R.B. 1967. The niche exploitation pattern of the blue-gray gnatcatcher. Ecology 37: 317-350.

Rosenberg, D.M. and A.P. Wiens. 1978. Effects of sediment addition on macrobenthic invertebrates in a northern Canadian River. Water Res. 12, 753-763.

Rosenberg, D.M. and N.B. Snow. 1975. Ecological studies of aquatic organisms in the Mackenzie and Porcupine river drainages in relation to sedimentation. Can. J. Fish. Mar. Serv. Res. Dev. Tech. Rep. 547.

Rosenberg, D.M. and N.B. Snow. 1975. A design for environmental impact studies with special reference to sedimentation in aquatic systems in the MacKenzie and Porcupine River Drainages. BEAK.

Ryan, P. 1970. Design and operation of an *in-situ* frozen core gravel sampler. Dept. Fisheries and Forestry, Canada.

Saunders, J.W., and M.W. Smith. 1965. Changes in a stream population of trout associated with increased silt. *Journal of Fisheries Research Board of Canada*. 22(2):396-404.

Schubert, J.P., W.S. Vinikour, and D.K. Gartman. 1985. Effects of gas-pipeline construction on the Little Miami aquatic ecosystem. Chicago, Illinois. Gas Research Institute, NTIS. GRI-86/0024.

Scullion, J., and N. Miller. 1979. Review of effects of natural and artificial flow patterns and sediment dynamics on benthic invertebrates and salmonids in upland rivers. The Univ. of Wales. Inst. of Sci. and Tech., Cardiff. Dept. of Applied Biol.

Selye, H. 1950. Stress and the general adaptation syndrome. British Medical Journal 1950(1):1383-1392.

Servizi, J.A. and D.W. Martens. 1992. Sub-lethal responses of coho salmon to suspended sediments. Canadian J. Fisheries and Aquatic Sciences, 49(7): 1389-1395.

Servizi, J.A. and D.W. Martens. 1991. Effect of temperature, season, and fish size on acute lethality of suspended sediments to coho salmon (Oncorhynchus kiutch). Can. J. Fish. Aquat. Sci. 48:493-497.

Shaw, P.A. and J.A. Maga. 1943. The effect of mining silt on yield of fry from salmon spawning beds. California Fish and Game. 29(1):29-41.

Sheehan, R. J.; Lewis, W. M.; Bodensteiner, L. R.; King, D.; Logsdon, D. E.; Scherck, S. D.; Wills, P. S. 1990. Winter habitat requirements and overwintering of riverine fishes. U.S. Fish and Wildlife Service and the Illinois Department of Conservation.

Sherk, J.A, O'Connor JM, Neumann DA. 1973. Effects of suspended and deposited sediments on estuarine environments. *Estuarine Research*. 2:541-58. In: L.E. Cronin (ed). Estuarine Research. Academic Press, N.Y.

Shields, A. 1936. Anwendung der aehnlichkeitsmechanik und der trubulenz-forshung auf die geschiebebewegung. (Application of similarity principles and turbulence research to bed-load movement). Mitteilungen der Preuss. Versuchsanst fur Wasserbau und Schiffbau, Berlin. No. 26 (1936). Available also in a translation by W.P. Ott and J.C. van Uchelein, S.C.S. Cooperative Laboratory, California Institute of Technology, Pasadena, Calif.

Shirazi, M.A., and W.K. Seim. 1979. A stream systems evaluation - an emphasis on spawning habitat for salmonids. EPA - 600/3-79-109; U.S. Environ. Protection Agency, Corvallis, Oregon.

Sigler, J.W., T.C. Bjornn and F.H. Everest. 1984. Effects of chronic turbidity on density and growth of steelheads and coho salmon. *Transactions of the American Fisheries Society*. 113:142-50.

Simmons, R.C. 1984. Effects of placer mining sedimentation on Arctic grayling of interior Alaska. University of Alaska, Fairbanks; 1-75 pp.

Singleton, H.J. 1985. Water quality criteria for particulate matter. British Columbia Ministry of Environment. Resource Quality Section, Water Management Branch. Victoria, B.C.

Slaney, P.A., T.G. Halsey and H.A. Smith. 1977. Some effects of forest harvesting on salmonid rearing habitat in two streams in the central interior of British Columbia. Fisheries Management Rept. #71, Ministry of Recreation and Conservation.

Slaney, P.A., T.G. Halsey and A.F. Tautz. 1977. Effects of forest harvesting practices on spawning habitat of stream salmonids in the Centennial Creek watershed, British Columbia. Fisheries Management Rept. #73.

Smith, M.W. and J.W. Saunders. 1958. Movements of brook trout (Salvelinus fontinalis) between and within fresh and salt water. J. Fish. Res. Bd. Can. 15, 1403-1449.

Smith, O.R. 1940. Placer mining silt and its relation to salmon and trout on the Pacific coast. Transactions American Fisheries Society, 69: 225-230.

Sokal, R.R., and F.J. Rohlf. 1981. Biometry. 2nd ed., W.H. Freeman & Co., San Francisco. 859 pp.

Stober, Q.J., B.D. Ross, C.L. Melby, P.A. Dinnel, T.H. Jagielo, and E.O. Salo. 1981. Effects of suspended volcanic sediment on coho and chinook salmon in the Toule and Cowlitz Rivers. Technical Completion Report. FRI-UW-8124, Fisheries Research Institute, University of Washington, Seattle, Washington. 147 pp.

Stowell, R., A. Espinosa, T.C. Bjornn, W.S. Platts, D.C. Burns, and J.S. Irving. 1983. Guide for predicting salmonid response to sediment yields in Idaho Batholith watersheds. U.S. Forest Service, Northern and Intermountain regions, Ogden, Utah, 95 pp.

Strickler, A. 1923. Beiträge sur Frage der Geschwindigksitaformel und der Rauhigkeitasablen für Ströme, Janale und gescholoasene Leitungen (Some contributions to the problem of the velocity formula and roughness factors for rivers, canals, and closed conduits). Mitteilungen des eidgenössichen Amiss für Wasserwirtschaft, Bern, Switzerland, No. 16.

Stuart, T.A. 1953. Water current through permeable gravels and their significance to spawning salmonids. Nature. Lond. 172, 407-408.

Swales, S., F. Caron, J.R. Irvine, and C.D. Levings. 1988. Overwintering habitats of coho salmon (Oncorhynchus kisutch) and other salmonids in the Keogh River system, British Columbia. Can. J. Zool. 66:254-261.

Swales, S., R.B. Lauzier and C.D. Levings. 1986. Winter habitat preferences of juvenile salmonids in two interior rivers in British Columbia. Can. J. Zool. 64:1506-1514.

Swift, D.J. and R. Lloyd. 1974. Changes in urine flow rate and haematocrit value of rainbow trout Salmo gairdneri (Richardson) exposed to hypoxia. J. Fish. Biol. 6:379-387. (cf Noggle 1978).

Tack, E. Trout mortality from the formation of suspended ice crystals. Fischerei - Zeitung. 41(4): 42; 1938. ISSN.

Tagart, J.V. 1976. The survival from egg deposition to emergence of coho salmon in the Clearwater River, Jefferson County, Washington. M.Sc. Thesis, Univ. Washington, Seattle Washington.

Taylor, B.R. and J.C. Roff. 1986. Long-term effects of highway construction on the ecology of a southern Ontario stream. Environmental Pollution (Series A) 40: 317-44

Taylor, B.R. and B.A. Barton. 1992. Temperature and dissolved oxygen criteria for Alberta fishes in flowing water. Prepared for Alberta Fish and Wildlife Division, Edmonton, Alberta by EMA Environmental Management Associates. January 1992. 72 pp.

Terzi, R.A. 1981. Hydrometric field manual-measurement of streamflow. Environment Canada, Inland Waters Directorate, Water Resources Branch, Ottawa. 37 pp.

Toffaleti, F.B. 1966. A procedure for computation of total river sand discharge and detailed distribution, bed to surface. Committee on Channel Stabilization, U.S. Army Corps of Engineers, November 1966.

Trihey, E.W. and D.L. Wegner. 1983. Field data collection procedures for use with the physical habitat simulation system of the Instream Flow Group. Cooperative Instream Flow Service Group, Fort Collins. CO. DRAFT, January 1983.

Trow. 1994. Canadian pipeline industry sediment transport seminar. 58 pp.

Tsui, P.T.P. and P.J. McCart. 1981. Effects of stream-crossing by a pipeline on the benthic macroinvertebrate communities of a small mountain stream. Hydrobiologia 79, 271-276.

Velleux, M., J. Gailani, and D. Endicott. 1995. Screening - level approach for estimating contaminant export from tributaries. [Unpublished] 42 pp.

Vinikour and Schubert 1987. Effects of gas-pipeline construction on the aquatic ecosystem of Canada Creek, Presque Isle County, Michigan. Report to Gas Research Institute, Chicago, Illinois, 82 pp.

Vondracek, B. and D.R. Longanecker. 1993. Habitat selection by rainbow trout Oncorhynchus mykiss in a California stream: Implications for the instream flow incremental methodology. Ecology of Freshwater Fish 2:173-186.

Wagener, S.M. and J.D. LaPerriere. 1985. Effects of placer miner on the invertebrate communities of interior Alaska streams. Freshwater Invertebrate Biology, 4:208-214.

Walkotten, W.J. 1976. An improved technique for freeze sampling stream bed sediments. U.S.D.A. For. Serv. Res. Note PNW-281., Pac. Northwest For. and Range Exp. Sta., Portland, Oregon.

Ward, N. 1992. The problem of sediment in water for fish. Northwestern Ontario Boreal Forest Management Technical Notes TN-21:1-8.

Waters, T.F. 1964. Interpretation of invertebrate drift of stream invertebrates. Ecol. 43: 316-320.

Waters, T.F. 1995. Sediment in streams: sources, biological effects and control. American Fisheries Society Monograph 7. Bethesda, Maryland.

Weaver, T.M, Fraley J.J. 1993. A method to measure emergence success of westslope cutthroat trout fry from varying substrate compositions in a natural stream channel. *North American Journal of Fisheries Management.* 13:817-22.

Wedemeyer, G.A. , B.A. Barton, and D.J. McLeay. 1990. Stress and acclimation. pages 451-489. in C.B. Schreck and P.B. Moyle, editors. Methods for fish biology. American Fisheries Society, Bethesda, Maryland.

White, D.S. and J.R. Gammon. 1976. The effect of suspended solids on macroinvertebrate drift in an Indiana Creek. Proc. Indiana Acad. Soc. 86: 182-188.

Wickett, W.P. 1959. Effects of siltation on success of fish spawning. p16-22 *In* 5th Symposium on Water Pollution Research, Pacific Northwest Siltation - It's Source and Effects on the Aquatic Environment, U.S. Public Health Service, Portland, Oregon.

Wickett, W.P. 1954. The oxygen supply to salmon eggs in spawning beds. J. Fisheries Research Board Canada. 11(6): 933-953.

Williams, D.D. and H.B.N. Hynes. 1976. The recolonization mechanisms of stream benthos. Oikos 27: 265-272.

Williamson, D.A 1983. Surface water quality management proposal, Volume 1: Surface water quality objectives. Water Standards and Studies Report No. 83-2, Manitoba Department of Environment and Workplace Safety and Health, Winnipeg, Manitoba.

Wilson, D.J. and B.W. Zelt. 1990. Predicting outdoor and indoor exposure hazards from toxic gas releases. Software user's manual, model development and technical basis. Department of Mechanical Engineering. University of Alberta. Tech. Prt. 72, 73 and 74.

Winberg, G.G. 1956. Rate of metabolism and food requirements of fishes. Belorussian State University of Minsk. Translated from Russian: Fisheries Research Board of Canada Translation Series 194, 1960, Ottawa.

Yang, C.T. 1973. Incipient motion and sediment transport. Journal of the Hydraulics Division, ASCE, Vol. 99, No. HY10, Proc. Paper 10067, Oct. 1973, pp. 1679-1704.

Young, R.J. 1986. The effect of winter oil pipeline construction on the benthic macroinvertebrate community structure of Hodgson Creek, NWT. M.Sc. thesis, Univ. of Guelph. December 1986. 76 pp

Young, R.J. and G.L. Mackie. 1991. Effect of oil pipeline construction on the benthic invertebrate community structure of Hodgson Creek, Northwest Territories. Can. J. Zool. 69:2154-2160.

Zallen, M. 1931. Effects of pipeline construction on juveniles and incubating eggs of mountain whitefish (*Prosopium williamsoni* Girard) in the Moyie River, British Columbia. [Unpublished]

Zar, J.H. 1984. Biostatistical Analysis. 2nd ed., Prentice Hall. 718 pp.

Zelt, B.W. Concentration fluctuations in health risk assessment. Presented at 1995 CPANS Annual General Meeting and Tech. Conf. June 6-7. Edmonton Convention Centre. Edmonton.

APPENDIX 1

LITERATURE DATA-BASE ON SEDIMENT EFFECTS ON FISH

Anonymous 1992. Water and sediment in the middle Rio Grande Valley, New Mexico: Use of a sediment transport capacity index. Proceedings of the 12th Annual American Geophysical Union Hydrology Days. Hydrology Days Publication; Colorado State University, Fort Collins, Colorado. 67-80.

The cottonwood gallery forests of the Middle Rio Grande floodplain in New Mexico are an important habitat for birds and other animals. Selected results of a study to find techniques for improving the forest are reported. Two topics are explored. The first is about changes in streamflows and sediment flows in the river near Albuquerque and the second is on the use of a Sediment Transport Capacity Index. Peak flows in the Middle Rio Grande have been reduced by reservoirs. The concept of a sediment transport capacity index is introduced. The index is proportional to the discharge to some power, usually 2.0. The use of a sediment transport capacity index was useful in the analysis of the data for the Middle Rio Grande. The index for the Rio Grande shows the river has capacity to transport sand size material but has little capacity to transport gravel size material. Keywords : sediment transport; model; hydrology; sediment

A.D.Revill Associates. 1979. A study of stream turbidity induced by certain aspects of the construction of linear facilities and the consequent effects on fish. Belleville, Ontario. pp. 1-62.

The construction of linear facilities increases the sediment load of streams in the area. This effect becomes acute in the case of stream crossings. Fish are directly and adversely affected by the increase in undissolved solids. Under laboratory conditions the onset of direct mortality has been observed at concentrations as low as 90 ppm while 50% of specimens of one species (coho salmon) failed to survive 36 hours at concentrations of 1250 mg/L. It has bee demonstrated that fish exposed to levels of suspended solids, below those found to be lethal, have reduced oxygen uptake and impaired swimming ability. Furthermore increased sensitivity of fish to suspended solids under conditions of oxygen deprivation and susceptibility to predation while under stress have been reported. Increased sediment yields result primarily from the destruction of vegetation thereby increasing surface wash and gullying activity. In permafrost regions thermokarst activity is an additional problem. Increased sediment yield may also result from physical damage to the ground surface in the form of, for example, increased surface soil compaction and increased surface run-off, or the chuming and dislocation of soils by vehicles leading to increased erodibility, or the oversteepening of slopes leading to increased probabilities of mass movements and river bank slumping. No quantitative studies dealing specifically with the geomorphic effects of such activities at stream crossings were found in the literature. However, studies of the effects of construction activities in temperate regions suggest that slope sediment production may increase by as much as two orders of magnitude undisturbed areas. Various control measures will undoubtedly reduce the total among of sediment entering the stream at the site of the crossing, but the effectiveness of these measures does not appear to have been examined systematically. Keywords : turbidity; highway construction; pipeline; fish effects; instream sediment; coho; salmon; sediment; coho salmon

Aadland, L.P. 1993. Stream habitat types: their fish assemblages and relationship to flow. North American Journal of Fisheries Management 13:790-806.

To simplify the selection of target species for instream flow studies, 114 fish species-life stage combinations in six Minnesota streams were assigned membership in six habitat-preference guilds based on the habitat type supporting their highest densities. Shallow pools (<60 cm deep and velocities <30 cm/s) were preferred by most of the young-of-the-year fishes. Slow riffles (<60 cm deep and velocities 30-59 cm/s) were preferred by stonerollers *Campostoma* spp.; spawning sand shiners *Notropis stramineus*; adult river shiners *N. blennius*; juvenile spawning and age-0 suckers (*Moxostoma* spp., northem hog sucker *Hypentelium nigricans*, and white sucker *Catostomus commersoni*); and most age-0 darters. Fast riffles (<60 cm deep and velocities> or eq to 60 cm/s) were preferred by several adult catostomids. Medium pools (60-149 cm deep and velocities <30 cm/s) and deep pools (>150 cm deep) were preferred by adult channel catfish and most of the centrarchids. Shallow pool habitat was most abundant during low flows and was reduced during high flows. Medium and deep pool habitat area changed relatively little with changes in flow, whereas slow riffle, fast riffle and raceway habitat became scarce or absent during low flows. Exclusive use of pool-oriented game fish as target species in instream flow studies may result in recommendations that do not protect species occupying flow-sensitive riffles. To preserve fish community diversity and integrity instream flow assessments should include target species that occupy flow-sensitive habitat types. Keywords : behaviour; fish habitat; hydrology; methodology; flows; river

Alabaster, J.S. 1972. Suspended solids and fisheries. Proc R Soc London 180:395-406.

The effect of suspended solids on freshwater fish is illustrated from field and laboratory studies on china-clay wastes together with work on the effects of other chemically inert material, wood fibre, ferric hydroxide, and oxidizable organic solids, and mention is made of work in the marine environment, Tentative water quality criteria formulated by the European Inland Fisheries Advisory Commission for inert suspended solids and inland fisheries are outlined and compared with conditions prevailing in rivers in the United Kingdom. Reference is made to current work by the Water Pollution Research Laboratory on the role of organic suspended matter in the presence of soluble poisons and on the effect of hydraulic conditions on the settlement and oxidizability of suspended solids from sewage effluent. Keywords : suspended sediment; fish effects; laboratory; laboratory study; water quality; river

Alabaster JS, Lloyd R. 1982. 1, Finely divided solids. ; Alabaster JS, Lloyd R, editors. Water Quality Criteria for Freshwater Fish. 2nd ed. Butterworth, London: pp. 1-20.

Water quality criteria for suspended solids are needed by those who have to manage inland fisheries and must sometimes decide, for example, how much solid matter could enter a river of lake without undue risk to a fishery or whether it is worth attempting to develop a commercial or recreational fishery in water already containing a known concentration of such materials. There are at least five ways in which an excessive concentration of finely divided solid matter might be harmful to a fishery in a river or a lake. These are: (a) By acting directly on the fish swimming in the water in which solids are suspended, and either killing them or reducing their growth rate, resistance to disease, etc, (b) By preventing the successful development of fish eggs and larvae, (c) By modifying natural movements and migrations of fish, (d) by reducing the abundance of food available to the fish, (e) By affecting the efficiency of methods for catching fish. Some or all of these factors could operate together to harm a fishery.
There is evidence that not all species are equally susceptible to suspended solids, and that not all kinds of solids are equally harmful. Unfortunately there is very little information on these and many other aspects of the problem, and much of the evidence which does exist is less firmly established than is desirable. It has therefore been concluded that definite water quality criteria which distinguish between the many different kinds of finely divided solids to which different sorts of inland fisheries may be subjected cannot yet be proposed. Nevertheless, when the evidence is considered as a whole, certain general conclusions can be drawn.
There is probably no sharply defined concentration of solid above which fisheries are damaged and below which they are quite unharmed. It appears that any increase in the normally prevailing concentration of suspended matter above quite a low level may cause some decline in the status and value of a freshwater fishery, and that the risk of damage increases with the concentration. Although there is not enough evidence to allow the relation between solids concentration and risk of damage to be defined at all precisely, the Working Party considers that the degree of risk to fisheries may be divided into four arbitrarily defined categories and that rough estimates may be made of the ranges of concentration to which they would generally correspond. From the approach to the problem the following tentative criteria are presented. With respect to chemically inert solids and to waters which are otherwise satisfactory for the maintenance of freshwater fisheries, (a) There is no evidence that concentrations of suspended solids less than 25 mg/L have any harmful effects on fisheries. (b) It should usually be possible to maintain good or moderate fisheries in waters which normally contain 25-80 mg/L suspended

solids. Other factors being equal, however, the yield of fish from such waters might be somewhat lower than from those in category (a). (c) Waters normally containing from 80-400 mg/L suspended solids are unlikely to support good freshwater fisheries, although fisheries may sometimes be found at the lower concentrations within this range. (d) At the best, only poor fisheries are likely to be found in waters which normally contain more than 400 mg/L suspended solids.
In addition, although concentrations of several thousand mg/L solids may not kill fish during several hours or days exposure, such temporary high concentrations should be prevented in rivers where good fisheries are to be maintained. The spawning grounds of salmon and trout require special consideration and should be kept as free as possible from finely divided solids. Keywords : water quality; lake; fish eggs; methods; fish survival; silt effects on habitat; suspended sediment; river

Alderdice, D.F., Bams, R.A., and Velsen, F.P.J. 1977. Factors affecting deposition, development and survival of salmonid eggs and alevins. A bibliography, 1965-1975. Fisheries and Marine Service, Fisheries and Environment Canada. Research and Resource Services, Pacific Biological Station, Nanaimo, British Columbia. No. 743. pp. 1-276.

This bibliography is the result of an effort to organize a significant part of the available literature regarding physical, chemical and biological factors that influence egg deposition, and development and survival of eggs and alevins of Pacific salmon (*Oncorhynchus* spp.). Very early in the search it was apparent that much detailed information is available in original papers, but that few comprehensive reviews have been undertaken to organize the material. It was evident also that useful correlative material would be found in technical papers on other salmonid and non-salmonid species. Accordingly, the search was expanded to include these further sources of pertinent information. Furthermore, it was obvious that not all literature on the subject could be surveyed at one time. This bibliography covers the period beginning in 1965 and ends with material in the library of the Pacific Biological Station in January 1976. Keywords : salmonid; bibliography; fish eggs; fish survival; embryos; salmon; review

Alexander, G.R. and Hansen, E.A. 1977. The effects of sediment from a gas-oil well drilling accident on trout in creeks of the Williamsburg area, Michigan. Michigan Department of Natural Resources, Fisheries Division. Michigan. 1851. pp. 1-15.

A gas-oil well drilling accident caused abnormally large quantities of sediment-laden water to enter trout streams of the Williamsburg area, Michigan. No abnormal concentrations of dissolved solids or dissolved oxygen were noted and stream water temperatures were not elevated. However, sediment concentrations were greatly increased and some sediment deposition occurred on the streambed. Spring and fall trout populations of Williamsburg Creek, the most affected stream, were reduced for a number of years. No measurable change in the trout stocks of Acme Creek, a lesser affected stream, were detected. No significant change in individual trout growth rate was noted for any of the streams. However, growth of trout biomass was reduced for Williamsburg Creek. Keywords : suspended sediment; sediment concentrations; sediment deposition; fish growth; salmonid

Alexander, G.R. and Hansen, E.A. 1982. Sand sediments in a Michigan trout stream. Part II. Effects of reducing sand bedload on a trout population. Michigan Department of Natural Resources, Fisheries Division. Michigan. 1902. pp. 1-20.

A sediment basin excavated in a Michigan trout stream reduced sand bedload sediment by 86% (from 56 ppm down to 8 ppm). Following the reduction in bedload, trout numbers increased significantly. Small or young trout increased about 40% throughout the treated area. Larger and older trout increased in the portion of the treated area that had an erodible sand bed. Although production increased 28%, growth rate of trout changed little. Both brown and rainbow trout populations responded similarly to the bedload reduction. However, statistical tests were more conclusive for brown trout than for rainbow trout due to lower year-to-year variation of the brown trout population. The results suggest that in-stream sediment basins are an effective means for removing sand bedload and that even small amounts of moving sand bedload sediments can have a major impact on trout populations. Keywords : rainbow trout; brown trout; instream sediment; sediment; trout; Young

Alexander, G.R. and Hansen, E.A. 1983. Effects of sand bedload sediment on a brook trout population. Michigan Department of Natural Resources, Fisheries Division. Michigan. 1906. pp. 1-51.

An experimental introduction of sand sediment in Hunt Creek to increase the bedload 4 to 5 fold resulted in a significant reduction of trout and trout habitat. The trout population declined to less than half its normal abundance. The growth rate of individual trout was not affected. Population adjustment to the poorer habitat was via a decrease in the trout survival rates, particularly from the egg to fry and/or the fry to fall fingerling stage of the life cycle. Habitat for trout and trout food organisms became much poorer judged upon their drastic population reductions. Stream morphometry changed considerably with the channel widening and shallowing. Further, sand deposition aggradated the streambed and eliminated most pools. The channel become a continuous run, rather than a series of pools and riffles. Water velocities increased as did summer water temperatures. Relatively small bedload sediment concentrations of 80 to 100 ppm have a profound effect on trout and trout habitat. Keywords : brook trout; fry

Alexander, G.R. and Hansen, E.A. 1988. Decl'ne and recovery of a brook trout stream following an experimental addition of sand sediment. Michigan Department of Natural Resources, Fisheries Division. Michigan. 1934. pp. 1-35.

An experimental introduction of sand sediment into Hunt Creek in the northern Lower Peninsula of Michigan that increased the bed load four to five times resulted in a significant reduction of brook trout numbers and loss of habitat. The brook trout population declined to less than half its normal abundance. After the experimental treatment was stopped the stream was allowed to cleanse itself of sand naturally for a 5 year period, followed by another 5 year period when sediment basins were constructed to accelerate sand clean out. The gross channel morphometry, bed type, water velocities, and trout cover recovered in about 6 years. However, to date, some sand is still in deposition along the stream edge and within gravel riffles and still adversely effects trout spawning, nursery habitat, and production of invertebrate trout foods. Little improvement in the numbers of young-of-the-year brook trout has occurred 10 years after experimental sand additions were discontinued. In spite of this reduced recruitment the population of older brook trout has nearly completely recovered. This has come about through increased survival of age-1 and older trout, presumably because the habitat has been restored for these larger fish. The growth rate of individual trout showed little change over the course of the study. The decline in habitat quality induced by increased sand bed load caused a decrease in brook trout survival rates which reduced trout numbers. When there was less food, there were fewer fish. Thus, daily ration and growth did not change substantially. When sand bed load was reduced and habitat improved there were increases in trout survival, trout numbers, and food abundance, but little change in trout growth. This study has demonstrated that a relatively small sand bed load concentration of only 80 ppm had a profound negative effect on brook trout and their habitat. Moreover, it demonstrates that reduction of bed load can improve trout populations and trout habitat considerably. However, full recovery from the effects of elevated sand bed load levels will take a long time in low gradient streams with relatively stable flow regimes. Keywords : recovery; brook trout; suspended sediment; fish habitat; fish survival; sediment deposition; fish growth; trout; sediment

Anderson, D.W. 198. Factors affecting brown trout reproduction in southeastern Minnesota streams. Minnesota. 216 D-J/F-26-R. pp. 1-36.

Late winter and spring flooding was the major factor affecting reproductive success of brown trout in six southeastern Minnesota streams. Incubation success and fingerling abundance were high in stream sections where fry emergence occurred before spring runoff. Dates of hatch and emergence were determined by spawning dates and water temperature regimes. Fry survival was higher when spring runoff was gradual. Other factors such as redd superimposition, substrate composition, water velocity, hydraulic gradient, intra-redd dissolved oxygen and stream morphometry were not limiting to brown trout recruitment. Siltation, long believed to cause egg and fry suffocation, could not be related to low dissolved oxygen levels or to egg and fry survival. Dissolved oxygen was generally lower after high water periods but the silt content in the redds was not changed. Keywords : brown trout; winter; fry; siltation

Anderson, N.H., Lehmkuhl, D.M. 1968. Catastrophic drift of insects in a woodland stream. Ecology 40:198-206.

The effect of early fall rains on the downstream drift of displacement of insects was studied for two seasons by collecting the entire streamflow at one point through a drift net. Drift rate increased within 24 hr after the start of each rainy period, with the increase approximately proportional to the increase in stream flow. Freshets due to less than 1 in. (2.5 cm) of rain caused a fourfold increase in numbers and fivefold to eightfold increase in biomass. Major components of drift were Ephemeroptera, Plecoptera, Diptera, and terrestrial insects. Plecoptera and Ephemeroptera retained the day-night periodicity of behavioural drift during freshets, but drift of Chironomidae (Diptera) was attributed to catastrophic and constant drift. Mean weight per individual of several taxa was greater at night than day, in freshet than nonfreshet periods, and in drift compared with benthos samples. Though catastrophic drift due to fall freshets displaced large numbers of individuals, the standing crop of the benthos increased during the fall because of hatching. The drift may be beneficial in dispersing aggregations of young larvae. Removal of allochthonous food by increased water flow could be more detrimental to benthos populations than the direct mortality caused by catastrophic drift. Keywords : benthic invertebrate community; invertebrate community changes; disturbance; flushing flows; drift; Young; flows

Anderson, P.G., Chandler, T.C., and Fraikin, C. 1995. Assessment of impacts of pipeline construction on a stream ecosystem in the North Bay shortcut. Environmental Affairs Dept., TransCanada Pipelines and the Ontario Ministry of Natural Resources Prepared by B.A.R. Environmental Inc., Guelph, ON. Guelph, Ontario. pp. 1-84.

Sampling Period: May 1992-Sept. 1993
Study Objectives: The purpose of the study was to examine the impacts of pipeline construction on the ecosystem of a small coldwater stream. The study included an evaluation of changes to the invertebrate and fish communities of the stream, and the changes to the geomorphology which were generated by the installation of a natural gas pipeline in the summer of 1992.

Technical Perspective: A natural gas pipeline expansion program was conducted in the North Bay shortcut during the summer of 1992. Findlay Creek is a small coldwater stream which was crossed using conventional "wet" crossing techniques. The main disturbances to aquatic resources and habitats associated with pipeline construction are the suspension, transport, and subsequent deposition of sediments in streams. The physical components of this study included monitoring of the suspended sediment levels and the stream morphology throughout the construction activities. The biological components of the study included documenting changes to the invertebrate and fish community structure which were generated by pipeline construction.
A 1,067 mm O.D. natural gas pipeline was installed across Findlay Creek in late August 1992. The construction activities in the area consisted of the removal of a beaver dam which was located along the proposed alignment, (upstream of the crossing), the installation of a temporary road crossing and the actual pipeline installation (ie. trench excavation, pipe installation and backfill of the installed pipeline). An intensive sampling programme was initiated prior to, and immediately after each of these construction events. Sampling was also conducted twelve weeks and one full year after pipeline construction was complete to document any recovery in the physical and biological components of the stream ecosystem.

Technical Approach: The study design included eleven transects (2 upstream and 9 downstream). Sampling for invertebrates, fish, and channel cross section profiles were conducted at these locations. Suspended sediment levels were monitored at transect locations during construction activities, and invertebrate drift samples were also collected.
Results: Preconstruction suspended sediment levels were less than 10 mg/L. During the onset of pipeline trench excavation, suspended sediment levels approached 3,000 mg/L. Suspended sediment levels declined during pipeline installation and peaked again during backfill operations. Pipeline construction affected suspended sediment levels throughout the length of the creek section. Concentrations in samples collected 500m downstream of construction were similar to those collected immediately downstream of construction. Suspended sediment concentrations approached background levels within one day following the completion of instream activity.
Pipeline construction, particularly the release of sediment from the removal of the beaver dam, deposited up to 30 cm of sand on the stream bed within 100 m downstream of construction. By twelve weeks post construction, channel morphology recovered in many of the affected areas. Debris dams buffered the downstream transport of sediment and dense bank vegetation inhibited bank erosion. The number of brook trout collected declined following the removal of the beaver dam and following pipeline construction. Reductions in brook trout numbers in areas affected by pipeline construction may have been due to loss of habitat, accumulations of deposited sediments that filled interstitial areas, pools and areas of bank undercutting. Some recovery in fish habitat, that is flushing of accumulated sediment, and in fish numbers was evident by twelve weeks post construction. The September 1993 sampling indicated that, one year after the construction the fish community had fully recovered (ie. returned to pre-construction conditions).
Invertebrate community structure was affected up to 100 m downstream of construction. Episodic invertebrate drift was initiated by the onset of trench excavation and rapid increase in suspended sediment levels. Invertebrate communities in affected areas were reduced in diversity and became dominated by more tolerant taxa. Total recovery of invertebrate communities richness, diversity and balance was documented by one year post disturbance. Changes in the invertebrate community corresponded closely with changes in channel cross section.
Project Implications: Results of this study indicate dramatic increases in suspended sediment levels due to pipeline construction. Exposure to such levels could result in severe ecological stress and even mortality for some organisms (ie sensitive spp. and/or lifestages); however, actual changes to the physical channel parameters and the stream population structure documented in this study suggest that impacts to Findlay Creek were localized, and full recovery was documented in affected areas by one year post construction sampling period. This study concurs with other research investigating the impacts of pipeline construction, in that impacts on the aquatic fauna appear to be short term in duration and non-residual in nature. Keywords : pipeline; sampling

AOSERP, A.O. 1978. The effects of sedimentation on the aquatic biota. Alberta Environment and Environment Canada. Edmonton, AB, Canada. AF 4.9.1. pp. 1-86.

A review of the effects of sedimentation on aquatic biota is presented. The detrimental effects of increased suspended and settled sediments on fish, bottom invertebrates, and primary productivity are documented. It is shown that the upper tolerance level for suspended sediment is between 80-100 mg/L for fish, and as low as 10-15 mg/L for bottom invertebrates. Recovery of the aquatic biota from increased sedimentation is dependent on the severity of sediment additions and the discharge level of the rivers or streams. Recovery from short-term additions of sediment is usually complete within one year.
The use of remote sensing and biomonitoring to locate sources of sedimentation is discussed. Remote sensing can generally be used to identify point sources of sedimentation, define flow patters, choose sampling station, interpret ground survey data, and maintain permanent records of changes in water quality. Biomonitoring can be used to monitor water quality, especially with regard to sedimentation, since alterations in the environment are reflected by the indigenous biota.

The sedimentation characteristics in the Álberta Oil Sands Environmental Research Program (AOSERP) study area are presented and observations are made on the potential for erosion and sediment production. The AOSERP study area is divided into twelve hydrological zones and each zone is classified for erosion potential. The zones having a high erosion potential are (1) lower Ells basin and eastern slopes of Birch Mountains (Zone 1); (2) tributaries immediately north of Fort McMurray (Zone 6); (3) Christina River basin (Zone 7); (4) Hangingstone and Horse River basins (Zone 8); (5) MacKay River basin(Zone 9); (6) Dunkirk River basin (Zone 10); and (7) upper Ells River basin (Zone 11).
Road construction, pipeline construction, general construction (urban and industrial sites), vegetation removal, overburden removal, and pit excavation, tailing ponds, settling ponds, and diversion channels were identified as possible sources of unnatural increases in suspended and settled sediments in the AOSERP study area. The effect of development activities on the hydrological regime and the aquatic biota is shown. The scale of the disturbance and the length of the recovery period are also predicted. Development activities such as road building and pipeline construction will affect a number of the water shed basins; therefore, they were classified as having regional effect and were considered to be of greatest concern. Keywords : sedimentation; benthic invertebrate community; water quality; suspended sediment; recovery; review; sediment; river

Avery, E.L. 1980. Factors influencing reproduction of brown trout above and below a flood water detention dam on Trout Creek, Wisconsin. Department of Natural Resources. Madison, Wisconsin. 106. pp. 1-26.

This study was initiated to determine the influence of a flood water detention dam upon the spawning environment and survival of brown trout eggs in Trout Creek, Wisconsin. Trout redds were counted above and below the detention dam during the fall of 1975, 1976, and 1977. Substrate composition, intragravel temperatures, and intragravel dissolved oxygen, (D.O.) were monitored in selected redds above and below the dam. Embryo development and survival were determined in each stream reach by excavating trout redds throughout the respective egg incubation periods. Stream temperature and discharge in each stream reach were also monitored. Brown trout spawning generally occurred from late October to mid-December and began 1 to 2 weeks earlier below the detention dam than above it. Each year, more than twice as many redds were constructed above the dam than below it. A higher incidence of superimposition and "false" redds occurred below the dam and was attributed to a lack of suitable spawning areas. The composition of redd materials above and below the dam was not significantly different. Sedimentation of trout redds during the respective egg incubation periods could not be demonstrated. Embryo survival to hatching was positively correlated to stream temperatures and to a lesser extent, to intragravel D.O. concentrations above 6 ppm. Stream temperatures and intragravel D.O. concentrations within redds were higher above the dam and resulted in significantly better overall survival to hatching than below the dam. An absence of heavy run-off and flooding during the 3 winters precluded any effect of the detention dam upon embryo survival, but the data provide a basis for future comparisons when winter flooding does occur. Keywords : brown trout; dam; adult fish; reproduction; embryos; sedimentation; winter; trout

B.A.R. Environmental Inc. 1992. Proposal for the assessment of impacts on pipeline construction on a stream community in the Northbay Shortcut. Prepared for Environmental Affairs Department, TransCanada Pipelines. Guelph, Ontario. pp. 1-21.

The following is a proposed study designed to assess the impacts of pipeline construction on the fish and macroinvertebrate communities of a watercourse. The study involves three main tasks. The first is to gather detailed baseline information regarding the stream dynamics, water quality, sediment transport, invertebrate and fish communities of the stream before pipeline construction. Second, the water quality of the stream will be assessed during construction, and finally, we will undertake a detailed assessment of the impacts that construction has imposed on the aquatic ecosystem after instream construction has been completed. Keywords : pipeline; proposal; macroinvertebrates; water quality; sediment; sediment transport

Baddaloo, E.G. 0. An assessment of effects of pipeline activity in streams in the Durham and Northumberland Counties of Ontario.[Unpublished]

An assessment of the effects of pipeline activity was carried out in streams in the Durham and Northumberland counties to observe the effects of construction downstream from the crossing areas.
Four different methods were analyzed during the construction period. These were: Total fluming (Method A); Partial fluming (Method B); Settling Ponds/coffer dams (Method C); No environmental protection (Method D).
Turbidity readings were significantly less when creeks were ditched using method A for minimizing environmental impact, than crossings done with any of the other methods. Heavier siltation deposits were observed downstream when Methods B, C, and D were used in comparison to crossings using method A. In addition, significant decreases in invertebrate populations were also observed where heavier siltation deposits were recorded. The significance of these findings will be discussed in relation to various methods used for stream crossings during pipeline construction. Keywords : pipeline; field study; turbidity

Bain, M.B. 1987. Structured decision making in fisheries management: trout fishing regulations on the Au Sable River, Michigan. North American Journal of Fisheries Management 7:475-81.

A simple decision-making method, based on multiattribute utility analysis, is presented for integrating multiple factors into fishery management plans. The method is described with a procedural outline and demonstrated for management of the brown trout, *Salmo trutta*, fishery on the Au Sable River, Michigan. Fishery research results and other information were used to evaluate 13 forms of fishery regulation on the basis of four attributes: trophy harvest, trout harvest, sublegal catch and regulatory complexity. Three management objectives were used to illustrate how different forms of fishery regulation could be selected, depending on the relative importance associated with each attribute. Results indicate how this decision-making method, and decision analysis in general, can be used to assist managers in developing fishery management plans. Keywords : trout; methods; management; brown trout; river

Barton, B.A. 1977. Short-term effects of highway construction on the limnology of a small stream in southern Ontario. Freshwater Biology 7:99-108.

A limnological investigation was carried out to document the effects of constructing a modern highway across a small stream in southern Ontario. During construction, suspended solids increased to as high as 1390 mg/L but later returned to pre-construction levels of <5mg/L. Similarly, sediment deposition increased ten -fold to 0.61 dry wt/cm^2/day directly below the construction site during stream rechannelization after completion of the culvert. Decreased proportion of organic matter in sediments indicated that they came from the construction site. Sediments were readily removed by spates and apparently settled out in downstream ponds. There was no change in water chemistry. Standing crop of fish was reduced from 24 to 10 kg/ha immediately below the site. This decrease did not occur further downstream and fish populations at the affected site returned to original levels after construction. No change in numbers of riffle macroinvertebrates was observed during or after construction. However, there was a noticeable shift in species composition. Invertebrates present during construction activities may have remained in sheltered areas avoiding sedimentation effects. Evidence from invertebrate sampling in denuded areas around the site strongly suggests that organisms which may have been removed during construction were replaced quickly by drift. Keywords : suspended sediment; biomass changes; invertebrate community changes; highway construction; sediment; sediment deposition; macroinvertebrates; sedimentation; sampling; drift

Berg, L., Northcote, T.G. 1995. Changes in territorial, gill-flaring, and feeding behaviour in juvenile coho salmon (*Oncorhynchus kisutch*) following short-term pulses of suspended sediment. Can J Fish Aquat Sci 42:1410-7.

The territorial, gill-flaring, and feeding behaviour of juvenile coho salmon (*Oncorhynchus kisutch*) in a laboratory stream was disrupted by short-term exposure to suspended sediment pulses. At the higher turbidities tested (30 and 60 nephelometric turbidity units (NTU)), dominance hierarchies broke down, territories were not defended, and gill flaring occurred more frequently. Only after return to lower turbidities (0-20 NTU) was social organization reestablished. The reaction distance of the fish to adult brine shrimp decreased significantly in turbid water (30 and 60 NTU) as did capture success per strike and the percentage of prey ingested. Implications of these behavioural modifications suggest that the fitness of salmonid populations exposed to short-term pulses of suspended sediment may be impaired. Keywords : behaviour; coho; salmon; suspended sediment; turbidity; salmonid; laboratory study

Beschta, R.L., Platts, W.S. 1986. Morphological features of small streams: significance and function. Water Resources Bulletin 22(3):369-79.

Throughout the United States, land managers are becoming increasingly aware of the importance of small streams for a wide range of resource benefits. Where channel morphology is modified or structural features are added, stream dynamics and energy dissipation need to be considered. Unit stream power, defined here as the time-rate loss of potential energy per unit mass of water, can be reduced by adding stream obstructions, increasing channel sinuosity, or increasing flow resistance with large roughness elements such as woody root systems, logs, boulders, or bedrock. Notable morphological features of small stream are pools, riffles, bed material, and channel banks. Pools, which vary in size shape and causative factors are important rearing habitat for fish. Riffles represent storage locations for bed material and are generally utilized for spawning. The particle sizes and distributions of bed material influence channel characteristics, bedload transport, food supplies for fish, spawning conditions, cover and rearing habitat. Riparian vegetation helps stabilize channel banks and contributes in various ways to fish productivity. Understanding each stream feature individually and in relation to all others is essential for proper stream management. Although engineered structures for modifying habitat may alter stream characteristics, channel morphology must ultimately be matched to the hydraulic, geologic, and (especially) vegetative constraints of a particular location. Keywords : stream morphology; fish habitat; flows; management

Bhowmik, N.G. and Clark, G.R. 1994. Sedimentation and in-stream sediment management. 1993; National Biological Survey, Environmental Management Technical Center; Onalaska, Wisconsin. 47-61.

Erosion and sedimentation are natural processes that cannot be stopped or eliminated entirely. Both processes have been accelerated by human intervention such as alteration of stream courses, construction of dams, changes in flow regime, constriction on and alterations of floodplains, and drastic changes in land use patterns. Consequently, erosion and sedimentation have a significant impact on the Illinois River, including its backwater and bottomland lakes. According to the Illinois State Water Plan Task Force report published in 1984, erosion and sedimentation is the major critical issue in water resources facing the state of Illinois. The Illinois River basin, which drains about 44 percent of the Sate obviously contributes significantly to this water resources problem.

Recent research on erosion and sedimentation in the Illinois River has shown that about 13.8 million tons of sediment is delivered to the Illinois River valley annually. Out of this total sediment, 8.2 million tons are trapped in the valley, and the remainder is delivered to the Mississippi River. Most backwater lakes along the Illinois River have lost about 72 percent of their original capacity, and sediment has already filled in some of these lakes. This excessive rate of sedimentation has reduced the ecological and recreational value of most lakes along the river, making sedimentation the most difficult and still unmanaged problem facing the Illinois

River valley. Research recently conducted by the Illinois State Water Survey has also shown that the Peoria and LaGrange Pools are the two major pools in which most of the sediments are produced and deposited. These are also the major areas in which most of the backwater lakes are located. The river changes significantly to a flatter gradient within Peoria and LaGrange Pools, forcing the deposition of sediments at a much higher rate. By 1985, Peoria Lake had lost about 68 percent of its original capacity. The US Army Corps of Engineers has been dredging the Illinois River at several locations to maintain adequate navigation depth with the Alton Pool requiring the most dredging.
The management of soil erosion and sedimentation in the Illinois River basin will be one of the major environmental issues in Illinois for years to come. Consequently, a comprehensive management plan needs to include two major components: erosion control and sediment management. The erosion control component includes developing programs to control watershed erosion., streambank erosion, and bluff erosion. The sediment management component will have to deal with four major issues: backwater sedimentation, main channel sedimentation, sediment removal at selected reaches, and sediment quality. Keywords : sedimentation; instream sediment; monitoring; erosion; dam; lake

Bianchi, D.R. 1963. The effects of sedimentation on egg survival of rainbow trout and cutthroat trout. Montana State College; 1-34 pp.

A study was conducted on Bluewater Creek during April, May and June 1962, to determine the effects of various amounts of suspended sediment on egg survival of rainbow and cutthroat trout. Water temperature, stream discharge and suspended sediment data were collected. A particle size analysis of the original material placed in the redds was compared with materials removed after the egg incubation periods. The apparent velocity and dissolved oxygen concentration of the ground water within the redds were determined by means of a Mark VI groundwater standpipe. When sediment settled into a redd the permeability of the gravel and consequently the apparent velocity of the ground water was decreased. A total of 60 or more tons of suspended sediment passed the redds before apparent velocity showed a perceptible decrease.. Apparent velocity decreased as the total suspended sediment load increased beyond this level. Redds exposed to 290 or more tons of suspended sediment had the highest egg mortality. Redds with the lowest suspended sediment load, highest apparent velocity and highest dissolved oxygen concentration had the highest egg survival. Multiple regression analysis of the results showed apparent velocity, dissolved oxygen, suspended sediment load and stream discharge were the important factors determining rainbow and cutthroat trout egg survival. Keywords : sedimentation; rainbow trout; cutthroat trout; fish eggs; suspended sediment

Bianchi, D.R. 1963. Stream sediment investigation. Montana Fish and Game. Montana. F-20-R-8. pp. 1-9.

Average monthly temperatures on Bluewater Creek varied from a maximum of 76F to a minimum of 34F. The extremes occurred in the lower two stations. Monthly average flows varied from a low of 2 cfs to a high of 75 cfs. The extreme flows in the lower two stations is due to irrigation diversions and returns and spring runoff. Monthly average sediment loads varied from 0.3 tons/day to a high of 358 tons/day. The high sediments were caused by spring runoff and irrigation returns. The highest sediments all occurred at station 5. Grayling egg mortalities varied from 66% to 100% from station 1 and station 4. Longnose sucker egg mortality varied 0.5% to 7% from station 2 to station 5. The trout population declined progressively from over 95% trout in station 1 to less than 1% in station 5. Keywords : grayling; trout; sediment

Bisson, P.A., Bilby, R.E. 1982. Avoidance of suspended sediment by juvenile coho salmon. North American Journal of Fisheries Management 4:371-4.

Some water quality standards established by the states permit only minor increases in suspended sediment when background turbidity is low, allow greater absolute increases as background levels rise, and do not consider acclimation of stream biota to high turbidity.

Juvenile coho salmon (*Oncorhynchus kisutch*) were subjected to experimentally elevated concentrations of suspended sediment and did not avoid moderate turbidity increases when background levels were low, but exhibited significant avoidance when turbidity exceeded a threshold that was relatively high (>70 NTU) and was varied according to previous suspended sediment exposure. Keywords : suspended sediment; coho; water quality; turbidity; juvenile fish; behaviour; laboratory study

Bjornn, T.C., Brusven, M.A., Molnau, M.P., Milligan, J.H., Klamt, R.A., Chacho, E., and Schaye, C. 1977. Transport of granitic sediment in streams and its effects on insects and fish. College of Forestry, Wildlife and Range Sciences, University of Idaho. 17. pp. 1-53.

We assessed the transport of granitic bedload sediment (<6.35 mm diameter) in streams flowing through central Idaho mountain valleys and the effects of the sediment on juvenile salmonids and aquatic insects. We measured bedload sediment transported in the streams during the spring snowmelt runoff and the summer low-flow periods for 2 years, to test the applicability of the Meyer-Peter, Muller equation for estimating transport. In both years the streams transported all the sediment available, including that under the armor layer of the stream bottom in the first year. The modified Meyer-Peter, Muller equation proved accurate in estimating the transport capacity of such streams using measurements of slope, hydraulic radius and mean diameter of streambed material.
In artificial stream channels, benthic insect density in fully sedimented riffles (>2/3 cobble imbeddedness) was one-half than in unsedimented riffles, but the abundance of drifting insects in the sedimented channels was not significantly smaller. In a natural stream riffle, benthic insects were 1.5 times more abundant in a plot cleaned of sediment, with mayflies and stoneflies 4 and 8 times more abundant, respectively. Riffle beetles (Elmidae) were more abundant in the uncleaned plot.
During both summer and winter, fewer fish remained in the artificial stream channels where sediment was added to the pools. The interstices between the large rocks in the pools provided essential cover necessary to maintain large densities of fish. Fish in sedimented channels exhibited hierarchical behaviour, while those in unsedimented channels were territorial in behaviour. In small natural pools (100 to 200 m^2), a loss in pool volume or in area deeper than 0.3 m from additions of sediment resulted in a proportional decrease in fish numbers. We did not, however, find significant correlations between riffle sedimentation and fish density in the two natural streams we studied. Fish abundance was significantly correlated with insect drift abundance in one stream, but not in the other. The amounts of sediment in the two streams studied did not have an obvious adverse effect on the abundance of fish or the insect drift on which they feed. Keywords : salmonids; sediment

Branson, B.A., Batch, D.L. 1972. Effects of strip mining on small-stream fishes in east-central Kentucky. Proc Biol Soc Wash 84(59):507-18.

Summary and Conclusions: 1. A 17-month study of the effects of strip mining on the fish faunas of two small creeks in east-central Kentucky demonstrated a low-level of acid-mine water effluence but a high level of siltation and turbidity originating from intensive erosion of the spoil banks.
2. Fishes are progressively eliminated from headwaters downstream, or are forced to emigrate downgrade.
3. Benthic food organisms were reduced in numbers and kinds by at least 90 percent.
4. Reproduction in darters and minnows was curtailed by siltation, either by prevention of mating or by kill-off of fry and eggs.
5. *Semotilus atromaculatus* is resistant to silt and turbidity pollution. This seems to be correlated with the fish's feeding habits, i.e., since the diet consists largely of terrestrial-type insects or aquatic ones taken from the surface, the fish is able to subsist following siltation of the bottom.
Although silt-correlated removal of fish life, by smothering the benthos, by interfering with reproduction or by direct effects, may not be as dramatic as that associated with acid-mine water kills, it is, nevertheless, an important disruptive force which is occurring on a large scale in

Appalachia and elsewhere. Fishes are eliminated. When rare or endangered species are involved, as *Etheostoma saggita* is here, the results could and probably will be extirpation. Keywords : siltation; turbidity; erosion

Brown, A.V. and Lyttle, M.M. 1992. Impacts of gravel mining on Ozark stream ecosystems. Arkansas Cooperative Fish and Wildlife Research Unit, Dept. of Biological Sciences, University of Arkansas. Fayetteville, Arkansas. pp. 1-122.

Removal of gravel from stream channels is practiced all over the world and is particularly common in Ozark streams of Arkansas. This study was designed to assess the impact of gravel mining on Ozark stream ecosystems with a special focus on game fish responses. Crooked Creek and the Illinois and Kings Rivers were chosen to represent streams of the region. One major site in each was selected for intense study of physical habitats, fish, invertebrates, biofilm, benthic particulates organic matter (BPOM) and siltation rates. Eight other (extensive) sites were surveyed for riffle-dwelling fish, and ten for invertebrates and BPOM. A manipulative experiment was designed to learn more about effects of disturbed patch size on recolonization dynamics of invertebrates and the time required to re-establish normal levels of BPOM on denuded patches. Physical habitat was studied using line transects to assess channel form and to record percent occurrences of several categories of fish and invertebrate habitat types. Fish estimates were obtained by sampling riffles and pools using electroshocking equipment and hand-held nets within areas limited by block nets. Invertebrates and BPOM were sampled using a vacuum benthos sampler. Biofilms (periphyton, etc,) were collected from an area of 15 cm^2 from the upper surfaces of large pebbles (gravel between 25-64 mm) using a wire loop, toothbrush and wash bottle. Sedimentation rates were assessed using Petri dishes filled with a layer of uniform artificial substrate (marbles) placed on the stream bed for known periods of several hours. The results indicate that gravel mining significantly degrades the quality of Ozark stream ecosystems and that effects of this are detectable even against the background characteristics developed by a long history of anthropogenic disturbances in these streams. Stream channel form was altered resulting in increased sedimentation rates and turbidity, shallower and larger pools downstream, and fewer downstream riffles. Resultant extensive, shallow flats favored large numbers of a few small fish species (eg Campostoma anonalum) Removal of riparian vegetation, large woody debris, and large substrate particles resulted in smaller invertebrates and smaller fish at disturbed and downstream sites. Patterns of invertebrate recolonization and distribution of silt-sensitive fish and invertebrates suggests that silt free substrate is a valuable resource for these Ozark stream biota. Alteration of physical habitat appears to more significantly influence the biotic community than limitation imposed on other resources ((such as food supply) but these probably interact synergistically to limit some populations.. Management recommendation focus on protection and restoration of physical habitats degraded by removal of gravel and associated activities. Keywords : gravel mining; suspended sediment; behaviour; fish habitat; benthic invertebrate community; siltation; sampling; sedimentation; disturbance; turbidity; organic matter; river; management; mining

Brown, R.S. 1994. Spawning and overwintering movements and habitat use by cutthroat trout (*Oncorhynchus clarki*) in the Ram River, Alberta. University of Alberta; 1-126 pp.

Spawning movements of cutthroat trout were evaluated using radiotelemetry in a montane river and a headwater tributary. The movements of 23 fish were monitored in spring 1991 and 1992. Fish moved upstream and downstream to spawning areas. The pre- and post-spawning movements made by fish that spawned in tributaries were longer than those of fish that spawned in the mainstem or sidechannels of the main river or headwater stream. Fish moved frequently during spawning, but stayed within a small area that included several spawning sites. Trout also moved both up and downstream after spawning. In both drainages, after fish finished their post-spawning movements, they stayed within a 400 m area until observations were ended. In both pre- and post-spawning movements I found two patterns, one of fish migrating to spawning locations in tributaries (migratory), and one of fish spawning in the river or stream where they reside all year (resident).

Fall and winter movement and habitat use by trout were evaluated using radiotelemetry in low, mid and high altitudes of a river system to evaluate what habitat shifts occurred when fish moved from summer feeding areas to overwintering areas. The movements of 45 fish were monitored throughout the fall and winter of 1991 and 1992. Cutthroat trout exhibited a two-stage shift in habitat use from summer to winter. In August and early September, trout used a wide range of habitats including pools, riffles and runs but in the last half of September, trout left shallower habitats and aggregated in large pools which had abundant cover. When anchor ice excluded fish from these pools in mid-November, trout moved to overwintering areas less likely to be influenced by frazil and anchor ice. These overwintering areas included deep pools, with ice cover, or areas where water temperatures were higher than the rest of the stream due to springs or upwelling warm water. Use and preference of macrohabitat, water depth, cover and substrate changed seasonally. Due to decreases in water discharge and exclusion of habitat by anchor ice, trout were forced into small amounts of suitable habitat leading to large aggregations. Keywords : cutthroat trout; trout; Alberta; fish habitat; winter; river

Brunskill, G.J. 1974. Sediment yield from tributaries to the Mackenzie River, N.W.T., Canada. Miami Beach, Florida. 1025-1026.

Rates of transport of suspended sediments from selected tributaries of the Mackenzie River varied from 0.017 metric tons/km^2/yr (low relief watersheds containing many lakes) to over 100 mt/km^2/yr (high relief watersheds draining the Mackenzie Mountains). The magnitudes of discharge and relief appear to be controlling factors on sediment yield in this region. Approximately 160 x 10^6 metric tons of suspended sediment are delivered to the Mackenzie Delta annually by the Mackenzie and Peel Rivers. The clay-sized sediments are largely illite, chlorite and amorphous clays, with small proportions of kaolinite and montmorillionite. Cation exchange capacities are low, ranging from 8 to 15 meq/100 g dry weight. Keywords : sediment; suspended sediment; lake

Buck, D.H. 1956. Effects of turbidity on fish and fishing. Trans N Am Wildlife Conf 21:249-61.

Summary:
1. At the end of two growing seasons, the average total weight of fish in clear farm ponds was approximately 1.7 times greater than in ponds of intermediate turbidity and approximately 5.5 times greater than in muddy ponds. Differences were due to faster growths by all species and to greater reproduction in clear ponds, particularly by bluegills and redear sunfish. 2. Of the 3 species used in farm ponds, largemouth bass were most affected by turbidity in both growth and reproduction. Redear sunfish appeared less retarded in growth than did bluegills during the first year, but the two sunfishes appeared equally restricted in both growth and reproduction during the second year. 3. Average volume of net plankton in surface waters of clear ponds during the 1954 growing season was 8 times greater than in ponds having intermediate turbidities; 12.8 times greater than in most turbid ponds. 4. In hatchery ponds, high turbidities reduced growth and total yield of bass and bluegills but increased channel catfish production. Individual catfish grew faster in clear ponds, but muddy ponds yielded much greater total weights of channel catfish than either clear or intermediate ponds. This was due to a higher rate of survival. 5. The presence of carp caused reduced growth of bass and bluegills but ponds with carp produced greater yields of channel catfish and young bluegills than ponds without carp. 6. Sodium silicate proved effective in sustaining hatchery pond turbidities when introduced in suspension with finely divided clay. 7. Growths of largemouth bass, white crappies, and channel catfish were much slower in turbid Heyburn than in clear Upper Spavinaw reservoir, as well as in all other Oklahoma reservoirs of similar age and size. 8. Growth of flathead catfish was most favorable of any Heyburn species studied, and it is apparently well adapted to the turbid environment. 9. The number of species, as well as individuals, of all scaled fishes was low in turbid Heyburn reservoir, apparently due to a lack of successful reproduction in turbid waters and also to competition from the better adapted catfishes. 10. Extreme scarcity of forage species, particularly gizzard shad, limited growth and development of bass, crappies, and other carnivorous species at Heyburn. 11. Heyburn largemouth bass and white crappie populations

exhibited unusual dominance by older individuals. This seemed to be due to successively smaller year classes as a result of increasing turbidities. 12. In 1954, the average volume of plankton in surface waters was 13.8 times greater in Upper Spavinaw than in Heyburn, and average volume from the 60-foot depth at the clear reservoir was greater than the combined total from surface, 15-foot depth, and 30-foot depth in the muddy reservoir. This contrast was less marked in 1955, possibly due to somewhat lower average turbidities at Heyburn. 13. The clear reservoir attracted more anglers, yielded greater returns per unit of fishing effort, as well as more desirable species, and was immeasurably more appealing in the aesthetic sense. Keyword : turbidity

Burns, J.W. 1970. Spawning bed sedimentation studies in northern California streams. Calif Fish and Game 56(4):253-70.

Changes in the size composition of spawning bed materials in six coastal streams were monitored for 3 years to determine the effects of logging on the habitat of silver salmon (*Oncorhynchus kisutch*) and trout (*Salmo gairdneri* and *S. clarkii*). Four test streams were sampled before, during and after logging. Two streams in unlogged watersheds and the undisturbed upstream section of one test stream served as controls. A variety of stream types in second-growth and old-growth forests was selected for observation. Spawning bed composition in the four test streams changed after logging, roughly in proportion to the amount of streambank disturbance. The heaviest sedimentation occurred when bulldozers operated in narrow stream channels having pebble bottoms. In a larger stream with a cobble and boulder bottom, bulldozer operations in the channel did not increase sedimentation greatly. Sustained logging and road construction kept sediment levels high in one stream for several years. Sedimentation was greatest during periods of road construction near streams and removal of debris from streams, confirming the need for special measures to minimize erosion during such operations. Control streams changed little in spawning bed composition during the 3 years. Keywords : sedimentation; logging; salmon; disturbance; trout; sediment; erosion

Burns, J.W. 1972. Some effects of logging and associated road construction on Northern California streams. Transactions of the American Fisheries Society 101(1):1-17.

The effects of logging and associated road construction on four California trout and salmon streams were investigated from 1966 through 1969. This study included measurements of streambed sedimentation, water quality, fish food abundance, and stream nursery capacity. Logging was found to be compatible with anadromous fish production when adequate attention was given to stream protection and channel clearance. The carrying capacities for juvenile salmonids of some stream sections were increased when high temperatures, low dissolved oxygen concentrations and adverse sedimentation did not accompany the logging. Extensive use of bulldozers on steep slopes for road building and in stream channels during debris removal caused excessive streambed sedimentation in narrow streams. Sustained logging prolonged adverse conditions in one stream and delayed stream recovery. Other aspects of logging on anadromous fish production on the Pacific Coast are discussed. Keywords : water quality; road construction; salmonid production; sedimentation; logging; trout; salmon; salmonids; recovery

Cairns, J., Jr. 1968. Suspended solids standards for the protection of aquatic organisms.[Unpublished]

In summary, a properly functioning aquatic community is essential to the ecosystem of which it is a part. Furthermore, the ability of such an aquatic community to digest various wastes is a definite economic asset which should be protected. It is not enough that the community referred to barely survives. Rather it must be healthy and function vigorously. We must therefore apply the concept of "quality control" to the most fundamental of nature's productions, viz., to the ecosystems which support life. But when it comes to the matter of control over suspended solids, we cannot merely set arbitrary standards of fixed concentrations for all systems; rather we should aim to keep within the tolerances for each system and region. Obviously this will require continuous surveillance of all the conditions which seriously affect the functioning of the aquatic communities concerned if the most beneficial use of each drainage basin is to become possible. The increased costs of such surveillance should be offset by the more intensive use and greater productivity of the better managed systems. Keywords : suspended sediment; macroinvertebrates

Calkins, D.J. 1989. Winter habitats of Atlantic salmon, brook trout, brown trout, and rainbow trout: a literature review. US Army Cold Regions Research and Engineering Laboratory. Hanover, N.H. 89-34. pp. 1-9.

A review of winter habitat studies in ice-covered streams for four species of salmonid (Atlantic salmon, brook trout, brown trout, and rainbow trout) provided some general information on substrate conditions and focal point velocities and depths. All species of fry are found at depths of less than 40 cm and at velocities of 10 cm/s or less; juveniles of all species are found at velocities of less than 15 cm/s. A lack of continuous physical, chemical, and biological measurements throughout the ice-covered season was a common deficiency of the studies reviewed. The interaction of ice cover with other physical processes in the stream was rarely addressed. Keywords : winter; salmon; brook trout; trout; brown trout; rainbow trout; review; salmonid; fry

Cashman, M.A. 1988. A compilation of sediment survey report series abstracts to 1987. Sediment Survey Section, Water Survey of Canada, Water Resources Branch, Environment Canada. IWL-HQ-WRB-SS-87-9.

Keywords : sediment; bibliography

Chapman, D.W. 1962. Effects of logging upon fish resources of the west coast. Journal of Forestry (August):533-7.

No abstract. Paper covers issues surrounding effects of logging on fish resources (logging and streamflow, water temperature, water quality, stream energy sources, barriers and fish movement and the need for research and management). Keywords : logging; water quality; British Columbia

Chapman, D.W., Weitkamp, D.E., Welsh, T.L., Dell, M.B., and Schadt, T.H. 1986. Effects of river flow on the distribution of chinook salmon redds. Transactions of the American Fisheries Society 115:537-47.

The distribution of redds of chinook salmon *Oncorhynchus tshawytscha* was evaluated in October-November 1978-1983 on Vernita Bar, about 6.5 km downstream from Priest Rapids Dam on the Columbia River. Minimum flows of 1,020 m3/s (license minimum set by the Federal Energy Regulatory Commission) and 1, 416 m3/s were maintained in six alternating years, but flows each day fluctuated widely above the minima because of power production; part of the spawning area was exposed for several hours on most days. We detected no effect on minimum flow regime on redd size. Chinook salmon spawned at depths as great as 7 m below the water surface as measured at a discharge of 1,020 m3/s. The highest redds occurred near the water's edge at the 1, 982 m3/s flow elevation. Vertical range of spawning use was 8.5 m. Water velocities at 23 cm above the substrate (facing velocity) on the area used for spawning varied greatly with river discharge, but usually exceeded 0.67 m/s. Chinook salmon females completed redds in areas that were not covered by water for up to 8 h/d and on other areas that had velocities near 2 m/s for part of each day. Chinook salmon spawned at Vernita Bar in areas with high fractions of cobble and low percentages of fines. They began spawning in early October below the 1, 020 m3/s flow elevation and increasingly used the area between the 1,020- and 1,982 m3/s flow elevations until spawning ended about the third week of November. The percentage of redds above the 1,020 m3/s flow elevation correlated strongly with mean daily discharge during late October and early November over 7 years. We found no evidence that the minimum daily flow affected redd distribution in any way. Egg retention in ovaries of postspawning females, one measure of spawning success, was minimal in all years, as was the proportion of excavated redds that contained no embryos. Daily flow fluctuations from minima to 3,400-4,250 m3/s did not prevent females from completing redds. We concluded that minimum flows of 1,020 m3/s for up to 8 h/d do not determine availability of spawning habitat and that use of spawning areas above the 1, 020 m3/s flow elevation could be reduced by managing the river discharge with storage manipulation upstream to provide lower mean daily flows, thus easing minimum flow restrictions during posthatch incubation and emergence. Keywords : salmon; dam; embryos; fish eggs; flows; river

Churchland, L.M. and Mah, F.T.S. 199. Potential sources of error in measurement of suspended sediments for water quality programs. Inland Waters Directorate, Pacific and Yukon Region. Vancouver, B.C. pp. 1-16.

The non-filterable residue method and the method for total concentration of suspended sediments are commonly considered to be equivalent. An examination of data collected on the Stikine River in northwestem British Columbia and Alaska showed a large difference between the two techniques. Comparisons between a peristaltic pump and USP63 sampler did not support the hypothesis that different sampling methods were responsible for this discrepancy. The two analytical methods were compared using water from rivers with varying concentrations of suspended sediment. The non-filterable residue method, in which an aliquot is used, underestimated the suspended sediment content by 46-89% when compared with the total concentration method, in which the whole sample is used. This difference was attributed to the difficulty in obtaining and accurate subsample from water samples containing a high proportion of sediments in the coarse size fraction. It was concluded that the whole water sample should be used for the measurement of non-filterable residue, which would then give an accurate estimate of total suspended sediment concentration. This same problem will potentially bias the results of chemical tests such as the total metals' measurement, in which a subsample is used for analysis. Keywords : suspended sediment; water quality; monitoring; methods; sampling; sediment concentrations

Ciborowski, J.J.H., Pointing, P.J., and Corkum, L.D. 1977. The effect of current velocity and sediment on the drift of the mayfly *Ephemerella subvaria* Mcdunnough. Freshwater Biology 7:567-72.

Experiments conducted in an artificial stream showed that significantly more nymphs drifted from an inorganic substrate at a mean current velocity of 28 cm/s than at 18.5 cm/s. Drift density, however, was not affected. Disproportionately large numbers of nymphs drifted while current velocities were being increased from 18.5 to 28 cm/s.
Both drift numbers and drift density were greater in turbid water, after the addition of large amounts of inorganic sediment, than under clear-flowing conditions during dark periods but not in the light. The interaction of increasing current velocity and sediment levels resulted in a significantly greater number of drifting nymphs under lighted conditions.
Minor spates which do not seriously disturb the stream bed may initiate significant increases in macroinvertebrate drift. Keywords : sediment; drift

Cooper, A.C. 1965. The effect of transported stream sediments on the survival of sockeye and pink salmon eggs and alevin. Intemational Pacific Salmon Fisheries Commission. New Westminster, B.C. 18. pp. 1-72.

Summary: Available data on the suspended sediment concentration in streams used by Pacific salmon shows that these streams normally carry relatively small amounts of suspended sediment during the spawning and incubation period of salmon. Methods of determining size of bed load materials that may be expected on a given portion of stream bed are presented. Reference is made to earlier work which shows how such layers of bed material can reduce the survival of salmon eggs by reducing flow of water through the gravel. The flow of water through a gravel bed is determined by the characteristics of the gravel and the imposed hydraulic gradient. The permeability of gravel is expressed in terms of particle size grading, porosity and particle shape, and a formula is developed relating permeability and flow. It is shown that fine sediment has a large influence on the permeability of gravel.

The effect of a flow of silty water over a gravel bed is measured, and it is shown that deposition of silt occurs within the gravel even though velocities are too high to permit deposition on the gravel surface. This deposition reduced the permeability of the gravel. Formulae are developed which relate time and silt size and concentration to the effect on a given gravel. The results show that the least damaging effect on salmon eggs would occur with a very coarse gravel, and the damaging effect on salmon eggs would occur with a very coarse gravel, and the most severe effect would occur with fine gravel such as found in typical spawning beds. The prevention of deposition of sediment upon or within a spawning bed is shown to be essential to high survival rate of salmon eggs to emergent fry.

The effect of suspended sediment on an upwelling type of artificial spawning or egg incubation bed is also examined. It is shown that permeability of these beds can be reduced by sediments in the water. This may be prevented by providing settling basins to clarify the incoming water. These basins should be capable of removing all sediments which could settle in the distribution system and also all sediment with a settling velocity less than the apparent upwelling velocity.

Keywords : salmon; sediment transport; fish eggs; fry; silt effects on habitat; sediment deposition; suspended sediment; sediment concentrations; methods; sediment

Cooper, R.H. and Charbonneau, A.L. 1972. Sedimentation study AGTL pipeline crossing on the Athabasca River: Interim Report. T. Blench and Associates Ltd., Consulting Hydraulic Engineers, for Gas Arctic Systems. Edmonton Alberta. TN880.5 B61. pp. 1-22.

Keywords : sedimentation; pipeline; winter

Cordone, A.J., Kelley, D.W. 1961. The influences of inorganic sediment on the aquatic life of streams. California Fish and Game 47:189-228.

Summary: Almost all of the investigations we have reviewed on the effects of sediment on aquatic life of flowing waters have been done on streams inhabited by trout and salmon. Only historical changes and the work of Ellis (1931a) are available to evaluate the warm waters. There is abundant evidence that sediment is detrimental to aquatic life of salmon and trout stream. The adult fishes themselves can apparently stand normal high concentrations without harm, but deposition of sediments on the bottom of the stream will reduce the survival of eggs and alevins, reduce aquatic insect fauna, and destroy needed shelter. There can scarcely be any doubt that prolonged turbidity of any great degree is also harmful. The question, "How much sediment is harmful?" has not yet been answered since most workers have failed to measure the amounts of sediment. The Aquatic Life Advisory Committee of the Ohio River Valley Water Sanitation Commission (1956) reviewed the problem and reached the following conclusion:

"...only a small amount of sand or silt shifting in and around the gravel of the bottom eliminates much of the area suitable for the attachment or hiding of the aquatic insects and drastically reduces the total production of these forms. Small amounts of sand, not discernible by casual inspection but evident only on close examination of the bottom materials, can bring about significant changes. "To the best of our knowledge, adequate data are not available on the amounts of inorganic materials which can be added to a stream without significant harm to its productivity capacity..."

This certainly agrees with our own observations. Field investigations with electric sampling gear in the Sierra Nevada over the past years have led us to develop the maxim, "Clean stream bottoms mean good trout populations." By "clean" we mean lacking much sand. Many of the sediment problems reported in the literature are the result of large-scale discharges of sediment from gravel washing or mining operations. These are often spectacular but probably less important than the gradual deposition being caused by erosion. The increasing activity of man on our mountain watersheds in California is resulting in obviously increased erosion and sediment deposition. Our failure to recognize that even small amounts of sediment may be harmful may well result in gradual destruction of the majority of our streams, while we work feverishly to solve more obvious and spectacular problems. We have been impressed by two facts. First, there has been sufficient work done to establish the fact that sediment is harmful to trout and salmon in streams; the only references found to be contrary (Ward 1938a and 1938b) have been adequately criticized. Second, our experience in the Sierra Nevada indicates that the bulk of the damage there is unnecessary. It can be prevented with known land use methods, often with little or no additional expense. Much of it is the result of carelessness. More than anything else we need to develop a philosophy of land husbandry that will avoid the creation of untreated and running sores across the earth's surface. Man must acquire a responsibility for future generations that matches the power he has gained through the development of heavy machinery. Our observations in the field and our review of the existing literature leads us to the unshakable conclusion that unless this can be done, many of our trout streams will be destroyed by the deposition of sediment. Keywords : fish habitat; fish survival; sediment concentrations; silt effects on habitat; settleable solids; trout; salmon; turbidity; sediment; river

Crabtree, A.F., Bassett, C.E., and Fisher, L.E. 1978. The impacts of pipeline construction on stream and wetland environments. Michigan Public Service Commission, Department of Commerce. Lansing, Michigan. pp. 1-115 + app.

Crouse, M.R., Callahan, C.A., Malueg, K.W., and Dominguez, S.E. 1995. Effects of fine sediments on the growth of juvenile coho salmon in laboratory streams. Transactions of the American Fisheries Society 110:281-6.

Juvenile coho salmon (*Oncorhynchus kisutch*) production (tissue elaboration) was monitored in 12 laboratory streams under six replicate treatment levels of fine sedimentation. Increasing sedimentation suppressed fish production. Our data confirm that habitats of salmonid juveniles, as well as spawning areas, should be protected against fine sediments. Substrate Score, a visual technique for evaluating stream substrate quality, correlated closely with both the geometric mean particles size of the substrate and fish production, and can be easily applied in the field. Keywords : sedimentation; salmonid; juvenile fish; laboratory study; fish growth

Cuker, B.E. 1987. Field experiment on the influences of suspended clay and P on the plankton of a small lake. Limnol Oceanogr 32(4):840-7.

Independent and interactive effects of phophorus and clay loading on pelagic community organization and productivity were tested in a small piedmont lake in North Carolina. Twelve limnocorrals (2 m diam, 3 m deep) were used for field manipulations Treatments (in triplicate) were unaltered controls, P loading of 3.3 $mg/m^2/say$, kaolinite clay loading of 100 $g/m^2/day$ and combined clay and P loading. Fertilization with P significantly increased rates of turbidity reduction in comparison to controls (Secchi depth increasing at 7.2 vs. 5.8 cm/day) and also significantly lowered sustained turbidity in treatments under clay loading. Clay loading reduced net community productivity (NCP), Chl a concentrations, and algal cell numbers. Suspended clay also caused a shift in algal community composition; *Trachelomonas superba* and other flagellates replaced the otherwise dominant blue-green *Spirulina major*. Fertilization with P increased NCP and algal densities and favoured development of the N_2 -fixing blue-green algae *Anabaena spiroides* and *Anabaena circinalis*. Combined P and clay loading produced intermediate values of turbidity, NCP and Chl a. Simultaneous clay loading eliminated the influence of P fertilization on algal community structure, yielding an assemblage dominated by flagellates. Clay turbidity also caused a shallowing in the daytime distribution of zooplankton. Keywords : lake; turbidity; zooplankton

Culp, J.M., Davies, R.W. 1982. Analysis of longitudinal zonation and the river continuum concept in the Oldman-South Saskatchewan River system. Can J Fish Aquat Sci 39:1258-66.

During the summer-fall periods, the benthic macroinvertebrate communities of the Oldman-South Saskatchewan River system demonstrated a longitudinal zonation related to the subalpine forest, fescue prairie, and mixed prairie terrestrial ecosystems through which it flows. This zonation was primarily attributable to significant downstream increases in periphyton biomass, plant nutrients, and water temperature. Zonation was reduced in the late winter-spring periods and absent in May , during spring runoff. Longitudinal trends in macroinvertebrate functional feeding groups generally followed the predictions of the river continuum concept, with trophic composition apparently more strongly affected by autotrophic processes in the summer, and heterotrophic processes in winter. By combining the river continuum concept with a watershed classification system based on geology, climate, soil type and terrestrial vegetation, we suggest that biological comparisons of longitudinal zonation are enhanced. Keywords : winter; river continuum concept; longitudinal zonation; macroinvertebrates

Cunjak, R.A. 1988. Physiological consequences of overwintering in streams: the cost of acclimatization? Can J Fish Aquat Sci 45:443-52.

Proximate body composition and hematological parameters of wild brook and brown trout from five sites were monitored over three winters. For both species and for immature and mature fish, lipid levels were lowest (and water content highest) in winter. Lipid levels were most rapidly depleted (to between 2 and 4% wet weight) in early winter (November-December). Brown trout and immature brook trout appeared to suffer a second period of depletion in late winter (February-March) in contrast with spent brook trout. Protein and ash components were relatively stable between dates. Serum protein levels varied greatly but generally indicated a decline in early winter from high summer (August) values prior to increasing in May. Such trends were most obvious during the winter of 1983-84, the harshest of the three winters of study. In the winter, serum glucose concentrations peaked in November. These physiological relationships corroborate earlier findings that early winter is a stressful period of acclimatization to rapidly changing environmental conditions. Even the relatively stable discharge and temperature regimes of spring-fed tributaries are insufficient to offset the effects of an early winter. Keywords : winter; brook trout; fish survival; adult fish; immature fish

Cunjak, R.A. 1995. Behaviour and microhabitat of young Atlantic salmon (*Salmo salar*) during winter. Can J Fish Aquat Sci 45:2156-60.

Underwater observations at two sites along a small Nova Scotian river were carried out between December and April (water temp. range = 0.5-7.0C) to describe the winter microhabitat of young Atlantic salmon. Salmon (5-15 cm fork length) were consistently found hiding beneath rocks (mean diameter = 16.8-23.0 cm) in riffle-run habitats where mean water depths were 40.9-48.9 cm and mean water velocities were 38.7-45.7 cm/s. Many of the salmon were found overwintering within redd excavations. "Home stones" were distributed closer to midstream than to river banks and where sediment compaction was minimal. Monthly collections of fish (ages 1 and 2) indicated that feeding continued over winter. The data suggest a nocturnal activity pattern and photonegative response by young salmon during winter. Keywords : behaviour; salmon; winter

Cunjak, R.A. [In Press]Winter habitat of selected stream fishes and potential impacts from land-use activity. Can J Fish Aquat Sci 1996.

Winter studies of fish, particularly in stream environments, have increased markedly in the past decade. The objective of the present paper is to review the winter habitat characteristics and the winter behaviour of selected stream fishes in temperate/boreal ecosystems. Emphasis is placed on salmonid fishes upon which most winter research has been directed. As space is considered to be the primary factor regulating stream fish populations in winter, aspects of winter habitat are considered at various spatial scales from microhabitat to stream reach to river basin. Choice of winter habitat is governed by the need to minimize energy expenditure with the main criterion being protection from adverse physical/chemical conditions, (e.g., ice, strong streamflow, low oxygen). The distance moved to wintering habitats, and the continued activity by many fishes during winter, need to be considered when making management decisions regarding fish habitat. How habitat is affected by land-use activity in stream catchments is discussed with reference to impacts from water withdrawal, varying discharge regimes, and erosion/sedimentation. Even stream "enhancement" practices can deleteriously affect winter habitat where project managers are unaware of the seasonal habitat requirements of resident fishes and winter stream conditions. Maintenance of habitat complexity, at least at the scale of stream sub-basin, is recommended to ensure the diversity of winter habitat requirements for aquatic communities. Keywords : winter; fish habitat; review; behaviour; salmonid; river; management

Cunjak, R.A., Curry, R.A., and Power, G. 1987. Seasonal energy budget of brook trout in streams: implications of a possible deficit in early winter. Transactions of the American Fisheries Society 116:817-28.

The seasonal diet and energy budget of brook trout were investigated in three southern Ontario streams in 1983-84. stomach analyses were performed and the calculated energy value of prey items was compared with the calculated energy required for maintenance metabolism (both sets of calculations were based on literature values). Brook trout continued to feed throughout the winter, consuming a variety of prey species, especially insect larvae. Condition (weight/length^3) declined markedly from late summer (August) to early winter despite continued feeding. It appeared that low winter temperatures restricted the rate of food consumption (due perhaps to a direct effect on gastric evacuation rates) which thereby limited energy intake This restriction is believed to be responsible for the metabolic deficit condition when minimal costs of maintenance metabolism could not be offset by energy intake. In November and December, this deficit occurred in two of six instances for immature brook trout and in four of six instances for mature brook trout. In the stream, where ground water minimized temperature fluctuation, winter deficits only occurred in reproductively spent brook trout. Acclimatization to rapidly declining temperatures in early winter, coupled with reproductive costs for mature fish and an insufficient energy intake, resulted in the depletion of energy stores. In November-December, such a condition may limit the extent to which fish can survive unusually long winters or atypical environmental perturbations. Keywords : brook trout; winter; fish growth; fish biology; turbidity; trout; Ontario; temperature

Cunjak, R.A., Power, G. 1986. Seasonal changes in the physiology of brook trout, *Salvelinus fontinalis* (Mitchill), in a sub-Arctic river system. J Fish Biol 29:279-88.

Brook trout were sampled from two sites on the Koksoak River system in northern Quebec to determine seasonal physiological changes in hematology and proximate body condition. Water content increased over the winter at both sites, whereas body lipids decreased. The relationship was most pronounced in the anadromous trout of the Caniapiscau River compared with the smaller resident trout of a tributary stream. Serum protein levels decreased significantly over the winter with the greatest depletion being realized by Caniapiscau River trout. Despite the severity of the winter stream environment in the north, the extent of depletion was similar to that encountered in temperate latitudes, suggesting compensatory physiological mechanisms within the species' latitudinal range. By mid-summer both populations had restored their depleted energy stores, especially the anadromous trout which accumulated the greatest amount of lipids after feeding in the estuary. Serum glucose levels were maintained at high levels during the winter, then declined in the summer. Differences between the two sites for the degree of physiological change are discussed in relation to specific overwintering strategies and life history variation. Keywords : brook trout; winter; fish biology; behaviour; adult fish; trout; river

Dahlberg, M.D. 1979. A review of survival rates of fish eggs and larvae in relation to impact assessments. Marine Fisheries Review (March):1-12.

Enormous fecundities of fishes are balanced by high egg and larval mortalities resulting from natural interacting environmental stresses. Survival rates generally increased inconsistently with

age of eggs and larvae. Few published studies provided the data needed to compare relative mortality among the three major developmental stages. Mortality was greatest during the egg stage in the walleye and striped bass, but during the postlarval stage in some marine species. Wide ranges of egg survival for Atlantic herring, northem pike, rainbow smelt, and walleye depend on whether egg production is based on fecundity or field counts, and whether survival is measured to a stage of drifting larvae or late eggs.
Among freshwater species, hatching success was low in unprotected eggs and high in species which exhibit parental care, construct nests, but do not exhibit parental care, have special protective mechanisms (yellow perch) and apparently in species which deposit eggs in vegetation. Among anadromous species, egg survival in striped bass was particularly low in comparison to that in salmon. In the sea, hatching success of demersal eggs was much higher than in pelagic eggs. Survival of yolk-sac larvae was generally higher in marine and freshwater species than in anadromous species. Survival of postlarvae was highest in freshwater species in relation to high daily survival rates and short developmental periods.
The occurrence of brief critical periods of high mortality was generally not supported when data were corrected for larval extrusion. The potential for high mortality to be offset by compensatory mechanisms is supported by literature. A direct relationship of survival rates and development time suggested that high mortality rates were an expected mechanism for regulation of populations having short developmental periods. The availability and applicability of survival data to modelling of impact is assessed. Many environmental factors should be considered when extrapolating survival data from one site to another. Keywords : review; fish eggs; bass; pike; walleye

de la Fuente, J. and Haessig, P.A. 1993. Salmon sub-basin sediment analysis. USDA Forest Service, Klamath National Forest. Yreka, California. #14-16-0001-91522. pp. 1-388.

Hydraulic mining from about 1870-1950 delivered about 15.8 million yds^3 of sediments to the Salmon River system. By comparison, from 1904-1988, landslides delivered about 10.4 million yds^3 and surface erosion delivered about 1.5 million yds^3. Channel erosion was not quantified, but its contribution was probably greater than that for surface erosion, and less than that for landslides. Landslide occurrence was episodic, and controlled by climate. The most important landslide episodes occurred during a wet climatic cycle which lasted from about 1950-1975, and accounted for 84% of the total landslide volume produced from 1904-1988. Major floods in 1955, 1964, 1972 and 1974 severely modified the river channel and those of its larger tributaries. By far, the 1964 flood had the greatest effect on stream channels, and produced the most landslides. The influx of large volumes of landslide-derived sediment to flooding streams and rivers resulted in widespread disruption of channel beds and removal of riparian vegetation. Low gradient reaches were filled with sediment, and many of the steeper tributary channels were scoured by the passage of debris flows.
Large fires in excess of 50,000 acres occurred in 1917-1918, 1977, and 1987. None of these fires initiated significant landslide episodes. This may be due to the fact that all were followed by drought periods. Surface erosion was observed to increase markedly on bumed granitic lands after the fires of 1987, but data are not available on earlier fires. There is a high risk of future catastrophic fire in the Salmon River watershed due to accumulation of fuel over the past 50 years. This is important because fire can greatly increase landslide and surface erosion rates. There was little correlation between historic sediment production and the current condition of fish habitat. That is, watersheds which produced large volumes of landslide-derived sediment did not necessarily exhibit poor quality habitat. This may be due to the fact that the last landslide producing storm occurred about 18 years prior to the time that the habitat surveys were conducted, allowing sufficient time for channels to recover.
The large landslide producing storms of the 1960's and 1970's occurred when the Salmon River watershed has less than 3% of its area disturbed by roads, harvest or recent fire. In 1989, about 18% of the watershed was disturbed, due in large part to the fires of 1977 and 1987. Roaded lands were found to produce landslides at a rate about 100 times greater than undisturbed land, and harvested lands produced landslides at a rate about 5 times greater than undisturbed land. Thus, it is estimated {by the landslide sediment model} that the Salmon River watershed would

produce 2.68 million yds^3 of landslide sediment if a wet climatic sequence such as that of 1965-1975 {excluding the 1964 flood} were to occur today. This compares to an estimate of 1.33 million yds^3 if the watershed were completely undisturbed. The basin-wide air photo inventory measured a total of 1.79 million yds^3 if the watershed were completely undisturbed. The basin-wide air photo inventory measured a total of 1.79 million yds^3 of landslide-derived sediment for the time period of 1965-1975.
Certain geomorphic terrains were found to produce the vast majority of the landslide volume. Similarly, certain soil types produced most of the surface erosion. Disturbance of these lands can further increase their landslide and erosion potential. Keywords : salmon; model; forestry; landslide sediment input; erosion; sediment

Dehoney, B. and Mancini, E. 1982. Aquatic biological impacts of instream right-of-way construction and characteristics of invertebrate community recovery. The Third Symposium on Environmental Concerns in Right-of-Way Management. 15 February 1982; San Diego, California.

Two major impacts associated with the construction of a pipeline through an aquatic habitat are the disturbance of habitat through the removal of substrate and the increase in stream siltation/turbidity. Quantities of macroinvertebrates that would be affected through substrate removal are estimated. The potential secondary impact of invertebrate removal on fish productivity is also estimated. Impacts from increases in siltation/turbidity are discussed for all life cycle stages of fishes and macroinvertebrates. It was concluded that the egg and larval stages of fishes and macroinvertebrates would be the most adversely affected by increases insiltation/turbidity due to the relative immobility. Adult fishes would likely vacate the affected area at least temporarily, although increased siltation could disrupt reproduction by covering potential spawning grounds. Recovery of the area would be dependent upon the time needed for silt to be removed from the substrate, but after the silt has been removed recovery should occur fairly rapidly (less than 6 weeks). Keywords : recovery; pipeline; siltation; reproduction; disturbance; macroinvertebrates

Dieter, C.D. 1990. Causes and effects of water turbidity: a selected annotated bibliography. South Dakota Cooperative Wildlife Research Unit. South Dakota State University, Brookings, South Dakota. Tech. Bull. No. 5. pp. 1-64.

(from introduction): Literature included in the bibliography deals with the various aspects affecting turbidity. Some literature addressing methodology, laboratory equipment, and scientific modeling have also been reviewed. The papers in this bibliography are arranged alphabetically by author, numbered consecutively, and are listed in the Author-Subject Index. The annotations are intended to provide a general summary of the information relating to turbidity contained in the articles. All efforts were made to avoid errors or misrepresentations of original publications. Literature included has been gleaned from computer searches by U.S. Fish and Wildlife Service and an expansive search of documents and journals in University libraries. A copy of the annotated bibliography is available on computer disc from South Dakota Cooperative Wildlife Research Unit, South Dakota State University, P.O. Box 2206, Brookings, South Dakota 57007. Keywords : turbidity; bibliography; methodology

Dinneford, W.B. 1978. Final report of the commercial fish - technical evaluation study: Salcha River. Joint State/Federal Fish and Wildlife Advisory Team, State of Alaska. Alaska. 21. pp. 1-93.

The third and final year of Commercial Fish Division Pipeline Technical Evaluation Studies on the Salcha River measured adult king and chum salmon escarpment, distribution, sex-ratio, age class trends, fecundity and egg retention. The distribution and relative numbers of juvenile king salmon, as well as their summer food habits, were evaluated in the main river and six tributary streams.

Analysis of 1972 to 1977 king salmon data and 1973 to 1977 chum information allowed determination of some of the effects, both observed and potential, of the Trans-Alaska hot oil pipeline upon these resources. Construction activities associated with implacement of the pipeline in March of 1976 were estimated to introduce a 1, 177 tons of sediment into the Salcha. The lower than average percentage of both king and chum salmon spawning downstream from the pipeline crossing in that year was possibly due to the sediment; the 1977 distribution approximated the averages for both chums and kings.
Measurements of water depth in the vicinity of the buried pipeline crossing on the Salcha show the depth twice as great directly over the pipe as was found 20 feet up and downstream from the pipe. This is apparently the result of incomplete backfilling of the trench following construction activities and the failure of hydraulic action to move new material into the trench since 1976.
The potential impact of an oil spill on the Salcha River is estimated for king salmon adults, eggs and adult chum salmon. As much as 85% of the rearing kings and 26% and 29% of spawning chum and kings, respectively, could be lost as a result of a spill at the McCoy Creek crossing during average distribution. During periods when smolts or spawners are concentrated below pipe crossing sites, complete loss of a year class could result. Keywords : salmonids; adult fish; juvenile fish; pipeline; behaviour; salmon; instream sediment; river

Doeg, T.J. and Koehn, J.D. 1994. Effects of draining and desilting a small weir on downstream fish and macroinvertebrates. Regulated Rivers: Research and Management 9(1):263-77.

Draining a small off-take weir in February 1991 before desilting introduced large amounts of sediment (at least 100 m3) into the downstream creek. Increased suspended solids concentrations up to 4610 mg/l were recorded downstream during the release. Large volumes of sand were deposited close to the weir, with finer fractions (silt) deposited up to 2 km further downstream. Very fine silt was washed through the system to a major river 4.5 km below the weir. Over the first day of the release, at a site 2.1 km below the weir, there was a reduction of 19.4% in the total number of benthos macroinvertebrate taxa, and average reductions of 63.9% in the abundance of and 39.7% in the number of taxa per sample. Over the following 45 days the fauna recovered towards pre-release diversity and density. The recovery was not sustained and further reductions in diversity and abundance were recorded over the following five months, probably due to fresh disturbance from desilting works and further mobilization of sediment during high flows. A major storm and flood in September 1991 apparently flushed all additional silt from the creek and the macroinvertebrate fauna subsequently recovered to higher diversity levels than before the release.
Compared with densities recorded in 1985 and 1988, the population of river blackfish (*Gadopsis marmoratus*) was reduced by 93% after the release at a site 250 m downstream of the weir, with reductions of 81 and 59% at distances from the weir of 2.1 and 2.7 k, respectively. An additional reduction in this fish population occurred at a lower site in late 1991, probably due to further flushing of sediments during the September flood. Although reductions in fish numbers occurred across the whole population, greater reductions were recorded for the younger age classes. Small subsequent increases in fish numbers at upper sites during 1992-1993 indicated that a recovery of blackfish population may be occurring through recruitment, but such a recovery will only be confirmed over the long term. Keywords : macroinvertebrates; sediment; recovery; disturbance; Weirs; blackfish; river; flows

Doeg, T.J., Milledge, G.A. 1991. Effect of experimentally increasing concentrations of suspended sediment on macroinvertebrate drift. Aust J Mar Freshwater Res 42:519-26.

The effect of artificially elevating concentrations of suspended sediment on macroinvertebrate drift was studied in the Acheron River, 100 km north-east of Melbourne. Two experimental channels were established in the stream and suspended sediment was introduced into one channel over a period of 1.5 hr. The second channel was left undisturbed as a control. The concentration of suspended sediment was altered every 15 min, rising and falling to imitate concentrations reported during natural flood events. Drift was collected from two nets at the

downstream end of each channel during each 15-min period. Collections were made for three 15-min periods before the introduction of the sediment and for three periods after the release.
The addition of suspended sediment at a mean concentration of 133.4 mg/L over a 15-min period (compared with around 20 mg/L in the control channel) resulted in a sevenfold increase in the total number of drifting invertebrates. At lower concentrations (both before and after this peak concentration), drift densities were more similar to prerelease conditions. The number of drifting taxa also showed and increase during the period of high release.
Although the experiment did not conform strictly to a full experimental design, the results indicated that there may be a threshold level of suspended sediment that initiates macroinvertebrate drift, and this experiment represents an appropriate starting point for future investigations. Keywords : suspended sediment; sediment; macroinvertebrates; drift; river

Doran, L.D. 1974. Fishes and aquatic systems. Environment Protection Board. Winnipeg, Manitoba. pp. 205-267.

Field and office studies have been completed to provide the biological setting for fishes and aquatic systems along the proposed gas pipeline routes; to assess the impacts of the project upon fishes; and to make recommendations for the amelioration and mitigation of anticipated impacts. In the Mackenzie River watershed, 34 species of fish were identified. The Yukon River watershed was found to contain 16 species of fish, and the North Slope watersheds , 7 species. Recurrent groups of fishes were identified in the Mackenzie and Yukon systems. Information on life history phases and distribution and abundance of fish species although limited, was summarized. Data on lakes in the Mackenzie study area were few; more are needed because of their importance for understanding the relative productivities of aquatic systems there. Use of fish resources by people who utilize them for subsistence appeared to be declining, but domestic use is not known well enough to make adequate judgements about effects of the development on the people's prime protein resource. Anticipated impacts of the project on fishes and fish habitat include: increased siltation and reduced oxygen levels in the watercourses; possible addition of toxic chemicals to fish habitats; increased human access to the resource (and more sport fishing); and obstructions to fish movements. It is recommended that silt concentrations in streams be allowed to increase to no more than Level IV by Inland Waters Branch criteria as a result of development. Oxygen concentrations should not go below level III by Inland Waters Branch criteria. No toxic chemicals should enter any watercourse; contingency plans are needed for high risk areas. Fishing should be monitored where access to the fish resource is increased. No physical or velocity barriers to fish movements should be allowed. Keywords : pipeline; Alberta; lake; fish habitat; siltation; Yukon; river

Dryden, R.L. and Jessop, C.S. 1974. Impact analysis of the Dempster Highway culvert on the physical environment and fish resources of Frog Creek. Resource Management Branch, Central Region, Environment Canada, Fisheries and Marine Service. CEN/T-74-5. pp. 1-59.

The impact from improper culvert design and effects on the hydrology and fish biology of Frog Creek, NWT are discussed. Fish migration discharge design, as required by Fisheries and Marine Service, Environment Canada for northern highway culverts is defined. At this or lower discharges, flow conditions within the discharge for Frog Creek NWT is calculated at 22.4 m^3/s (800 cfs). If the culvert at Frog Creek had been designed to allow fish passage at this discharge, the delay to fish migration would only have been 3 to 4 days. Water velocities in the Frog Creek culvert during 1973 exceeded the maximum allowable velocity of 1.5 m/s (5 fps) for 40 days from May 26 to July 5.
Bank erosion downstream from the culvert caused retreat of the river bank at a rate of 15 cm (6 inches) per day. Siltation of the stream resulting from construction was evident, but appeared to be insignificant. During the peak discharge period , extensive ponding occurred upstream of the culvert. Ice buildup inside the culvert occurred primarily during early spring as a result of over ice flow.
High water velocities within the culvert blocked the spawning migration of approximately 600 northern pike *Esox lucius* (Linnaeus) and appeared to block movements of some broad whitefish

Coregonus nasus (Pallas). Fish passage did not become generally possible until July 5 when water velocities of less than 1.5 m/s (5 fps) were attained. After passage became possible, both pike and broad whitefish dispersed equally in upstream and downstream directions. It was estimated that only a small proportion of the total pike population of the Frog Creek drainage was blocked by the culvert. No physiological effects of culvert delay on ripe pike were evident. Feeding habits of northern pike and broad whitefish are described in relation to available food organisms, as indicated by drift and artificial substrate samples. Age and growth and length frequency distributions for pike and broad whitefish are described. Maximum ages recorded in Frog Creek were 8 years for pike and 6 years for broad whitefish. Keywords : highway construction; fish biology; instream sediment; pike; whitefish; behaviour; hydrology

Dryden, R.L. and Stein, J.N. 1975. Guidelines for the protection of fish resources of the Northwest Territories during highway construction and operation. Department of the Environment, Fisheries and Marine Service, Fisheries Operations Directorate, Central Region, Resource Impact Division, Resource Management Branch. CEN/T-75-1. pp. 1-32.

Based on the results of fisheries investigations conducted between 1971 and 1974, guidelines have been designed to protect the fish resources of the Districts of Keewatin and Mackenzie, as well as Baffin and Southampton Islands, from major disruptions resulting from the construction and operation of highway and road systems. These guidelines are not intended to serve as regulations but merely as an aid in meeting Fisheries and Marine Services requirements, as defined by the Fisheries Act of Canada.
Culvert average cross-sectional velocities must not exceed 0.9 m/s (3 fps) when fish passage is a requirement, unless it can be satisfactorily demonstrated that the culvert design includes a selected region wherein velocities are low enough to permit fish passage. This selected region must be continuous throughout the culvert length and of sufficient size to permit fish to locate it and to swim through it. Alternatives such as baffles should be considered when these velocity criteria can not be met through regular design procedures. The minimum desirable water level within culverts during periods of fish movement should be 20.3 cm (8 inches).
In general, no instream construction activity should be attempted from May 1 to June 30 and from September 1 to November 15, as these periods are considered critical to fish migrations and spawning. However, these dates vary slightly with geographical spread and variations in the timing of freeze-up and break-up. The spring or fall restrictions may be lifted if it can be satisfactorily demonstrated that fish spawning activities do not occur during either or both of these period in the stream under consideration. Three days is considered the maximum time period during which the blockage to annual spawning migrations can be tolerated without causing serious disruption to the spawning cycle. During this three day period, the above mentioned velocity criteria need not be adhered to. Variables such as the timing of fish migration and the timing and duration of peak flows will determine when this three day delay limitation should be in effect. The removal of stream gravel may seriously damage spawning habitat and therefore should not be attempted without first determining the spawning potential of the area in question and consultation with Fisheries and Marine Services. Highway routing should avoid close proximity or paralleling of streams or water bodies, and should cross river systems as far upstream from the river mouth or as far downstream from a lake outlet as possible. Specific restrictions, other than those discussed within these guidelines, may have to be imposed where unique fish species or life history aspects are involved. Conversely, the guidelines may be tempered upon consideration of species composition or the individual characteristics of a stream system. Fisheries and Marine Service is available to provide advice and guidance with respect to the fisheries resource for any highway design or construction proposal in the Northwest Territories. Keyword : highway construction

Duchrow, R.M., Everhart, W.H. 1971. Turbidity measurement. Transactions of the American Fisheries Society 4:682-90.

A quick and reliable method of measurement is necessary to set standard limits on the amount of suspended sediment to be tolerated in streams near land-use operations. Turbidity

measurements may be useful if a major portion of the total turbidity is contributed by settleable solids, if a relationship exists between turbidity readings and weight per unit of volume of suspended sediment and if a reliable meter is available. Water with turbidity readings greater than one JTU (Jackson Turbidity Unit) is generally composed mostly of settleable solids unless distorted by color. Non-filterable and total dissolved solids contribute variable amounts of light penetration reduction. Percentage contribution to turbidity of settleable solids is highly variable from sample to sample and from station to station.
A high correlation exists between turbidity readings and weight from individual sediment types of suspension, but a poor relationship exists when sediment type is varied. Experiments conducted on the Hach model 2100, the Hellige, and the Jackson Candle turbidmeters resulted in a highly significant difference (alpha=0.01) between readings on the same sample of suspended sediment. Turbidity is a questionable measure of suspended solids in water. A more accurate index would be suspended solids measured gravimetrically. Keywords : turbidity; suspended sediment; settleable solids; methods; sediment; light penetration

Eaglin, G.S., Hubert, W.A. 1993. Effects of logging and roads on substrate and trout in streams of the Medicine Bow National Forest, Wyoming. North American Journal of Fisheries Management 13:844-6.

We examined the influence of logging and road construction on substrate and standing stocks of trout (*Salvelinus* and *Salmo*) in 28 stream reaches in the Medicine Bow National Forest, Wyoming. The extent to which roads crossed watercourses (culvert density) within a drainage and the proportion of the drainage that was logged were positively correlated to both the amount of fine substrate and embeddedness. Trout standing stocks had a negative relation with the density of culverts. Erosion of soil from road surfaces, ditches, and disturbed areas adjacent to roads that subsequently is deposited in stream channels seems to be an important mechanism by which logging has affected stream habitat. Keywords : logging; trout; erosion

EIFAC. 1964. Water quality criteria for European freshwater fish: report on finely divided solids and inland fisheries (EIFAC Technical Paper No. 1). pp. 151-168.

This is the first of a series of reports on water quality criteria for European freshwater fish prepared for and approved by the European Inland Fisheries Advisory Commission. The background of the project is described and reasons for establishing water quality criteria for fish explained. This is followed by a literature survey of : the direct effects of solids in suspension on death or survival of fish, their growth, and resistance to disease; suspended solids and reproduction: effects on behaviour; effect on food supply; and total effect of suspended solids on freshwater fisheries. Finally tentative water quality criteria are suggested. Keywords : water quality; suspended sediment; fish effects; review; reproduction; behaviour

Ellis, M.M. 1936. Erosion silt as a factor in aquatic environments. Ecology 17(1):29-42.

Keywords : erosion; benthic invertebrate community; suspended sediment; settleable solids

Elwood, J.W., Waters, T.F. 1969. Effects of floods on food consumption and production rates of a stream brook trout population. Transactions of the American Fisheries Society 2:253-62.

Food consumption and production rates were estimated for a stream population of brook trout over a two-year period (1965-1966) in which four severe floods occurred. Two year classes were nearly eliminated as producing components of the population. Standing crops of older age groups were reduced as a result of a decrease in the stream's carrying capacity after sand and debris carried into the stream by flood waters filled pools and blanketed riffle areas. Invertebrate populations were also severely damaged by floods, reducing the food supply and causing an apparent decrease in growth rates in 1965 when three of the four floods occurred. Results of laboratory feeding experiments at four different temperature-season combinations were used to estimate food consumption rates of the brook trout in their natural environment.

Maintenance requirement increased with increasing temperature in the spring and summer and decreased with decreasing temperature in the fall and winter. Net efficiency of food utilization increased with increasing temperature in the spring and summer and decreased in the fall and winter. The smaller fish, < 63 g, had a greater percentage maintenance at all temperature-season combinations except in the fall when they had a lower percentage maintenance requirement than the larger fish 63 g and >. Annual production rates in 1965 and 1966 were 61.4 and 43.5 kg/ha respectively. Annual food consumption rates in the same two years were 855.6 and 370.1 kg/ha. The two year classes entering the population during the study contributed only 7 percent to the total accumulated production during the two-year study period. Keywords : brook trout; fish biology; disturbance; biomass changes; winter; trout

Engel, S. 1990. Ecosystem responses to growth and control of submerged macrophytes: a literature review. Dept. of Natural Resources. Madison, Wisconsin. 170. pp. 1-22.

Submerged macrophytes alter the physical, chemical, and biological makeup of aquatic ecosystems. The plants improve water clarity by preventing shore erosion, stabilizing sediment, and storing nutrients needed by algae. They cast shade and retard water movement, creating vertical temperature gradients. Their photosynthesis and respiration cause daily fluctuations in pH, alkalinity, and concentrations of dissolved oxygen and carbon dioxide. Even the lake bottom is altered from oxidation of organic matter in decaying plants. Living foliage provides substrate for invertebrates, shelter for fry, and food for water birds.

Herbicides and harvesting impact ecosystems directly by killing plants and animals and indirectly by destroying habitat. Herbicides leave plants to decay, causing loss of dissolved oxygen and release of nutrients. Harvesting removes plants with their nutrients, but disrupts invertebrate habitat and exposes fry to predation. Both treatments can lead to algal blooms, poor water clarity, and shifts in plant community composition.

Lake managers can reduce unwanted ecosystem change by thoughtful planning and judicious treatment. Integrating several techniques, each used only when and where needed, can improve control and reduce harm to the ecosystem. Rather than being tools of destruction, herbicides and harvesting can build more useful and diverse ecosystems. Keywords : macrophytes; review; lake; fry; bass; herbicides; erosion; sediment; organic matter

Envirocon Limited, B., B.C. 1986. Investigation of the magnitude and extent of sedimentation from Yukon placer mining operations. Volume 1. Department of Indian and Northern Affairs. Ottawa. Env. Studies No. 45.

Summary: This report examines the effect of sediment generated by placer mining operations on downstream water quality. Seven watersheds in the Yukon were studied, including: Clear Creek and Haggart Creek in the Mayo District, Allgold Creek, Sixty Mile River and Indian River in the Dawson District, and South Big Salmon River and Kimberley Creek in the Whitehorse District.

Ninety-eight active placer mining operations were initially identified at the start of the study. Mines where the operator was not present and those where the operator requested that data not be collected are not assessed in this study. The mines visited ranged in size from one-man operations to very large operations processing several hundred tons of soil each day. Included in the mines visited was a dredging operation on Clear Creek, the only one of its kind in the Yukon.

During each mine-site visit, data were gathered to gain an understanding of the type and size of operations, the types of soils processed, and the quality and quantity of water entering the operation and subsequently being discharged. Information collected during this study is used to assess the incremental effect of mining operations on downstream water quality.

Several different types of settling facilities have been constructed to control the amount of suspended sediment, generated by mining activities, entering downstream watercourses. Settling ponds, created by constructing earthen berm with either an over-berm outlet or groundwater seepage are the most common effluent treatment facility. Another common facility was simply a discharge to a large area of gravels and/or tailings (from previous mining operations) where the effluent was allowed to filter through the soil with no direct flow to the stream.

A particular settling facility was judged to be effective if its effluent discharge was meeting the 0.2 ml/l settleable solids concentration objective suggested by the Yukon Territory Water Board. Approximately 40% of the settling facilities studied were effective. Conversely, many settling ponds were observed to be essentially full, providing little, if any settling.

The effectiveness of the settling facilities observed during the study period was determined by several factors including; pond size, location, current status (some settling ponds were essentially full), maintenance, types of pay materials being processed, rate of loading, volume of muck being hydraulically stripped, and the method used to regulate pond discharge.

Paydirt samples were collected from the pits of forty-three mines (some of the operators requested that a paydirt sample not be collected). The majority of these samples contained less than 15% silt or smaller sized material (smaller than 0.067 mm). A majority of the samples also contained less than 2% clays (smaller than 0.002 mm). The largest proportion of fine grained soils were contained in samples collected near the headwaters of Dominian Creek and in the upper drainage of the Sixty Mile River watershed.

Placer gravels in most mining areas were covered with varying amounts of a silt-like material composed of loess and variable amounts of organics (muck). In may cases this muck was shallow enough that it could be mechanically stripped and moved to the side of the valley, away from the stream. In areas here the muck was deep it was usually stripped hydraulically, which added significant sediment loadings to the settling facilities and/or receiving stream. The largest volumes of muck were present in the Indian River and Sixty Mile River watersheds.

A muck sample was collected from one mine on Sixty Mile River and analyzed for grain size distribution. This sample contained 67.5% fine grained material less than 0.063 mm, 7.5% of which was clay size less than 0.002 mm. Extensive hydraulic stripping was being performed within both these watersheds during the site visits. The organic component of the non-filterable residue (NFR) recorded in water samples collected in these areas were among the highest recorded in the entire study area. No or very small amounts of muck were present in areas studied in the Haggart Creek and South Big Salmon River watersheds. Most of the suspended sediment in the main receiving streams was observed to originate from active placer mines operating within these watersheds.

Concentrations of NFR measured in sub-drainages of the Indian River watershed were among the highest recorded. The largest concentrations of NFR measured in each of Sulphur, Eureka and Quartz Creeks were recorded near the headwaters where mines were regulating total creek flow with combined storage/settling ponds.

In each watershed studied, NFR concentrations and suspended sediment loadings were observed to vary in response to mining operations. Magnitudes of these parameters typically increased immediately below industrial inputs and then decreased downstream. The rate of decrease in NFR below industrial inputs was dependent on the amount of dilution from increased non-industrial inflows, stream velocity and length of stream over which the suspended material could settle prior to input from an additional industrial source.

With the exception of Sixty Mile River and Haggart Creek, NFR concentrations in water samples collected near the mouth of the mainstem water courses in each watershed were higher than NFR concentrations in their receiving streams. Concentrations of NFR at the mouth of Sixty Mile River were approximately half the concentration recorded in Yukon River. Concentrations of NFR in Haggart Creek and South McQuesten River appeared to be similar. Keywords : sedimentation; Yukon; placer mining; sediment; salmon; water quality; river

ESL Environmental Sciences Limited, Aquatic Environments Limited, DPA Group Limited, and K Rood and Associates. 1990. Yukon placer mining study - phase II: 1989 investigations. ESL Environmental Sciences Limited. pp. 1-86.

Placer mining operations are widespread in the Yukon but historically, most of the gold has been produced in unglaciated portions of the Klondike, Sixtymile, Lower Stewart and Indian River drainages, lying primarily in the Yukon Plateau. Physical characteristics, hydrology, mining activity and principal fishery resources (chinook salmon and arctic grayling) have been surveyed for the Duncan and Mayo Creeks, Clear and Moose Creeks, McQuesten River, Flat and Allgold Creeks, Klondike River, and Bonanza and Hunker Creeks. Study watercourses were selected based on logistics, occurrence of salmon or grayling, physical characteristics and presence/absence of placer activity. Field investigations in 1989 included sedimentology (grain size, rugosity, suspended sediments), fish collection at a reconnaissance level, and habitat evaluation. A survey of Yukon placer operations was also undertaken to develop a current economic profile of the industry and to provide industry projections of compliance activities and costs arising from the 1988 guidelines. The final survey coverage, when complete should be 40% of the operators and 60% of recorded gold production. Results and preliminary data analyses are presented. The habitat description of 4 major fish species, chinook salmon, Arctic grayling, slimy sculpin and longnose sucker, is discussed. 1990 studies will address the effects of placer mining on abundance, distribution and species composition. Keywords : Yukon; placer mining; suspended sediment; hydrology; salmon; grayling; sediment

Everhart, W.H. and Duchrow, R.M. 1970. Effects of Suspended Sediment on Aquatic Environment. Fishery and Wildlife Biology Department. Colorado State University. 14-06-D-6596. pp. 1-106.

Effects of suspended sediment on aquatic fauna have been well documented in the literature. Sublethal concentrations of suspended sediment can be tolerated by organisms as long as mechanisms which remove sediment from the body surfaces function. Field studies on 4 high mountain streams in south-western Colorado indicate no harmful effects on aquatic fauna from suspended solid concentrations. A quick and reliable method of measurement must be found to set standard limits on the amount of suspended sediment to be tolerated in streams near land-use operations. Turbidity measurement may be useful if: 1) a major portion of the total turbidity is contributed by suspended solids; 2) a relationship between turbidity readings and the weight per unit volume of suspended sediment exists; 3) a reliable meter can be found to give consistent readings. Turbidity is a questionable parameter to use as an index to suspended solids in water. Too many factors must remain constant before a turbidity reading can be converted to weight per unit volume of suspended solids. Suspended solids should be measured gravitationally according to standard procedures suggested by the Federal Water pollution Control Administration (1969). Keywords : suspended sediment; sediment; aquatic environment; Colloids; light penetration; water quality standards; suspended load; stream ecology; field study; methods; turbidity

Fairchild, J.F., Boyle, T., English, W.R., and Rabeni, C. 1987. Effects of sediment and contaminated sediment on structural and functional components of experimental stream ecosystems. Water, Air, and Soil Pollution 36:271-93.

Three experimental stream ecosystems were used to determine the effects of sediment and contaminated sediment: one stream received 1.7 g/L uncontaminated sediment for 2 hr each week for 6 wk; one stream received 1.7 g/L contaminated sediment (50-16000 ppm triphenyl phosphate applied in increasing doses each week) for 2 hr each week for 6 wk; and the third stream was maintained as a control. Each stream was monitored for changes in nutrient dynamics, leaf decomposition, primary production, and invertebrate dynamics. Both sediment and sediment/triphenyl phosphate altered the drift dynamics of benthic invertebrates. Invertebrates in the sediment treatment exhibited delayed nocturnal drift, while those in the sediment /triphenyl phosphate treatment drifted immediately once a threshold of toxicity was reached. Both sediment and sediment /triphenyl phosphate decreased the percent similarity of benthic invertebrates, reduced the drift of filamentous algae, increased the production of rooted flora and increased net nutrient retention. However , neither treatment altered leaf decomposition rates, or affected benthic invertebrate dynamics (total number, number of species, or diversity) or insect emergence. Keywords : suspended sediment; invertebrate community changes; contaminants; sediment; drift

Foothills Pipe Lines (Yukon) Ltd. 1982. Chinook salmon emergence studies in Teslin, Morley and Swift Rivers in Yukon Territory.[Unpublished]

Introduction: Foothills Pipelines (South Yukon) Ltd. (Foothills) is in the design stage for construction of the Alaska Highway Gas Pipeline in southern Yukon Territory. The pipeline route enters Yukon Territory near Beaver Creek and generally parallels the Alaska Highway before continuing on to B.C. near Watson Lake. Activities related to construction, operation, and abandonment of the pipeline have the potential for adversely affecting fish populations. In order to assess and minimize the effects of pipeline activities, Foothills has executed numerous fisheries studies in the past. The programme described here is a continuation of that process.
In Yukon Territory, there are substantial differences in river water levels depending upon the time of year. For ease of pipeline installation in a watercourse it is preferable for construction to occur during low water. Low flow in some rivers coincides with the development of chinook salmon (*Oncorhynchus tshawytscha*) embryos in substrate material which is generally thought to occur between August 15 and June 30 in Yukon. Construction activities at such times could have detrimental effects upon developing eggs. However, dates of emergence for salmon are known to vary in different streams. If the final date of emergence could be accurately determined for specific streams, then it might be possible to schedule instream construction to occur immediately after emergence and still take advantage of low water levels for pipeline installation activities. The purpose of the present study was to investigate the time of salmon emergence in three Yukon streams; these being the Teslin, Morley and Swift Rivers.
Since two of the streams in question had not been visited for the purpose of undertaking salmon emergence studies in the past, it was of importance to know whether or not such a programme was possible during spring in Yukon Territory. The programme was, therefore, initiated not only to obtain some results on emergence times, but also to identify difficulties that might be experienced for future more definitive studies. The following objectives were pursued: 1. collection of data regarding chinook salmon emergence in the areas; 2. determination of water depth, temperature, and ice thickness, during early spring; 3. observation of any other condition that might assist during further emergence work at all locations, and ; 4. recording of weather conditions that might effect the programme. Keywords : salmon; pipeline; lake; Yukon; salmonid production; embryos

Fraikin, C. and Anderson, P.G. 1994. A description of the condition and use by fish of Enhancement Works at the Nipigon River and analysis of the invertebrate drift one and two years after construction. Prepared for Environmental Affairs Department, TransCanada Pipelines. B.A.R. Environmental Inc., Guelph, Ontario. pp. 1-26.

Summary: During the 1992 summer construction program, TransCanada Pipelines Limited installed a pipeline across the Nipigon River approximately 1.5 km downstream of the Ontario Hydro Alexander dam. One of the OMNR in-stream work permit conditions for the crossing was to undertake a fish habitat enhancement program. An item of the fish habitat compensation agreement was to conduct a monitoring program of the fish habitat enhancement works and of the invertebrate drift downstream of the crossing. This monitoring was to take place in the fall season following construction as well as one year two years after the construction period.
The fish enhancement works at the crossing included the construction of chinook salmon spawning shoals and the implementation of bank revetment measures, which included the installation of root wads and river bank revegetation with shrubs, trees and grasses. In October, 1993 and 1994 (one and two years after pipeline construction respectively) chinook salmon in spawning condition were observed using the shoals on both sides of the river. Areas where gravel excavation activities had occurred were also observed. The spawning shoal design consisting of projecting "fingers" of gravel intended to optimize the exchange of stream and inter-gravel flows, was alluring to the fish. The shoals were in the same physical condition as in the previous year and appeared to be structurally very stable.
A large scale salmonid habitat enhancement program was also undertaken in areas outside of the crossing site. Located in a back bay area upstream of the crossing, brook trout reproductive habitat was constructed by making use of groundwater from several springs that were present in

the area. Using SCUBA, the area of the created upwellings was clearly visible two years after their construction. Though fish were not seen utilizing these habitats, a number of small excavations were apparent. An alcove area that was also excavated to create areas of upwellings was also examined. The upwellings were clearly visible during both the one and two year post-construction surveys, and excavations by brook trout and salmon were observed. Other areas of ground water upwelling, previously covered with clay and silt, remained clear of depositional materials following the construction, and brook trout were observed in these areas. Works were also conducted in a tributary to the back bay in order to provide rearing habitat for brook trout. Examination of the added gravel substrate and re-contoured stream channel indicated that the banks of the modified section of creek were stable; however, siltation had occurred over much of the streambed. Though not suitable for spawning, this tributary has the potential to provide good rearing habitat for brook trout.
The benthic invertebrate drift in the Nipigon River was examined in order to evaluate the species composition of the Nipigon River benthos. This technique was used as it was the only feasible method for the strong currents and water depths encountered in the Nipigon River. Chironomids were the most dominant invertebrate in the drift before and after construction. Chironomids were also present in samples collected one and two years after construction; however, hydras were the dominant organism both upstream and downstream of the crossing. Rather than being attributed to a disturbance episode such as pipeline construction, the variation found among the sampling periods was likely due to many influential, natural factors, as well as to the large natural variations commonly found in the structure of benthic invertebrate communities. Keywords : drift; fish effects; fish habitat; pipeline; invertebrate community changes; dam; monitoring; river; Ontario

Fudge, R.J.P., Bodaly, R.A. 1984. Postimpoundment winter sedimentation and survival of lake whitefish (*Coregonus clupeaformis*) eggs in southern Indian Lake, Manitoba. Can J Fish Aquat Sci 41:701-5.

Flooding of Southern Indian Lake for hydroelectric power development has resulted in extensive wave erosion of glacio-lacustrine clay shore material and greatly increased suspended sediment levels. Winter sedimentation on spawning grounds of lake whitefish ranged from 0.03 to 0.14 g dry wt sediment/cm^2. This deposited a layer of 1-4 mm in depth. The sediment, low in organic content, was categorized as silty clay. The effect of this winter sedimentation on survival of whitefish eggs was tested at four sites over a range of winter sedimentation rates. Three of the sites were whitefish spawning area. Egg survival was significantly higher for eggs incubated in cages designed to minimize exposure to sedimentation compared with survival in cages allowing full exposure to sedimentation. Winter sedimentation rates and whitefish egg survival were negatively correlated for cages designed to minimize exposure to sedimentation, while egg survival in the exposed cages was uniformly low. Keywords : winter; sedimentation; lake; whitefish; fish eggs

Gammon, J.R. 1970. The effect of inorganic sediment on stream biota. Environmental Protection Agency, Water Quality Office. Washington, D.C. pp. 1-142. Water Pollution Control Research Series.

Fish and macroinvertebrate populations fluctuated over a four year period in response to varying quantities of sediment produced by a crushed limestone quarry. Light inputs which increased the suspended solids less than 40 mg/L during a part of each day caused a 25% reduction in macroinvertebrate populations below the quarry. Heavy inputs caused elevations of more than 120 mg/L with some periods of sediment accumulation and a 60% reduction in macroinvertebrate populations. Diversity indices were not affected. Experimental sediment introductions caused immediate increases in drift rate proportional to the concentration of suspended solids. The standing crop of fish decreased drastically when heavy sediment input occurred in the spring, but fish remained in pools during the summer when sediment input was very heavy and left the pools only after deposits of sediment accumulated. After winter floods removed sediment deposits, fish returned to the pools during spring months and achieved 50%

normal standing crop by June. Only slight improvements occurred during summer even with light sediment input. Only spotted bass (*Micropterus punctulatus*) was resistant to sediment, but its growth rate was lower below the quarry than above. Most fish were much reduced in standing crop below the quarry. Keywords : winter; bass; field study; sediment concentrations; benthic invertebrate community; suspended sediment; recovery; behaviour; macroinvertebrates; sediment; drift

Gardner, M.B. 1981. Effects of turbidity on feeding rates and selectivity of bluegills. Transactions of the American Fisheries Society 110:446-50.

Turbidity, caused by suspended clay particles, significantly reduced feeding rates but not size selectivity of bluegills (*Lepomis macrochirus*) preying on two size classes of *Daphnia pulex.* Bluegill feeding rates in a 3-min period declined from approximately 14 per min in clear water to 11, 10, and 7 per min in pools of 60, 120, and 190 NTU, respectively. Size selectivity was independent of turbidity level; the proportion of large daphnia consumed was approximately 0.70 in all treatments and the control. These turbidity levels covered the range of turbidities found in North Carolina Lakes. Keywords : turbidity; bluegill; behaviour; lake

Gartman, D.K. 0. Pipeline crossings of streams: Benthos recovery and habitat enhancement.[Unpublished]

Four buried natural gas pipeline stream crossings were investigated in Pennsylvania, New York, and Maryland relative to density and diversity of the macroinvertebrate community at the crossing. Benthos populations were sampled from the streams at the crossings and at points up and down stream. Time intervals since instream construction activities and sampling dates varied from several decades to 26 days. The latter stream crossing was sampled before construction and at approximately monthly intervals for one year.
Results indicate that benthos recovery is relatively rapid and the pipeline crossing itself often results in favourable aquatic habitat, especially where excavation and backfilling creates a more diverse substrate available for colonization by macroinvertebrates. No long term damage to the benthic community was noted. Pipeline construction techniques can be modified on a site-specific basis as indicated by stream substrate and bank soil conditions to minimize sedimentation impacts to downstream reaches. Keywords : pipeline; recovery; macroinvertebrates; sampling

Gartman, D.K. 1982. The impact of a pipeline crossing on the benthos of a Pennsylvania trout stream. Third Symposium on Environmental Concerns in Right-of-Way Management. 15 February 1982; SanDiego, California. 1-12.

In August 1980, Columbia Gas Transmission Corporation constructed a buried 14 inch (36 cm) natural gas pipeline across Bushkill Creek, a trout stream in Northhampton County, Pennsylvania. Construction techniques were planned to minimize downstream sedimentation. Analysis of the benthic community on a pre- and post-construction basis in the area of the pipeline crossing noted a major increase in mean benthic densities within 30 days. Samples from the pre-construction period indicated 25 taxa with a mean density of 872/ m^2. Samples taken from the same area 26 days after pipeline construction had a total of 27 taxa and a mean density of 5391/m^2. This extraordinary increase in macroinvertebrates was dominated by *Hydropsyche* spp. which readily colonized the recently exposed dolomite substrate, a result of blasting and trench excavation. Little impact in terms of benthic community and substrate changes were noted downstream Samples collected monthly from August 1980 through July 1981 and compared with pre-construction data and previous studies on this reach of Bushkill Creek. Keywords : pipeline; sedimentation; benthic invertebrate community; recovery; trout; macroinvertebrates

Goodchild, G.A. and Metikosh, S. 1992. Fisheries-related information requirements for pipeline water crossings. Canadian Manuscript Report of Fisheries and Aquatic Sciences, Fisheries and Oceans, Canada. North Bay, Ontario. 2235. pp. 1-20.

This report contains the results of a Department of Fisheries and Oceans and Ministry of Natural Resources workshop held in 1992 at North Bay to determine the minimum information needed to assess the impact of pipeline water crossings on fish and fish habitat. The report addresses activities associated with crossings, related impacts, and information requirements for developing effective mitigation and compensation strategies. The information requirements discussed in the report include: 1) erosion and sedimentation potential of right of way soil including substrate particle composition; 2) a photograph or video of pre-construction site conditions, and mapping of basic fish habitat inventory data and physical conditions; 3) detailed habitat assessment within the impact zone;, and 4) presence or absence of cold and warm water fish species based on historical and anecdotal data (on a watershed basis) for construction timing windows. Keywords : pipeline; instream sediment; methodology; model; fish habitat; erosion; sedimentation; Young

Gore, J.A. 1979. Patterns of initial benthic recolonization of a reclaimed coal strip-mined river channel. Can J Zool 57:2429-39.

Benthic macroinvertebrate samples were taken at sampling stations upstream of, downstream of and within a newly opened channel of the Tongue River in Wyoming. The channel, reclaimed from coal strip-mining, contained layers of topsoil, gravel, and small to medium cobble. Benthic recolonization progressed towards maximum densities following terms of a power function. The mayflies of the genus *Baetis* were the primary colonizers. Colonization occurred primarily by drift of aquatic insects and algal mats in the first 14 days of channel opening. Some upstream migration, particularly by the dragonfly *Ophiogomphus*, was observed. Attainment of maximum diversity lagged density by 20 to 30 days. This period represented a time of dynamic adjustment within the community to match the undisturbed source area communities. The combined effects of differential drift rates and distances for aquatic insects and detrital material were responsible for the rather predictable patterns of colonization as well as the sequentially decreasing diversity values as distance from the upstream source areas increased. Keywords : sampling; benthic invertebrate community; disturbance; macroinvertebrates; river; drift

Gradall, K.S., Swenson, W.A. 1982. Responses of brook trout and creek chubs to turbidity. Transactions of the American Fisheries Society 111:392-5.

The influence of red-clay turbidity on behaviour and distribution of brook trout and creek chubs *Semotilus atromaculatus* was measured in the laboratory. Creek chubs preferred highly turbid water (56.6 formazin turbidity units - FTU) over moderately turbid water (5.8 FTU) but brook trout did not show a preference. In moderately turbid water, both species were more active, and used overhead cover less than in clear water. The results indicate that turbidity may represent an important isolating mechanism that promotes production of creek chubs. Keywords : brook trout; turbidity; behaviour; creek chub; laboratory study

Gray, L.J., Ward, J.V. 1982. Effects of sediment releases from a reservoir on stream macroinvertebrates. Hydrobiologia 96:177-84.

Effects of sediment release from Guernsey Reservoir on macroinvertebrates of the North Platte River, Wyoming, were investigated during summer 1981. Suspended solids concentrations during sediment release increased from <20 mg/L to >300 mg/L. Because fine particulates remained in suspension, mean particle size of substrates was unaltered. Densities of chironomids decreased 90%+ during sediment release but recovered to initial levels in 3 weeks after the release ended. Densities of mayflies and oligochaetes increased. Changes in benthic populations were highly correlated with increases in suspended solids. Keywords : suspended sediment; benthic invertebrate community

Gregory, R.S., Servizi, J.A., and Martens, S.W. 1993. Comment: Utility of the stress index for predicting the suspended sediment effects. North American Journal of Fisheries Management 13:868-73.

A commentary on Newcombe and MacDonald's (1991) concentration-duration response model for assessing environmental effects caused by suspended sediment. Gregory et al., here, complain that the data used were highly variable, therefore predictive power of the model was low and that the model was unrealistically simplistic. - the following response to this from Newcombe and MacDonald was that Gregory et al. were using the model improperly. Keywords : suspended sediment; model

Griffith, J.S., Smith, R.W. 1993. Use of winter concealment cover by juvenile cutthroat and brown trout in the South Fork of the Snake River, Idaho. North American Journal of Fisheries Management 13:823-30.

During February-April 1990 the number of age-0 cutthroat trout and brown trout concealed during the day in several types of cover was assessed in a large river, the South Fork of the Snake River in southeastern Idaho. Fish typically were concealed along the edge of the wetted perimeter at water depths shallower than 0.5 m. Population estimates for age-0 cutthroat trout ranged from 0 in rounded cobble (<20 cm in diameter) to 4.56 fish per meter of bank in clean boulder substrate. Abundance of age-0 brown trout varied with substrate in a similar manner but ranged from 0 to 0.50 fish per meter of bank. Cobble and boulder habitat that was heavily embedded with fine sediment contained fewer juvenile trout of either species. The first electrofishing pass extracted 78% of the age-0 cutthroat trout and 76% of the age-0 brown trout estimated to be present in concealment cover. The fraction of fish emerging from concealment to swim in the water column at night was 61-66% of the numbers estimated to be in concealment during the day. Keywords : winter; brown trout; cutthroat trout; fish habitat

Griffith, J.S., Smith, R.W. 1995. Failure of submersed macrophytes to provide cover for rainbow trout throughout their first winter in the Henrys Fork of the Snake River, Idaho. Journal of the North American Benthological Society 15:42-8.

Submersed aquatic plants that are abundant in some stream reaches have a potential to provide winter concealment cover for juvenile salmonids. We monitored an index of macrophyte abundance in a portion of the Henrys Fork of the Snake River during two winters that differed in severity and assessed the densities of age-0 rainbow trout associated with the macrophytes. The macrophyte index averaged 84-87% in November 1989 and 1992, and an average of 10-13 fish/100m^2 were concealed there. In 1990, macrophyte cover declined to 59% in January and 46% in early February; fish density declined by about one-third by January and dropped to nearly zero in February. In 1992-1993, the macrophyte index declined to an average of 39% following anchor ice formation in December and to 32% in January. Fish density in December was reduced to about half of the November density and to about 1 fish/100m^2 in January. Movement of marked fish in 1989-1990 was predominantly from macrophytes into cobble and boulder cover along the bank. During these 2 years, cover provided by submersed macrophytes in the study area was not adequate to hold age-0 rainbow trout throughout the winter. During the winter of 1992-1993 no natural bank habitat was available because of low water flows, and we believe that none of the 1992 cohort of rainbow trout survived in the sandy area. Keywords : winter; salmonids; rainbow trout; macrophytes; fish habitat; trout; river; flows

Hakanson, L. 1984. Sediment sampling in different aquatic environments: statistical aspects. Water Resources Research 20(1):41-6.

The aim of this paper is to discuss statistical aspects on sediment sampling and sample representativity. The study is based on empirical data from three different sedimentological environments: a river, a river mouth area, and a lake. The sediments have been analyzed for physical sediment character (water content, and loss on ignition) and chemical/contaminational status (Pb, Cu and Cd). The prevalent bottom dynamics influence the character of the sediments and the representativity and information value of sediment samples. An informative fraction is defined by the portion of a sediment sample that passes a 63 um mesh by wet sieving. This fraction corresponds approximately to deposits from areas of accumulation. Direct analysis of surficial sediment samples from areas of erosion or transportation, such as in rivers and river mouths, yield low information, ie. many samples would be required to obtain a given statistical certainty. Correction with the water content (or similar parameters eg. grains size and bulk density) or organic content would improve the information but still not yield optimal results. Simple wet sieving through a 63 um mesh seems to yield best information, ie. the lowest number of necessary analysis for the least amount of work. Fractionated centrifugation (or similar approach, eg. ultrafiltration) would not improve the information value. Keywords : lake; suspended sediment; methods; sampling; monitoring; sediment; erosion

Hansen, E.A., Alexander, G.R., and Dunn, W.H. 1982. Sand sediments in a Michigan trout stream Part 1. In-stream sediment basins: a technique for removing sand bedload from streams. Michigan Department of Natural Resources, Fisheries Division. Michigan. 1901. pp. 1-26.

Erosion control techniques such as streambank stabilization and revegetation of eroding upland areas reduce only part of a stream's sediment load. This study demonstrated than an in-stream sediment basin can trap and remove almost all sand bedload sediments. Other advantages of sediment basins are that they can : 1) produce streambed downcutting to create deeper pools and improve streambed composition, and 2) keep critical spawning areas relatively free of sediment. Sediment basins should be used with caution in eroüible bed streams that have no areas of erosion-resistant streambed to prevent possible excessive downcutting. Sediment basins can be added to the variety of techniques used to improve fish habitat, or they can be used alone to renovate sand-choked streams not amenable to the usual erosion control treatments. Keywords : instream sediment; fish habitat

Hart, R.C. 1988. Zooplankton feeding rates in relation to suspended sediment content: potential influences on community structure in a turbid reservoir. Freshwater Biology 19:123-39.

Summary: 1. Changes in zooplankton composition and abundance in Lake le Roux, a turbid subtropical reservoir on the Orange River in South Africa, were correlated with changes in water transparency (related to suspended sediment levels) during a 7 year field study. Results of radiotracer studies of the effect of mineral turbidity on zooplankton feeding rates which potentially influence competitive ability and thus community structure are reported here. 2. Feeding rates of five zooplankters were very variable, but consistently declined with rising turbidity; rates of decline differed between species. A regression estimate of the critical turbidity threshold at which food intake matched the estimated respiratory need was derived for each species. this yielded the following 'turbidity tolerance' ranking: *Moina brachiata* Jurine>*Metadiaptomus meridianus* (van Douwe) >> *Daphnia gibba* Methuen> *D. barbata* Weltner> *D. longispina* O.F. Muller. The consistency between this ranking and one based on abundance-transparency relationships in the field study suggests that community structure is related to differential feeding capabilities, although other influences are not excluded. 3. Tests on *D. gibba* and *M. meridianus* failed to reveal any detectable feeding rate saturation (incipient limiting food level) below 1.2 mg/LC. The relative reduction in feeding rates at elevated turbidity was nearly 3 times greater for the daphnid than the copepod over a range of food concentrations and considerably reduces the competitive ability of this and other daphnids. The turbidity tolerance disparity between *Moina* and the daphnids demonstrates a more complex situation than a simple copepod/cladoceran dichotomy. These finding and their implications are discussed in relation to wider features of zooplankton ecology. Keywords : suspended sediment; lake; turbidity; zooplankton; behaviour; sediment; field study

Hausle, D.A., Coble, D.W. 1976. Influence of sand in redds on survival and emergence of brook trout (*Salvelinus fontinalis*). Transactions of the American Fisheries Society 1:57-63.

Alevins of brook trout were buried in laboratory troughs in spawning gravel containing 0-25% sand. Sand slowed emergence and reduced the number of fry emerging. Weight of fry was not related to proportion of sand in gravel, but was related to time; the fry were heaviest near the time of peak emergence, and lighter before and after the peak. Survival was estimated to be 84% from egg deposition to hatching for brook trout in Lawrence Creek, Wisconsin, and 70% from hatching to emergence, providing a total estimate for survival from egg deposition to emergence of 59%. Keywords : brook trout; fry; instream sediment; laboratory study; trout; laboratory

Heimstra, N.W., Damkot, D.K., and Benson, N.G. 1969. Some effects of silt turbidity on behavior of juvenile largemouth bass and green sunfish. United States Dept. of the Interior, Fish and Wildlife Service, Bureau of Sport Fisheries and Wildlife. Washington, D.C. 20. pp. 3-9. Technical Paper.

Behaviour of juvenile largemouth bass and green sunfish in aquariums was measured under conditions of clear water, 4-6 JTU, and 14-16 JTU for 30 days. The activity of bass was significantly reduced by turbidity; sunfish activity was reduced, but not significantly. Feeding and attack behaviour was not influenced. Scraping behaviour of both species was higher under turbid conditions. There was evidence that turbidity disturbed normal social hierarchies in green sunfish. Keywords : turbidity; bass; behaviour; laboratory study

Heinrich, J., Lick, W., and Paul, J. 1981. Temperatures and currents in a stratified lake: a two-dimensional analysis. J Great Lakes Res 7(3):264-75.

Two-dimensional, time-dependent numerical models are used to predict the temperatures and currents in a stratified lake. In this study, (1) essential features of the observed distributions of temperatures and currents in large, stratified lakes, especially Lake Erie, are reproduced, (2) the effects of various governing parameters such as heat flux to the water, wind stresses, and turbulence are examined, and (3) the effects of changes in various parameters appearing in the turbulent eddy coefficients are investigated. The emphasis is on the general characteristics of thermocline formation, maintenance, and decay and therefore the time scales of interest are weeks and months rather than hours or even days. Keywords : lake; model; temperature

Herbert, D.W.M., Merkens, J.C. 1961. The effect of suspended mineral solids on the survival of trout. Int J Air Wat Poll 5(1):46-55.

This paper consisted of a laboratory study, examining the effects of finely divided solids on the survival of adult trout. Kaolin and diatomaceous earth were used with 5 different particle sizes at 5 concentrations (including a control). The following effects were observed.

Fish effects: *on survival* - feels that mortality in aquaria were due to added sediment as controls were distinctly different - no effect at 30 ppm - at 90 ppm some effect (but still fairly low) - at higher concentrations (270 and 810 ppm) usually in excess of 50% mortality but varied with test - sediments used were kaolin and diatomaceous earth - also noted that trout kept at highest concentrations of SS became very pale almost white in colour.
Effects on growth: comparisons made between control fish and survivors of other test -no significant difference in mass or length of fish exposed to different concentrations of diatomaceous earth - survivors grew as well as controls.
Effects on gills: noted gill thickening. Keywords : fish effects; laboratory study; fish growth; fish survival; sediment concentrations; salmonid; trout; laboratory

Herbert, D.W.M., Richards, J.M. 1963. The growth and survival of fish in some suspensions of solids of industrial origin. Int J Air Wat Poll 7:297-302.

Discussion and conclusions: Although the data from polluted streams, and from the laboratory studies by Herbert and Merkens (1961), show that a fishery is likely to be seriously harmed if the average concentration of suspended matter in the water is greater than about 600 ppm, it is more doubtful what effect average concentrations in the approximate range 90 and 300 ppm are likely to have. In laboratory experiments 200 ppm wood fibre and 270 ppm koalin and diatomaceous earth have killed substantial proportions of the trout kept in them for long periods, and 90 to 100 ppm have been harmful to a lesser degree, but the data from the questionnaire indicate that there are some rivers which support reasonable fish populations even though the suspended solids concentration is often about 200 ppm and sometimes higher, while the present study has shown that trout can be kept in good health for 9 months in 200 ppm coal -washery waste solids. Whether or not concentrations within this range will be harmful may depend on the nature of the solid material itself or on whether or not other features of the environment favour survival.

However, none of the laboratory experiments in 30 ppm kaolin and diatomaceous earth and in 50 ppm wood fibre and coal-washery solids have provided any evidence that such concentrations make well grown trout more susceptible to disease or reduce their chances of survival, and the data from polluted rivers show that there are many streams containing up to 60-70 ppm of a variety of industrial waste solids which support reasonable populations of fish. The only evidence for any adverse effect of such concentrations is that 50 ppm wood fibre and coal-washery solids reduced the growth of rainbow trout in the laboratory. However, these trout grew quite well, more than trebling their weight in 8 months, and the lengths and weights of brown trout from a stretch of the river Camel containing 60 ppm suspended solids differed very little from those in unpolluted Cornish streams (Herbert, et al 1961). The effect of 50-60 ppm solids on growth thus seems rather unlikely to be serious in practice. Keywords : fish survival; fish growth; laboratory study; salmonid; suspended sediment; trout; laboratory; river

Hesse, L.W., Newcomb, B.A. 1982. Effects of flushing Spencer Hydro on water quality, fish, and insect fauna in the Niobrara River, Nebraska. North American Journal of Fisheries Management 2:45-52.

Hydroelectric facilities with a low generating capacity (approximately one megawatt) such as Spencer Hydro on the Niobrara River in Nebraska are important, as referenced by the renewed interest in the revival of many that were deactivated with the advent of large fossil fuel and nuclear generating stations. The water reservoir impounded by the Spencer Dam is shallow and entrapped sediment quickly fills the pond, reducing power generating potential and threatening the internal components of the hydro station. This action requires periodic flushings to allow settled sediment to move past the station, resulting in adverse impacts on water quality, fish, and fish-food organisms in the 63.3 km of Niobrara River downstream from the dam. Investigations in 1979 revealed unacceptable low levels of DO (3.5-4.0 mg/L), pronounced increases in turbidity (>400%) and suspended solids (4-fold) and a doubling of dissolved solids. Thirty species of fish were affected, with a conservative count of 22,471 dead fish plus others under extreme stress. Young fish were most affected. There also were large changes in the abundance of many species of immature aquatic insects. A series of corrective recommendations are proposed to alleviate the problem and enhance the fishery in the lower river. Keywords : dam; siltation; turbidity; water quality; fish kill

Horkel, J.D., Pearson, W.D. 1976. Effects of turbidity on ventilation rates and oxygen consumption of green sunfish, *Lepomis cynanellus*. Transactions of the American Fisheries Society 1:107-13.

Ventilation and oxygen consumption rates of green sunfish exposed to bentonite clay suspensions were measured at 5, 15, 25, and 35 C. Ventilation rates were not affected by bentonite clay suspensions below 2, 125 FTU at 5C, 1,012 FTU at 15C, and 898 FTU at 25C. At turbidity levels exceeding 1,012 FTU at 15C and 898 FTU at 25C ventilation rates increased 50-70%. Tests were inconclusive at 35C due to high mortality. Oxygen consumption rates were not affected by turbid suspensions of up to 3,500 FTU at any of the four temperatures. Evidence suggests that increased ventilation rates under highly turbid conditions are a means of compensating for reduced respiratory efficiency and a strategy for maintaining a constant oxygen uptake. The costs of increased ventilation rates were probably met by a reduction in activity. Keywords : turbidity; fish effects; temperature

Hynes, H.B.N. 1970. The effects of sediment on the biota in running water.[Unpublished]

Synopsis: Unaltered streams are usually clear, and running-water animals and plants have in general become adapted to silt-free situations. Most of their specializations relate to the substratum which provides them with shelter, attachment sites and food. Our knowledge of the effects of turbidity and siltation by inert solids on plants, benthic animals, fishes and their eggs is reviewed. It is concluded that the upper tolerable level of turbidity is probably less than 80 mg/L of inert silt, and that any considerable amount of deposition is bound to have biological consequences. Keywords : turbidity; siltation; fish effects; fish eggs; suspended sediment

Inman, D.L. 1952. Measures for describing the size distribution of sediments. Journal of Sedimentary Petrology 22(3):125-45.

Numerous measures are used in the literature to describe the grain-size distribution of sediments. Consideration of these measures indicates that parameters computed from quartiles may not be as significant as those based on more rigorous statistical concepts. In addition, the lack of standardization of descriptive measures has resulted in limited application of the findings from one locality to another. The use of five parameters that serve as approximate graphic analogies to the moment measures commonly employed in statistics is recommended. The parameters are computed form five percentile diameters obtained from the cumulative size-frequency curve of a sediment. They include the mean (or median) diameter, standard deviation, kurtosis, and two measures of skewness, the second measure being sensitive to skew properties of the "tails" of the sediment distribution. If the five descriptive measures are listed for a sediment, it is possible to compute the five percentile diameters on which they are based (rho5, rho16, rho50, rho 84, rho95) and hence five significant points on the cumulative curve of the sediment. This increases the value of the data listed for a sediment in a report, and in many cases eliminates the necessity of including the complete mechanical analysis of the sediment. The degree of correlation of the graphic parameters to the corresponding moment measures decreases as the distribution becomes more skew. However, for a fairly wide range of distributions, the first three moment measures can be ascertained from the graphic parameters with about the same degree of accuracy as is obtained by computing rough moment measures. Keywords : methods; sediment particle size

Israelsen, C.E., Clyde, C.G., Fletcher, J.E., Israelsen, E.K., Haws, F.W., Packer, P.E., and Farmer, E.E. 1980. Erosion control during highway construction: research report. Transportation Research Board. Washington, D.C. 220. pp. 1-30. National Cooperative Highway Research Program Report.

Summary: Highway construction as it is known today is a high-risk activity with respect to engendering soil erosion. In earlier days of road building, when rights-of-way were generally narrow and excavations mostly shallow, erosion was rarely a serious problem. Only occasionally was it considered necessary to design and apply specific measures for erosion control. With the advent of the toll roads and Interstate Highway System involving far greater widths of right-of-way, and much deeper disturbance of the natural ground to afford the horizontal and vertical highway geometry necessary for high-speed travel, came a several-fold increase in erosion potential and a direct need for specific action aimed at its control. Highway engineers have reacted by revising construction specifications to include many protective measures. Increasing public awareness of the desirability of protecting the environment has been a source of both support and pressure in the application of erosion control in highway construction.
Although improvement has been significant, unwanted soil erosion and accompanying sedimentation resulting from highway construction activity continue to be problems. A lack of

knowledge within the highway industry of improved erosion control measures developed outside the industry, perhaps some resistance to change because of a lack of familiarity with erosion control measures, and in some instances, a need for information not now available anywhere are probably the major contributors to continuation of the problem.

The present project was directed at improving erosion control practice in highway construction by providing assistance in all three of the foregoing areas contributory to the problem. The research is documented in two reports: NCHRP Report 220, "Erosion Control During Highway Construction - Research Report"; and NCHRP Report 221, "Erosion Control During Highway Construction - Manual on Principles and Practices". The research team found, through questionnaire returns from 177 sources and visits to construction sites in 32 states, that: (1) Technology is available in the United States to control within reasonable limits the erosion and sedimentation that may originate on highway locations both during and following construction. (2) Erosion control specifications currently being prepared for specific highway construction projects are adequate in many instances to maintain erosion within reasonable limits if properly enforced and followed. (3) More effective means of ensuring compliance with erosion control specifications during construction are needed. (4) Over-all construction costs may be lower if erosion control measures are implemented on a project than if they are omitted. (5) Erosion amounts can be significant even in areas where the average annual rainfall is comparatively low.(6) Numerous small erosion control measures implemented at the proper times and locations may be more effective and less expensive than a few large or poorly timed ones.. (7) Written erosion control specifications are effective only if they are enforced and followed by design, administrative and construction personnel (8) Training courses for administrative, design, and construction personnel are needed both to create an awareness of the importance of controlling erosion and of the advantages that accrue from doing so, as well as to provide information on control measures and techniques that are available. (9) The universal soil loss equation (1, 52, 56, 57) developed by the Agricultural Research Service is probably the best tool presently available for predicting soil loss caused by rill and sheet erosion during highway construction and for estimating the relative effectiveness of various erosion control measures. (10) A soil loss equation developed by Chepil and associates (24, 39, 58) appears to have application to highway construction sites for estimating potential soil losses due to wind.

The manual on erosion control principles and practices (NCHRP Report 221) focuses on techniques for predicting the erosion potential of highway construction sites, and for estimating the effectiveness of various erosion control measures. A wide variety of control measures are listed and described, and information that will aid in selecting measures to meet specific site requirements is presented. Design standards for control measures, and information on such matters as size selection for mechanical control measures, are not included in the manual because these are already widely available in highway engineering offices. To develop the erosion control manual on which the project effort was centered, means had to be established for estimating the water and wind soil erosion potentials on highway construction sites and the effectiveness of various measures that might be considered for controlling the erosion. The universal soil loss equation (1, 52, 56, 57) developed by the Agricultural Research Service, was modified and extended to serve as a basis for estimating water soil loss potentials. An equation developed by Chepil and Woodruff (24), Skidmore et al. (39) and Woodruff and Siddoway (58) was adapted for estimating wind soil loss potentials. Appropriate maps, graphs, and tables providing information necessary for the solution of the equations for the United States and Puerto Rico were prepared and included in the manual. Nomographs and tables were constructed and included in the manual for solving the equations, and the process was illustrated by detailed examples. Keywords : highway construction; suspended sediment; erosion; disturbance

Jensen, J.W. 1982. A check on the invertebrates of a Norwegian Hydroelectric Reservoir and their bearing upon fish production. Canadian Fish Culturist :39-50.

The 36.7 km^2 Aursjoen reservoir has been regulated since 1953, and includes a main basin regulated 28 m and the Gautsjoen basin regulated 5 m. Brown trout (*Salmo trutta* L.) and grayling (*Thymallus thymallus* L.) are the only fishes present. The crustacean plankton seemed unaffected by the water fluctuations. The soft bottom and littoral fauna was dominated by Oligochaeta, Chironomidae, *Pisidium* and the Cladocera *Eurycercus lamellatus*. Besides small numbers of Hydracarina and unidentified Diptera, 6 species of other insects and 8 species of littoral Entomostraca were recorded. The material identified to the species level revealed only minor qualitative differences between the two basins. The biomass of benthos, mainly Chironomidae, in the Gautsjoen basin was several times higher than before regulation started. The basis of this high production of chironomidae has to be the peat deposits of the impounded, boggy ground. Based on the biomass data and probable figures of the P/B relations the estimated production of planktonic food organisms for fish exceeded the corresponding benthos with a factor of 140 for the main and 5 for the Gautsjoen basin. Stocking with a plankton-consuming fish, for example Arctic char, *Salvelinus alpinus* (L.), would probably tenfold the yield of fish. Keywords : brown trout; trout; grayling; plankton; reservoir

Kennedy, H.D. 1955. Colonization of a previously barren stream section by aquatic invertebrates and trout/. The Progressive Fish-Culturist July:119-22.

Study examined the recovery of a barren stream section in a small stream in California. Sampled for aquatic invertebrates and trout. Found that recovery period was slightly less than 3 months. Keywords : salmonid; brown trout; recovery; trout

Kerr, S.J. 1995. Silt, Turbidity and Suspended Sediments in the Aquatic Environment: an annotated bibliography and literature review. Ontario Ministry of Natural Resources, Brockville, Ontario. Southern Region Science and Technology Transfer Unit, Technical Report. TR-008. pp. 1-277.

Keywords : bibliography; suspended sediment; siltation; turbidity; review

Kite, G.W. 1991. A watershed model using satellite data applied to a mountain basin in Canada. Journal of Hydrology 128:157-69.

A simple watershed model has been developed which uses Landsat and National Oceanic and Atmospheric Administration (NOAA) data to simulate basin runoff on a daily basis. The paper describes the application of this model to the Kootenay Basin in the Canadian Rocky Mountains and compares the results obtained using satellite data with those obtained using only ground-based data. Snow cover data from NOAA/Advanced Very High Resolution Radiometer (AVHRR) improved the model performance but cloud cover data were not found to be helpful in improving estimates of precipitation input. Keywords : model; landsat; Kootenay

Klein, R.D. 1984. Effects of sediment pollution upon the aquatic environment.[Unpublished]

Keywords : fish effects; suspended sediment

Knowlton, M.F., Jones, J.R. 1993. Testing models of chlorophyll and transparency for midwest lakes and reservoirs. Lake and Reserv Manage 8(1):13-6.

Seasonal means of chlorophyll (Chl) total phosphorus (TP), total and non-volatile suspended solids (TSS, NVSS) and Secchi depth from 28 reservoirs and natural lakes in Iowa, Kansas, and Oklahoma were used to test predictions of log-log regression models developed from Missouri reservoirs by Jones and Knowlton (1993). Waterbodies in Iowa, Kansas and Oklahoma exhibited a curvilinear relation between log-Chl and log-TP similar to that for Missouri reservoirs. These data fit the Missouri regressions for Chl-TP and Chl-(TP NVSS) fairly well; although the Missouri models usually underpredicted Chl for Iowa waterbodies. Missouri models provided an excellent fit to outstate transparency data. Keywords : model; lake; reservoir

Koenings, J.P., Edmundson, J.A., and Barto, D.L. 1989. Glacial silt - help or hindrance to lake productivity? Alaska Dept. of Fish and Game, Division of Fisheries Rehabilitation, Enhancement and Development. Juneau, Alaska. 93. pp. 1-36.

Residents of the city of Haines expressed concern over the effect of the periodic influx of cold, turbid water from the Tsirku River on the sockeye rearing capacity of the clearwater Chilkat Lake. Studies on the rearing environments of glacial and clearwater sockeye nursery lakes were used to describe the benefits and the risks of glacial silt. It was determined that turbidity levels <5 NTU could serve as an empirical point were potential benefits outweighed the risks. In addition, comparisons of the zooplankton and sockeye smolt populations of Chilkat and statewide glacial lakes suggest that the intrusions of turbid, cold water of the Tsirku River have not caused Chilkat Lake to reflect exceeding the 5 NTU barrier. This analysis serves as a prime example of how information gathering leads to discovery of patterns in nature which in turn leads to public benefit. Keywords : lake; turbidity; zooplankton

Kondolf, G.M. 1995. "Use of pebble counts to evaluate fine sediment increase in stream channels" by John P. Potyondy and Terry Hardy. Discussion paper. Water Resources Bulletin 31(3):537-40.

The authors have applied the pebble count method to monitor changes in bed material size in response to two fires and an upstream dam failure, documenting differences in the percentage of sediment finer than 6 mm over these areas. They are to be commended for anticipating the changes and then systematically applying a simple, inexpensive, replicable technique at a large number of sites representing a wide range of conditions. Such efforts by US Forest Service hydrologists should be encouraged, rewarded, and emulated throughout the National Forests.
The author's comments here are offered to clarify some points of method, suggest refinements and to enhance replicability, and point out some limitations of the method not emphasized in the paper. Keywords : sediment; methods; dam; hydrology

Krishnappan, B.G. and Engel, P. 1995. Critical shear stresses for erosion and deposition of fine suspended sediments in the Fraser River. National Water Research Institute. NWRI No. 94-60.

Keywords : erosion; suspended sediment; sediment; Fraser River

Kruzynski, G.M. and Sekerak, A.D. 1980. Development of an economical water quality monitoring program for winter pipeline crossing construction, based on studies of the Fort Nelson River, 1980. Westcoast Transmission Company Limited. Vancouver, B.C. pp. 1-46.

no abstract. Report produced by LGL Limited, Vancouver, B.C., covers effects of pipeline crossing - examines construction activities and field monitoring program. Discusses invertebrate drift. Makes recommendations for a standardized water quality monitoring program for the Fort Nelson River. Keywords : water quality; monitoring; winter; pipeline; drift

Kunkle, S.H., Comer, G.H. 1971. Estimating suspended sediment concentrations in streams by turbidity measurements. Journal of Soil and Water Conservation Jan/Feb:18-20.

Turbidity and suspended sediment analyses were made on stream samples collected in the Sleepers River watershed of northeastern Vermont. Results showed that turbidimeter readings could be used to estimate suspended sediment concentrations in the 16-6,366 mg/L range observed by using the predictive equation $Y=AX^b$. The equation was similar for the three watersheds studied, where soils, topography, and other factors were essentially the same. Samples were collected during two years of storm and snowmelt runoff on catchments draining from 16.2 to 43.5 km^2. Discharges ranged from 140 to 18,000 L/sec. The sediment particles were mostly of streambank origin and were primarily silt or very fine sand. Keywords : suspended sediment; sediment concentrations; turbidity; sediment; river

Lamberti, G.A., Gregory, S.V., Ashkenas, L.R., Wildman, R.C., and Moore, K.S. 1991. Stream ecosystem recovery following a catastrophic debris flow. Can J Fish Aquat Sci 48:196-208.

We studied recovery processes for 3 yr in Quartz Creek (Cascade Mountains, Oregon), a third-order stream catastrophically impacted by a February 1986 debris flow for which both predisturbance data and an upstream control reach were available. The debris flow altered channel geomorphology and destroyed riparian vegetation for 500 m, resulting in a reach with short, disordered channel units, low hydraulic retention, and an open canopy. High irradiance levels and reduced grazing by macroinvertebrates contributed to rapid accrual of benthic algae in the disturbed reach, which formed the bioenergetic basis for ecosystem recovery. Macroinvertebrates (mostly herbivores) recovered to upstream densities and taxonomic richness within 1 yr, although effects on community structure persisted into the second year. Cutthroat trout (*Oncorhynchus clarki*) populations were locally decimated by the disturbance, but by the following year, recruitment of young-of-the-year trout into the reach exceeded that of the upstream reach and populations had recovered to predisturbance densities. Despite the general rapid recovery of the biota within the disturbed reaches, most populations showed broad temporal fluctuations in abundance, suggesting that ecosystem stability was diminished by the debris flow. Long-term monitoring of Quartz Creek may yield additional insight into the role of episodic disturbance in stream ecosystems. Keywords : disturbance; recovery; invertebrate community changes; fish survival; stormflow

Landeen, B.A. and Brandt, W.C. 1975. Impressions on the construction of the Pointed Mountain Gas Pipeline. Northern Operations Branch, Fisheries and Marine Service, Dept. of the Environment, Northern Operations Branch, Pacific Region, Environment Canada. PAC/T-75-24. pp. 1-58.

Environmental problems related to pipeline construction in a sub-arctic region are discussed. Both overland and river crossing phases are discussed. Various construction situations creating environmental concern such as permafrost, bank instability and siltation to rivers are mentioned. An attempt was made to sample the extent of siltation resulting from the dredging activity. It appears that the trenching introduces more silt than the bank filling operation. Specific results and theoretical calculations are presented and compared. Problems of winter sampling and proposals for future research needs are outlined. This report attempts to familiarize the reader with pipeline construction and problems evident to the researcher during pipeline construction . Appendix IV includes the editor's corrections of literature citing this report as a source. The collection of additional data to assess the levels of siltation during winter construction should be stressed. Keywords : pipeline; siltation; winter; sampling

Lane, C.B. 1971. Sources of siltation on Beaverdam Creek in the McIntyre-Porcupine strip mining lease area (59-9-W6).[Unpublished]

During the fish sampling (with shocker) phase of the program, we experienced a sudden rainstorm. Within 0.5 hr the water in the section of the stream we were sampling became too turbid to work in. The crew immediately attempted to locate the sources of suspended sediment. Water samples were collected and some photographs taken. The samples were submitted to the Environmental Health Services Laboratory, Edmonton for suspended sediment analysis. Keywords : siltation; sampling; suspended sediment; sediment; laboratory; turbidity

Lane, C.B. 1972. A siltation problem on Luscar Creek (23-47-24-W5).[Unpublished]

Luscar Creek flows through the Cardinal River Coals Limited mine lease area. The upper section of stream is located within 100 yards of the coal storage and railroad car loading sites. Such proximity makes Luscar Creek very susceptible to siltation from coal fines contained in water run-off during rains and snow melt. Keywords : siltation; flows; river

Lees, A. 1985. Pipeline construction and stream sedimentation: a study of construction through Windfall Creek and the Red Deer River. NOVA, an Alberta Corporation, Environmental Affairs. Calgary, Alberta. pp. 1-46.

no abstract. Keywords : pipeline; sedimentation

Leis, A.L., Fox, M.G. 1994. Effect of mine tailings on the in situ survival of walleye (*Stizostedion vitreum*) eggs in a northern Ontario river. Ecoscience 1(3):215-22.

We investigated the effects of a gold mine tailings spill on the survival of walleye (*Stizostedion vitreum*) eggs in a northern Ontario river. The spill, which occurred in the fall of 1990, dumped 300 000 tonnes of fine tailings with high concentrations of heavy metals that were dispersed along a 5 km stretch of the Montreal River. Eggs were collected from resident walleye, artificially fertilized and reared in small plexiglass incubators that held 50 eggs each. Incubators were placed on the substrate and in the water column in control and tailings sites in May 1992 and 1993. Mortality in the substrate incubators averaged 64% at control sites and 81% at tailings sites, and was significantly higher in the latter in both years. Temperature, pH, dissolved oxygen, water velocity, conductivity and alkalinity were monitored at each site during the incubation experiments. No significant correlations were detected between egg mortality and any of these factors. In 1993, suspended sediment was collected at incubation sites. Significantly higher concentrations of lead, copper and nickel were found in tailings sites, whereas there was no significant difference between control and tailings sites in suspended sediment quantity. Egg mortality was significantly correlated with the concentration of lead (r^2 = 0.50) and copper (r^2 = 0.57). Our results suggest that the higher mortality of walleye eggs in the tailings sites was due to metal toxicity and/or hypoxia from the resuspension and settling of mine tailings. Keywords : temperature; suspended sediment; sediment; walleye; Ontario; river

Lemly, A.D. 1982. Modification of benthic insect communities in polluted streams: combined effects of sedimentation and nutrient enrichment. Hydrobiologia 87:229-45.

Responses of the benthic insect community of a southern Appalachian trout stream to inorganic sedimentation and nutrient enrichment were monitored over a period of eight months. Entry of pollutants from point sources established differentially polluted zones, allowing an assessment of impacts due to sedimentation alone and in association with elevated nutrient levels. Input of sediment resulted in a significant increase in bed load and decrease of pH at the substrate-water interface ($p<0.05$). The zone receiving nutrient runoff from livestock pasture exhibited elevated levels of nitrate and phosphate, but available data indicated such concentrations to be quite low. Species richness, diversity, and total biomass of filter feeding Trichoptera and Diptera, predaceous Plecoptera, and certain Ephemeroptera were significantly reduced in the polluted zones. Inorganic sedimentation, operating indirectly through disruption of feeding and filling of interstitial spaces, was considered to be the primary factor affecting filter feeding taxa. Decomposition of compounds associated with materials in the bed load may depress pH and eliminate acid sensitive species of Plecoptera and Ephemeroptera. Such processes of acidification may be particularly important to Appalachian streams since the pH of regional surface waters is characteristically acidic prior to sedimentation. Accumulation of particles on body surfaces and respiratory structures, perhaps as a function of wax and mucous secretion or surface electrical properties, appears to be the major direct effect of inorganic sedimentation on stream insects. Growths of the filamentous bacterium *Sphaerotilus natans* were also frequently associated with silted individuals in the zone receiving nutrient addition. Distribution of the bacterium suggested that silted substrates, perhaps as related to the presence of iron compounds, are required for colonization in dilute nutrient solutions. The primary effect of *Sphaerotilus* colonies appears to be augmentation of particle accumulation through net formation by bacterial filaments. Data indicate that inorganic sedimentation and nutrient addition operate synergistically, eliminating a significantly greater number of taxa than exposure to one pollutant alone. Keywords : sedimentation; benthic invertebrate community; contaminants; trout; sediment

Lenat, D.R., Penrose, D.L., and Eagleson, K.W. 1981. Variable effects of sediment addition on stream benthos. Hydrobiologia 79:187-94.

Two upper Piedmont streams were studied to determine effects of road construction, especially sediment inputs. Benthic macroinvertebrate data suggest that the stream community responded to sediment additions in two different ways. Under high flow conditions the benthic fauna occurs mainly on rocky substrates. As sediment is added to a stream the area of available rock habitat decreases, with a corresponding decrease in benthic density. There is , however, little change in community structure. Under low flow conditions, stable-sand areas may support high densities of certain taxa. Density of the benthic macroinvertebrates in these areas may be much greater than the density recorded in control areas, and there are distinct changes in community structure. Keywords : suspended sediment; invertebrate community changes; highway construction

Lisle, T.E., Lewis, J. 1992. Effects of sediment transport on survival of salmonid embryos in a natural stream: a simulation approach. Can J Fish Aquat Sci 49:2337-44.

A model is presented that simulates the effects of streamflow and sediment transport on survival of salmonid embryos incubating in spawning gravels in a natural channel. Components of the model include a 6-yr streamflow record, an empirical bedload-transport function, a relation between transport and infiltration of sandy bedload into a gravel bed, effects of fine-sediment infiltration on gravel properties, and functions relating embryo survival to gravel properties. High-flow events drive temporal variations in survival; cross-channel variations in bedload transport cause spatial variations. Expected survival, as a result, varies widely from year to year and between spawning runs in a single year. Alternative functions from previous research that relate survival to fine-sediment concentration in spawning gravel and to intergravel rates of flow yield categorically different results. The relative uncertainty of the components of this model indicates that the greatest research needs are to understand how sediment transport affects the intergravel environment and how these changes affect embryo development and survival. Keywords : sediment transport; model; salmonid; embryos; fish eggs; fish habitat; fish survival; sediment; flows

Lloyd, D.S., Koenings, J.P., and LaPerriere, J.D. 1987. Effects of turbidity in fresh waters of Alaska. North American Journal of Fisheries Management 7:18-33.

Turbidity results from the scattering of light in water by organic and inorganic particles; however, high turbidities usually are caused by suspended inorganic particles, particularly sediment. For several Alaskan lakes, we found that the depth to which 1% of subsurface light penetrated had a strong inverse correlation with sediment-induced turbidity. We also developed a model that describes the decrease in primary production in shallow interior Alaskan streams caused by sediment-induced turbidity. Euphotic volume in lakes correlated strongly with production of juvenile sockeye salmon (*Oncorhynchus nerka*). We also observed reduced abundance of zooplankton, macroinvertebrates, and Arctic grayling (*Thymallus arcticus*) in naturally and artificially turbid aquatic systems. Turbidity measurements correlated less consistently with measures of suspended sediment concentration (total nonfilterable residue), but provided an adequate estimator for use as a water quality standard to protect aquatic habitats. Keywords : turbidity; lake; model; salmon; zooplankton; grayling; sediment; macroinvertebrates; sediment concentrations; water quality; water quality standards

Luedtke, R.J., Brusven, M.A. 1976. Effects of sand sedimentation on colonization of stream insects. Journal of Fisheries Research Board of Canada 33(9):1881-6.

Driftnets, basket samplers, and artificial streams were used to investigate the influence of heavy sand accumulations on insect drift, colonization , and upstream movements in Emerald Creek, northern Idaho. Most riffle insects successfully passed through low-velocity, sandy reaches 80 m long. Upstream movements on sand were impeded by flows as low as 12 cm/s, except for the heavily cased caddisfly *Dicosmoecus* sp. Keywords : sedimentation; benthic invertebrate community; silt effects on habitat

Lyons, J. and Courtney, C.C. 1990. A review of fisheries habitat improvement projects in warmwater streams, with recommendations for Wisconsin. Dept. of Natural Resources. Madison, Wisconsin. 169. pp. 1-38.

Literature review - based on review, contacts and observations - made the following general recommendations for warmwater stream habitat improvement projects in Wisconsin: (1) Consider the entire stream ecosystem and watershed when planning projects, and try to address fundamental underlying causes of habitat problems whenever possible. (2) Before beginning a project, collect quantitative data that demonstrate a need for habitat improvement and indicate probable limiting habitat characteristics. (3) Use the most cost-effective techniques to improve habitat, and rely on natural objects or simple, easily replaced structures whenever possible. (4) Use all available data and expertise in determining the proper placement and installation of habitat improvement objects and structures. (5) Completely and thoroughly evaluate responses of habitat and fish populations to habitat improvement.
For warmwater streams in Wisconsin, we believe that bank revegetation coupled with the judicious use of riprap is the best approach to bank stabilization. Careful placement of boulders, trees and rock wing dams should be effective in reducing sedimentation and increasing channel depth. Stable banks and deeper channels will improve in stream cover. If further increases in cover are warranted, the placement of additional rocks and logs or the installation of half-log structures will be beneficial. Keywords : review; fish habitat; methods; suspended sediment

MacDonald, D.D., Newcombe, C.P. 1993. Utility of the stress index for predicting suspended sediment effects: response to comment. North American Journal of Fisheries Management 13:873-6.

A response to Gregory et al.'s (1993) comments on Newcombe and MacDonald's model. Gregory et al state that the model is too simple - here MacDonald and Newcombe respond with basically that the model was intended for general guidance for managers and that Gregory et al were extending the application beyond that intended - basically they were using it wrong. Keywords : suspended sediment; model

Marcus, M.D., Young, M.K., Noel, L.E., and Mullan, B.A. 1990. Salmonid-habitat relationships in the western United States: a review and indexed bibliography. Rocky Mountain Forest and Range Experiment Station, US Dept. of Agric., Forest Service. Fort Collins, Colorado. RM-188. pp. 1-84.

This report includes a general review and analysis of the literature summarizing the available information relevant to salmonid-habitat relationships, particularly as it pertains to the central Rocky Mountains. Also included is a comprehensive indexed bibliography. Keywords : review; fish habitat; salmonid

Marcuson, P. 1966. Stream sediment investigation. Montana Fish and Game. Helena, Montana. F-20-R-11. pp. 1-7.

Mean monthly water temperatures on Bluewater Creek varied from a high of 73F at station 4 to a low of 36F at station 5. Mean monthly discharge ranged from a high of 81 cfs at station 5 to a low of 3 cfs at station 4. Mean monthly sediment concentrations and loads were lowest at Station 1 and progressively increased downstream. Two streambank improvement projects were completed during the report period. Data collected after completion of these projects indicated a marked reduction in suspended sediment at two stations immediately downstream from the improvements. The brown trout population declined progressively from 100% of the fish population at station 1 to less than 1 percent at station 5. Brown trout comprised 79% of the fish captured at station 3 during the 1966 report period, 12% in 1963 and 20% in 1961. Keywords : sediment concentrations; suspended sediment; brown trout; trout

Marcuson, P. 1968. Stream sediment investigation. Montana Fish and Game Department. Helena, Montana. F-20-R-13. pp. 1-10.

This report describes findings of data gathered during the report period and compares current data with data collected before completion of three stream habitat improvement projects on Bluewater Creek. Maximum and minimum water temperatures, mean monthly discharge and mean sediment data are tabled and discussed for the report period. Mean monthly sediment concentrations and loads were lowest at station 1 and progressively increased downstream. Average suspended sediment load has been reduced by 1.9 tons/day or 32% at station 2, 14.0 tons/day or 52% at station 3 and 10.5 tons/day or 44% at station 4 following the three stream bank improvement projects located near station 2. Trout composition at all stations on Bluewater Creek represented 37% of the fish sampled in 1968 compared to 13% in 1963 prior to habitat improvement. Trout:rough fish ratios were not appreciably altered following a 32% reduction in sediment load at station 2. Corresponding with a 52% reduction in sediment load at station 3, there has been a change in weight ratios of trout:rough fish from 39:61 in 1963 to 63:37 in 1967 to 78:22 in 1968. At station 4, the trout:rough fish weight ratio had changed from 12:88 in 1963 to 34:66 in 1967 to 51:49 in 1968. Keywords : sediment concentrations; suspended sediment; trout; sediment

Marshall, K.E. 1975. An index to the publications of the staff of the Freshwater Institute, Winnipeg; the Biological Station and Technological Unit, London; and the Central Biological Station, Winnipeg: 1944-1973. Res. and Dev. Directorate, Freshwater Institute. Winnipeg, Manitoba. Tech. Rep. No. 505. pp. 1-94.

The scientific publications of the staff of the Freshwater Institute and its forerunners are listed. An index provides access to the publications by individual staff members, about particular species, specific water bodies, and individual subjects. Keyword : bibliography

Martz, L.W., Campbell, I.A. 1980. Effects of a pipeline right-of-way on sediment yields in the Spring Creek watershed, Alberta. Can Geotech J 17:361-8.

Very few data are available on the sediment yield of Alberta watersheds especially in the northern portion of the province. In the 175 000 km^2 Peace River basin, which covers about 25% of Alberta, sediment data are collected regularly at only four stations. One of these is the 112.7 km^2 Spring Creek watershed. In 1977 a pipeline was installed near the mouth of Spring Creek, disturbing an area of about 5000 m^2 near the stream channel. The effects of this were to increase the local sediment yields by over 1600 mg in a 4 month period. This compares with regional averages for the Peace River basin of 18-88 mg/km^2/year. This study indicates the magnitude of spatial variation of sediment production and shows some effects of geotechnical activities on sediment yields. Keywords : pipeline; sediment; Alberta; river

Mason, J.C. 1974. A further appraisal of the response to supplemental feeding of juvenile coho (*O. kisutch*) in an experimental stream. Dept. of the Environment, Fisheries and Marine Service, Research and Development Directorate. Nanaimo, B.C. 470.

Does food or space limit the production of juvenile coho salmon in rearing streams during the summer months? The carrying capacity of the stream during this season can be increased 6-7 times above the natural levels by augmenting the natural food supply with a daily feeding of thawed euphausiids. Growth and biomass yield were inversely related to population density. Supplemental feeding cancelled the density effect on survival and outmigration, accelerated growth rate, and substantially increased the pre-winter lipid reserve, thus corroborating the findings of a previous experiment. During the summer season of low stream flows, juvenile coho populations appear to be regulated at biomass levels commensurate with smolt yield in the subsequent spring. The 6-fold increase in potential smolt yield induced by supplemental feeding during this season was nullified by the natural carrying capacity of the stream overwinter. Projected smolt yield from the remnant population in late winter following several high freshets closely approximated that expected from natural levels of production (1 smolt/4 m^2). The probability of increasing smolt yield by relieving the natural food limits on production during the summer season remains most uncertain unless (1) the overwinter carrying capacity of the specific stream is known to already exceed natural levels of summer population to an appropriate degree, or can be increased to that degree by manipulating environmental factors that determine the overwinter carrying capacity, and (2) food supply is again augmented in the subsequent spring until the smolts migrate to sea. Attempts to increase overwinter carrying capacity by installing artificial refuges were unsuccessful and suggest that the winter behaviour of coho is complex and insufficiently understood to allow for effective manipulation aimed at stimulating overwinter residence at unnaturally high population densities during the winter. Keywords : coho; fish growth; biomass changes; salmon; winter; behaviour; coho salmon

Matthews, W.J. 1984. Influence of turbid inflows on vertical distribution of larval shad and freshwater drum. Transactions of the American Fisheries Society 113:192-8.

Tucker-trawl collections showed that behavior of larval shad *Dorosoma* spp. and freshwater drum *Aplodinotus grunniens* was altered by inflow of turbid water into Lake Texoma (Oklahoma-Texas) in two different years. During periods of increased turbidity, larval shad were concentrated in a reduced volume of water near the surface, and larval freshwater drum were distributed throughout the water column in contrast to their normal concentration near the bottom. In 1981 and 1982, greatest decline in abundance of larval shad came after zooplankton density fell below 100 per liter, and during or immediately following an extended period of high turbidity. Nutritional stress resulting from decline in zooplankton abundance and changes in larval-fish behaviour during turbid conditions could be one important factor in population dynamics of shad in reservoirs. Keywords : lake; turbidity; zooplankton; behaviour; larval fish

McAuliffe, J.R. 199. Competition, colonization patterns and disturbance in stream benthic communities.[Unpublished]

A discussion paper with data on benthic invertebrate community information from a fourth-order stream in Montana. Discusses competition, and coexistence of species of different benthic functional groups under various disturbance regimes (eg. spates, anchor ice formation, and frazil ice) all of which are capable of resulting in scouring the stream bottom. He also discusses predation as a form of disturbance and effects of predation on the benthic community. Keywords : disturbance; benthic invertebrate community

McCabe, G.D., O'Brien, W.J. 1983. The effects of suspended silt on feeding and reproduction of *Daphnia pulex*. The American Midland Naturalist 110(2):324-37.

This paper reports the effect of suspended silt on the feeding and reproduction of *Daphnia pulex* and the impact of suspended silt and clay on freshwater zooplankton community structure. The effects of suspended silt and clay on the filtering and assimilation rates of *Daphnia pulex* were determined using a ^{14}C radiotracer method. Both filtering and assimilation rates are severely depressed at even low concentrations of suspended silt and clay. Life table studies also showed population growth rate of zooplankton was significantly diminished by suspended silts and clays. The relative abundance of zooplankton varied markedly between two lakes of differing turbidity levels, the more turbid lake having a higher relative abundance of large zooplankton species. Suspended silt and clay reduced zooplankton feeding and production but probably influenced zooplankton community structure by impairing the ability of visually feeding planktivorous fish to locate their prey. Keywords : reproduction; zooplankton; methods; lake; turbidity

McCart, P.J. and deGraaf, D. 1972. Chapter IV: Effects of disturbance on the benthic fauna of small streams in the vicinity of Norman Wells, N.W.T. Canadian Arctic Gas Biological Report Series. Vol. 15, Chapter IV. pp. 1-31.

Keywords : disturbance; pipeline; benthos; sediment; drift

McElravy, E.P., Lamberti, G.A., and Resh, V.H. 1989. Year-to-year variation in the aquatic macroinvertebrate fauna of a northern California stream. Journal of the North American Benthological Society 8(1):51-63.

The benthic macroinvertebrate community of a third-order coastal stream in northem California was examined in mid-May (end of the wet season) and late August (near the end of the dry season in the prevailing Mediterranean climate of the region) over a 7 year period in which there was substantial year-to-year variability in precipitation and consequently, stream discharge. Ephemeroptera, trichoptera, and diptera were the dominant components of the macrobenthic community accounting for 93% of total individuals and 62% of the 81 taxa collected in mid May, and 96% of the total individuals and 64% of the 69 taxa collected in late August. In mid May, significant reductions in species richness and Simpson's diversity were observed during a year of extreme drought and in years with above-average wet season rainfall. Macroinvertebrate density decreased and relative abundance of Chironomidae increased as wet season rainfall increased. In late August, year-to-year variability in community parameters measured was substantially reduced. Drought conditions favored proliferation of a few tolerant taxa (eg the caddisfly). An understanding of the influence of abiotic conditions on biotic pattems can be useful in separating effects of perturbation from natural variability. Keywords : benthic invertebrate community; disturbance; invertebrate community changes; macroinvertebrates

McKinnon, G.A. and Hnytka, F.N. 1988. The effect of winter pipeline construction on the fishes and fish habitat of Hodgson Creek, NWT. Central and Arctic Region, Dept. of Fisheries and Oceans. Winnipeg, Manitoba. no. 1598. pp. 1-43.

During the winter of 1984/85 a small (30.5 cm) diameter underground pipeline was built across Hodgson Creek, NWT as part of a line from Norman Wells, NWT to Zama, Alberta. The effects of construction and operation of this ambient temperature oil pipeline on fish and fish habitat in Hodgson Creek were studied from 1983 to 1987.
There was no detectable effect of pipeline construction or operation on stream discharge, velocity, temperature, dissolved oxygen or water chemistry.
Winter bridge construction in December, 1984 increased the instantaneous total suspended sediment (TSS) level from 2 mg/L to 3524 mg/L. Other construction activities including pipe-laying and backfilling produced lesser increases in TSS than did trenching. High TSS levels attenuated quickly both over time and distance; four days after all in-stream construction ceased the TSS values downstream of the construction site equalled pre-construction values.
Twenty-four hour average deposition in sediment collectors placed 50 m downstream of the pipeline increased from <1 mg/hr to 140 mg/hr as a result of construction activity.
The headwaters of Hodgson Creek provide winter habitat for Arctic grayling (*Thymallus arcticus*), slimy sculpin (*Cottus cognatus*), and a small number of lake chub (*Couesius plumbeus*), longnose sucker (*Catostomus catostomus*), burbot (*Lota lota*) and northem pike (*Esox lucius*). Winter pipeline construction across the lower portion of this overwintering habitat appears to have had no effect on the fish which reside there during the winter.
It is postulated that the Arctic grayling which overwinter in the headwaters of Hodgson do not comprise a resident population because no mature Arctic grayling were captured there during winter. Keywords : pipeline; fish habitat; fish biology; suspended sediment; sediment deposition; winter; Alberta

McLeay, D.J., Birtwell, I.K., Hartman, G.F., and Ennis, G.L. 1987. Responses of arctic grayling (*Thymallus arcticus*) to acute and prolonged exposure to Yukon placer mining sediment. Can J Fish Aquat Sci 44:658-73.

Underyearling arctic grayling from the Yukon river system were exposed for 4 days to suspensions of fine inorganic (less than or equal to 250 g/L) and organic (less than or eq to 50 g/L) sediment and for 6 weeks to inorganic sediment (<or eq to 1000 mg/L) under laboratory conditions. The test sediments were collected from an active placer mining area near Mayo, Yukon Territory. The exposures evoked sublethal responses but did not cause gill damage. Mortalities (10-20%) occurred only in experiments at 5C with inorganic sediment concentration > or eq to 20 g/L. Six weeks of exposure to sediment concentrations >100 mg/L impaired feeding activity, reduced growth rates, caused downstream displacement, colour changes, and decreased resistance to the reference toxicant pentachlorophenol, but did not impair respiratory capabilities. Stress responses (elevated and/or more varied blood sugar levels, depressed leucocrit values) were recorded after short exposure (1-4 days) to organic sediment concentrations as low as 50 mg/L. Inorganic sediment strengths > or eq to 10 g/L caused fish to surface. The lethal and sublethal responses of arctic grayling to pentachlorophenol were similar to those determined for other healthy salmonid fishes. Keywords : grayling; sediment concentrations; salmonid; suspended sediment; fish effects; underyearling; Yukon; sediment; river; laboratory; placer mining

McLeay, D.J., Ennis, G.L., Birtwell, I.K., and Hartman, G.F. 1984. Effects on Arctic Grayling (*Thymallus arcticus*) of prolonged exposure to Yukon Placer Mining sediments: a laboratory study. Canadian Technical Report of Fisheries and Aquatic Sciences, Department of Fisheries and Oceans, Habitat Management Division, Field Services Branch. Vancouver, B.C. No. 1241. pp. 1-96.

The effects on underyearling Arctic grayling (*Thymallus arcticus*) of a six-week exposure to differing strengths of suspended placer mining sediment was examined under controlled laboratory conditions during the summer of 1983. Groups of sixty grayling captured from a Yukon River tributary stream were transferred to eight test streams and acclimated to laboratory feed and water quality conditions. Thereafter, sediment collected from the downstream end of a Yukon placer mine settling pond was introduced continuously to six streams at a controlled rate in order to expose fish to suspended sediment concentrations of 100, 300, or 1000 mg/L (two streams per treatment). Two control streams continued to receive clear (nonfilterable residue <5 mg/L) freshwater. Fish in each stream were fed a measured ration (7% wt/day) of Biodiet, 4-5 times daily, together with supplemental feeding of live zooplankton (*Daphnia pulex*). Water quality conditions for each stream including temperature (15± 1°C), ph (6.6 ± 0.1), conductivity (30 ±5 umho/cm), dissolved oxygen (9.4 ±0.2 mg/L), nonfilterable residue and turbidity, were monitored daily.

The survival of fish in each stream throughout the 6-week test period was high (87-95%) and unaffected by the sediment suspensions. Fish growth, as monitored by weekly weighings of individual fish, was decreased slightly (6-10% relative to control fish) but significantly by 100 and 300 mg/L and more markedly impaired (33% relative to controls) by 1000 mg/L. The linear distribution of grayling in each stream was unaffected by the lowest (100 mg/L) suspended sediment strength examined; however, the majority of fish held in each stream containing 300 to 1000 mg/L sediment were displaced downstream throughout the test period.

Feeding response trials were conducted in each stream using live surface drift (adult fruit flies; *Drosophila melanogaster*), sub-surface drift (brine shrimp, *Artemia salina*) and benthic invertebrates (tubificid worms). Times to detect and consume surface drift for naive fish (previously unexposed to sediment) or those held in test streams for 5 weeks increased progressively with increasing sediment strengths. All suspended sediment strengths examined increased the response times relative to those for control fish. For each respective concentration, naive fish were slower to respond to surface drift. The majority of naive fish held in 1000 mg/L sediment failed to accept the surface or sub-surface food types offered. Feeding trials conducted with grayling offered brine shrimp or tubifex worms in each test stream after 5 or 6 weeks sediment exposure indicated that the feeding activity of fish in 1000 mg/L suspended sediment was impaired, whereas those reared in 100 or 300 mg/L sediment responded to these sub-surface food types as quickly as control fish in clear water.

The colouration of fish exposed to 300 or 1000 mg/L suspended sediment was paler than that of controls or those held in 100 mg/L sediment for 6 weeks. Otherwise, the appearance of all sediment exposed fish (including gross observations of fish gills) was indistinguishable from that of controls. Biological characteristics determined for fish groups sampled from each stream after 6 weeks sediment exposure, including condition factor, body moisture content (%), blood hematocrit (%), blood leucocrit (%) and plasma glucose (mg%), were unchanged from control values for all sediment strengths examined.
The performance of fish groups sampled from each laboratory stream upon completion of the 6-week exposure was examined using standardized acute lethal tolerance tests with the reference toxicant pentachlorophenol, sealed jar bioassays (tolerance to hypoxia), and tests for upper lethal temperature tolerance. Both groups of fish chronically exposed to the two higher suspended sediment strengths examined (300 or 1000 mg/L) showed a decreased tolerance to this reference toxicant, and decreased times of death (increased oxygen uptake rates) in sealed jar bioassays. The ability of fish to withstand hypoxia or upper lethal temperature extremes was unaffected by the prolonged sediment exposures.
It was concluded that, whereas chronic exposure of Arctic grayling to suspended sediment concentrations < or = 1000 mg/L may not cause direct mortalities to fish or impair their respiratory capabilities, suspended sediment strengths above 100 mg/L causes a number of serious sublethal effects including impaired feeding ability, reduced growth rates, downstream displacement, decreased scope for activity and decreased resistance to other environmental stressors. The environmental relevance of these findings is discussed. Keywords : grayling; Yukon; placer mining; sediment; laboratory study; chronic; underyearling; water quality; suspended sediment; sediment concentrations; zooplankton; temperature; turbidity; laboratory; river

McLeay, D.J., Knox, A.J., Malick, J.G., Birtwell, I.K., Hartman, G., and Ennis, G.L. 1983. Effects on Arctic grayling (*Thymallus arcticus*) of short-term exposure to Yukon placer mining sediments: laboratory and field studies. Canadian Technical Report of Fisheries and Aquatic Sciences, Department of Fisheries and Oceans, Fisheries Research Branch. Vancouver, B.C. No. 1171. pp. 1-134.

A program of controlled laboratory and in situ field bioassays was conducted during 1982/83 to examine the acute effects of suspensions of Yukon placer mining sediment on underyearling Arctic grayling (*Thymallus arcticus*). Wild grayling captures as swimup fry or young fingerlings, were acclimated to warmwater (15°C) or coldwater (5°C) conditions for 7-12 weeks, and subjected to a range of concentrations of organic sediment (overburden) and/or inorganic sediment (paydirt) suspensions in recirculating test tanks. On two occasions (August and September 1982), grayling fingerlings were captured from central Yukon clearwater streams and held for 4 or 5 days in cages within turbid creekwater (Highet Creek) downstream of placer mining activities, and at a nearby clearwater site (Minto Creek upstream of its junction with Highet Creek).
Laboratory-reared grayling acclimated to 15°C survived a 4 day exposure to inorganic sediment suspensions < or = 250 000 mg/L, and a 16 day exposure to 50 000 mg/L. These fish also survived acute (4 day) exposure to all strengths of organic sediment examined (<50 00 mg/L). All fish acclimated to 5°C and held in paydirt suspensions < or= 10 000 mg/L survived for 4 days, whereas 10-20% mortalities occurred in the higher strengths examined.
Inorganic sediment strengths > or = 10 000 mg/L caused fish to surface, a direct response to elevated sediment levels. No other behavioural anomalies were evident. Other signs of fish distress or damage were not observed for any grayling surviving exposure to either sediment type. The gill histology of fish surviving these 4 day exposures was normal.
The tolerance of laboratory-reared grayling to temperature extremes (critical thermal maxima) was not impaired appreciably by either sediment type. Slight but consistent declines in critical thermal maxima were noted for warmwater-acclimated fish held in inorganic or organic sediment strengths > or= 500 mg/L and > or= 5 000 mg/L respectively, whereas changes in thermal

tolerance were not found for fish acclimated to cold water and held in high strengths of inorganic sediment.

The acute tolerance of warmwater- or coldwater-acclimated fish to hypoxic conditions (oxygen deficiency) in sealed jar bioassays was not impaired by suspended sediment. Tests with overburden suspensions showed a decreased time to death in these bioassays, which was attributed to the sediment's oxygen demand. High concentrations of paydirt increased time to death (decreased respiratory rate) in sealed jar bioassays for warmwater-acclimated fish only.

Suspensions of inorganic and organic sediment caused acute stress responses (elevated and/or more varied blood sugar levels, depressed leucocrit levels) for grayling acclimated to either temperature. Responses were noted for sediment strengths as low as 50 mg/L (overburden), although confirmation of threshold-effect levels requires further studies. Hematocrit values for these fish were not affected by sediment.

Acute (short-term) effects toward Arctic grayling of the reference toxicant pentachlorophenol were examined in laboratory bioassays. Median lethal concentrations were similar to those found previously with this aquatic contaminant and other species of salmonid fish, and were not affected by acclimation temperatures. The effects on grayling of sublethal strengths of pentachlorophenol noted for temperature tolerance tests, sealed jar bioassays and acute stress bioassays were also similar to those determined before with other juvenile salmonids.

During the August field bioassays, all grayling held in Highet Creek (suspended solids < or= 100 mg/L) or Minto Creek (suspended solids < or =20 mg/L) for 4 days survived, with no overt signs of distress or physical damage. In September, all fish captured from Minto Creek and held in cages within Highet Creek (suspended solids < or =1 210 mg/L) or Minto Creek (suspended solids < or =34 mg/L) for 5 days also survived. Gill tissues of fish sampled in September from cages at each site showed moderate-to-marked hypertrophy and hyperplasia of lamellar epithelium, together with a proliferative number of gill ectoparasites. No histopathological differences were found between sites. The gill histology of uncaged grayling sampled directly from Minto Creek upstream of Highet Creek was normal, although occasional ectoparasites were observed.

All grayling captured from Mud Creek (a clearwater tributary of Minto Creek) and held for the same 5 day period during September in cages within Minto Creek survived; whereas 16% (5 of 32 fish) of the Mud Creek fish held at this time in Highet Creek, died within 96h. The cause of these deaths was attributed to an intolerable stress loading imposed by the combined effects of fish capture, transport, confinement, and exposure to suspended sediment and temperature fluctuations within Highet Creek.

Although hematocrit values measured for fish caged at either site were similar, mean plasma glucose values for fish held for 4 days within Highet Creek during August were elevated 30% from values for fish caged in Minto Creek at this time. During September, grayling captured from either Minto Creek or Mud Creek and caged in Highet Creek showed a 100% increase in mean plasma glucose levels, relative to values for corresponding groups held in Minto Creek. These differences were thought to be caused by the more stressful water quality conditions (suspended sediment loadings and/or more extreme temperature differences) within Highet Creek, compared with the Minto Creek site.

It was concluded that the short-term exposure of Arctic grayling to sublethal concentrations of suspended inorganic and organic sediment can cause a number of effects including acute stress responses. In light of these findings, the environmental impact of placer mining sediments on the immediate and long-term adaptive capabilities (including feeding and other behavioural responses, disease resistance, growth and chronic well-being) of this sensitive fish species needs to be more fully understood. Keywords : grayling; Yukon; placer mining; sediment; field study; laboratory; underyearling; fry; Young

Meehan, W.R., Farr, W.A., Bishop, D.M., and Patric, J.H. 1969. Some effects of clearcutting on salmon habitat of two southeast Alaska streams. USDA Forest Service Research Paper. Juneau, Alaska. PNW-82. pp. 1-45.

Summary: One of the first major timber harvests in Alaska began in the mid-1950's on Prince of Wales Island, providing an opportunity to study some of the physical effects of logging on salmon stream habitat. Three watersheds in the vicinity of Hollis, on Prince of Wales Island, were selected as the study area; about one-fourth of the Maybeso Creek watershed (total area, 15.2 square miles) and one-fifth of the Harris River watershed (31.8 square miles) were clearcut by high-lead cable logging methods.

Streamflow from the two logged watersheds did not change in comparison with nearby, unlogged Indian Creek. Similarly, Harris River showed no influence of clearcutting on the relationship between rainfall and peak flows. Likely changes in streamflow as a result of logging might have been detected if precipitation and streamflow had been measured with an accuracy of 2-3 %. This accuracy was not approached.

Although sampled concentrations of suspended sediment for given levels of Harris River were higher during logging than before, these changes were not statistically significant. Maximum increase in average monthly stream temperature at the gauging sites in Harris River and Maybeso Creek was 4F. However, maximum observed temperatures appear to have increased up to 9F in summer months. The temperature increase is believed to be associated with removing streamside timber. Although changes in winter stream temperatures resulting from logging are not conclusive, the data suggest that logging has little effect on the 32 to 34F temperatures that extend to spring.

Mapping and aerial photography indicated that logs and debris increased in Maybeso Creek during and after logging. This is probably due to logging of relatively high-volume timber and to poisoning of alder on the streambanks. A small increase in absolute number of logs and debris pieces occurred in Harris River during and after clearcutting. The initial number of pieces was small compared with Maybeso Creek and remained so during and after logging.

Clearcutting apparently did not adversely affect the salmon spawning habitat, based upon the returns of pink and chum salmon spawners to the study streams in the years during and after logging. An increase in numbers of spawners following clearcutting undoubtedly was associated with nonrelated factors. The greatest increases in summer stream temperatures occurred when pink and chum salmon spawning runs were just beginning to enter the systems in sizable numbers; somewhat higher stream temperatures in October and November conceivably could alter the normal incubation, emergence and seaward migration of salmon eggs and fry, although supporting evidence is lacking. Increased amounts of logs and debris in the streams during and after clearcutting could reduce access to and amount of suitable spawning area; however, such barriers were not observed during the study. Keywords : salmon; logging; suspended sediment; fish eggs; methods

Megahan, W.F., Kidd, W.J. 1972. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. Journal of Forestry (March):136-41.

Erosion plots and sediment dams were used to evaluate the effects of jammer and skyline logging systems on erosion and sedimentation in steep, ephemeral drainages in the Idaho Batholith of central Idaho. Five-year plot data indicated that no difference in erosion resulted from the two skidding systems as applied in the study. Sediment dam data obtained concurrently showed that the logging operations alone (excluding roads) increased sediment production by a factor of about 0.6 over the natural sedimentation rate. Roads associated with the jammer logging system increased sediment production an average of about 750 times over the natural rate for the six-year period following construction. Keywords : logging; erosion; sediment; sediment deposition; dam; sedimentation; forestry

Megahan, W.F., Platts, W.S., and Kulesza, B. 1980. Riverbed improves over time: South Fork Salmon. Symposium on Watershed Management. Am. Soc. Civ. Eng. New York. 380-395.

The South Fork of the Salmon River historically supported one of Idaho's largest chinook salmon runs as well as a large run of steelhead trout. During the period from 1950 to 1965, considerable logging and attendant road construction activities took place in the South Fork watershed. A combination of highly erodible soils, steep slopes, widespread soil disturbances from logging and road construction, and some large storms in 1955, 1962, 1964 and 1965 caused severe sedimentation in the river that literally buried many of the prime salmon spawning and rearing areas with sand. The USDA Forest Service responded to the problem by developing a restoration program that included a moratorium on all road construction and logging activities and a variety of watershed rehabilitation practices. River responses were monitored by photographic documentation, surveys of channel cross sections to document changes in bottom elevation, a series of transects to evaluate the particle-size distribution on the surface of the riverbed in both chinook salmon spawning and rearing areas, and core samples of the channel bottom to determine changes in the particle-size distribution of the channel substrate in the spawning areas. Data collected over the years from 1966-1979 show statistically significant decreases in bottom elevation and increases in the particle size of bottom materials indicating an improvement in fish habitat conditions. Improvement was dramatic enough to provide the basis for a cautious reentry into the South Fork watershed for timber harvest purposes beginning in 1978. A second paper describes how this is to be accomplished. Keywords : salmon; highway construction; logging; silt effects on habitat; recovery; steelhead; trout; disturbance; sedimentation; fish habitat

Mende, J. 1989. River and stream investigations: Portneuf River Assessment. Idaho Dept of Fish and Game and Idaho State University. Pocatello, Idaho. F-71-R-12 sub. 3, J4. pp. 1-72.

Sediment levels varied between transects on the upper Portneuf River, showing possible evidence of the effect macrophytes exert on sediment transport. For the period June through September 1986, transect D consistently had the greatest level of accumulated sediment. For the period July through October 1987, transect A sediment levels increased while those of transect D decreased. Average sediment depth for the study was 7.7 cm.
Diptera was the most numerous taxon in the benthos, accounting for 49.5% of the total abundance. It was followed by two species of Ephemeroptera (20.5%) and several Trichoptera species, with *Helicopsyche borealis* the most abundant. Invertebrate densities declined overall in 1987 as compared to those of 1986. Values ranged from 133 organisms/m^2 in 1987 to 76, 400 organisms/m^2 in 1986. Species richness at transect A ranged from 8 species in June 1986 to 25 in August 1986. Drift was also reduced in 1988 as compared to samples collected in 1979.
The aquatic herbicide, xylene, was lethal to test organisms at a distance of 7 km downstream of the injection site. The herbicide was not detected in the Portneuf River downstream of the application site in the Portneuf-Marsh Valley Canal. More than fifty wild rainbow trout redds were located below the Anderson Bridge area. Lesser numbers were noted at the Slaughterhouse and Pebble Bridge sites. Spawning areas were associated with mid-channel islands. A total of 2153 fish were collected by electrofishing selected river sections. Wild rainbow trout accounted for 67% of the total with cutthroat 24%. A total of 498 sexually mature wild rainbow trout were collected; 58% females and 42% males. Males preceded females in readiness to spawn.
McNeil core results of fine sediments less than 6.3 mm ranged from 32.9% at the Anderson Bridge site to 88.7% at the Broxon Bridge site. Sediment levels increased within the redds over a four week period. Embryo survival was found by examination of two redds each from the Slaughterhouse and Anderson Bridge sites. A total of 417 eggs were collected at the two sites; 146 remained alive (35%) and 271 dead (65%). Keywords : salmonid production; fish habitat; benthic invertebrate community; fish eggs; macrophytes; sediment transport; sediment

Milhous, R.T. 1994. Flushing flows for the water manager. Fontane, D.G. and Tuvel, H.N. editors. Water Policy and Management: Solving the Problems. Proceedings of the 21st Annual Conference. 23 May 1994; American Society of Civil Engineers; New York, New York. 226-229.

Summary: The need for a flushing flow to remove sand and fines from a gravel bed river has changed to one of managing sediment in a river. Some of the change is expressed as a need to have flushing flows for aquatic animals in addition to traditional needs associated with salmon and trout. But in many cases the need is to manage sediment in the stream as part of meeting the instream flow needs of the aquatic system. Keywords : hydrology; methodology; flushing flows; salmon; trout; sediment

Milhous, R.T. 1994. Sediment balance and flushing flow analysis: Trinity River case study. Proceedings of American Geophysical Union 14th Annual Hydrology Days. 05 April 1994; Publications; Atherton, California. 281-292.

The use of sediment yield as one aspect of a flushing flow analysis is explored in a case study of the Trinity River in northwestern California. Understanding sediment balance can help in the development of a flushing flow need, but hydraulic analysis must also be done. The most important flushing flow need for the Trinity River is to increase the Trinity River flows when flows in the Grass Valley Creek and other tributaries draining the Shasta Bally Batholith are high. The goal is preventing deposition of sand and fines. These flows should be followed by clear-water flushing (ie. flushing flows when the tributaries are not high) to remove fines and sand from the stream bed. Keywords : flushing flows; suspended sediment; recovery; hydrology

Milner, N.J., Scullion, J., Carling, P.A., and Crisp, D.T. 1919. The effects of discharge on sediment dynamics and consequent effects on invertebrates and salmonids in upland rivers. No Name :153-220.

Keywords : salmonids; review; sediment transport; model; silt effects on habitat

Morse, B., Townsend, R.D., and Sydor, M. 1991. Mathematical modelling of riverbed dynamics - a Canadian case study. Can J Civ Eng 18:772-80.

A new mobile-bed mathematical model for simulating sediment transport in river networks under unsteady flow conditions is presented. The new model, ONE-D-SED, is an extended version of the extensively validated fixed-bed, one-dimensional hydrodynamic model ONE-D. This paper reports the results of an application of ONE-D-SED to simulate bed profile development along a 43-km long tidal channel network of the Lower Fraser River in British Columbia. The sand-bed study reach has been undergoing degradation caused by navigational dredging and river training works in lower channel reaches and by borrow dredging within the study reach itself. ONE-D-SED was used to simulate bed degradation in the study reach during the 1979-1984 period. The simulated annual change in bed elevation at the downstream end of the study reach showed good agreement with that observed during 1968, the data year used to calibrate the model. The predicted cumulative change in bed profile from 1979 to 1984 also compared favourably with the overall degradation pattern observed during that same period. Keywords : model; sediment; sediment transport; flows; Fraser River; British Columbia; river

Neff, J.M., Cornaby, B.W., Vaga, R.M., Gulbransen, T.C., Scanlon, J.A., and Bean, D.J. 1988. An evaluation of the screening level concentration approach for validation of sediment quality criteria for freshwater and saltwater ecosystems. Aquatic Toxicology and Hazard Assessment: 10th Volume 10:115-27.

The U.S. Environmental Protection Agency (EPA) has initiated an effort to develop sediment quality criteria for both freshwater and marine ecosystems. The Screening Level Concentration (SLC) approach is one of several methods EPA is evaluating for calculating sediment quality criteria. The SLC approach uses field data on the co-occurrence in sediments of benthic infaunal invertebrates and different concentrations of the nonpolar organic contaminant of interest. The SLC method is designed to estimate the highest concentration (normalized to sediment organic carbon concentration) of a particular nonpolar organic contaminant in sediments that can be tolerated by approximately 95% of benthic infauna. As such the SLC value could be used in a regulatory context as the concentration of a contaminant in sediment that , if exceeded, could lead to environmental degradation. This paper describes the method for calculating the SLC and evaluates the SLC approach empirically for nonpolar organic contaminants in freshwater and marine sediments in terms of its statistical properties and its dependence on the characteristics of the data base. SLCs are calculated for five contaminants in freshwater sediments PCBs, DDT, dieldrin, chlordane, and heptachlor epoxide, and nine contaminants in saltwater sediments (total PCBs, DDT, naphthalene, phenanthrene, fluoranthene, benz(a)anthracene, chrysene, pyrene, and benzo(a)pyrene. The method used to calculate SLCs is illustrated for total PCBs in freshwater and saltwater sediments. Differences in SLC values for PCBs and DDT between freshwater and saltwater sediments are discussed. The SLC approach demonstrates sufficient merit to warrant further evaluation and elaboration. Given a large enough data base and minor modifications of the methods for calculating an SLC for a specific contaminant, the approach can provide a conservative estimate of the highest concentration, normalized to sediment organic carbon, that 95% of the benthic infauna can tolerate in sediment. Keywords : methods; contaminants; Screening Level Concentration; sediment

Neill, C.R. 1987. Effects of flow regulation on channel morphology, sediment transport and deposition and flushing flows. Expert Report for Nechako River Court Action. Prepared for the Department of Fisheries and Oceans. Northwest Hydraulic Consultants Ltd. Edmonton and Vancouver. DFOR-370. pp. 1-4.

none. Keywords : flows; sediment; sediment transport; flushing flows

Newcombe, C.P. 1994. Suspended sediment in aquatic ecosystems: ill effects as a function of concentration and duration of exposure. Habitat Protection Branch, Ministry of Environment, Lands and Parks, Province of British Columbia. Victoria, British Columbia. pp. 1-298.

Meta-analytical review of nearly 140 articles on suspended sediment pollution in aquatic ecosystems has generated statistically significant correlations, based on nearly 1200 data points, for severity of effect as a function of dose, where dose is defined as the product of concentration of suspended sediment and duration of exposure. Documentation of the rationale for each of these data points is provided.

Two mutually exclusive sub-sets of meta-data show similar patterns: i) meta-data for juvenile salmon show severity of effect (SE)=0.866 $\log_e$[mg*hr/L] - 0.73 (r^2 = 0.85; N=19, P<<0.01); and ii) pooled meta-data (including various life-history phases of fish, phytoplankton, zooplankton, algae, and damage to aquatic habitats) show severity of effect (SE)=0.738 $\log_e$[mg*hr/L] + 2.179 (r^2=0.638; N=20, P<0.01).

Impacts as a function of Stress Index (where Stress Index is defined as the natural logarithm of dose) can be displayed in a 3x3 matrix. Key findings are i) harmless transient effects are generally associated with a Stress Index less than 6; ii) sublethal effects and other effects such as reduced survival of egg incubation are generally associated with a Stress Index less than or equal to 12; and, lethal effects and habitat damage predominate when the Stress Index is greater than 12.

Other potential correlations exist in the data but have not been confirmed statistically: i) severity of effect is an inverse function of particle size (large particles are more harmful than small ones); ii) severity of effect is a function of particle roughness and angularity (angular particles are more harmful than smooth particles); iii) severity of effect is a function of water temperature (ill effects are generally least severe in cold water except for latent ill effects on incubation of eggs and survival of alevin; iv) among salmon and trout and other species of cold water fish post-larval forms -- adults and juveniles -- are relatively more hardy than eggs and alevin.

These findings are helpful for managers of cold water fisheries who must assess the probable severity of pollution episodes, thereby to allocate resources for remediation and to apportion penalties. Keywords : suspended sediment; sediment; fish effects; macroinvertebrates; turbidity; review

Newcombe, C.P. 1995. Suspended Sediment Pollution: Dose Response Characteristics of Various Fishes. Habitat Protection Branch, Ministry of Environment, Lands and Parks. Victoria, B.C. pp. 1-50+.

This study establishes the most probable severity-of-effect (MPE) thresholds for the onset of behavioural, sublethal, and lethal effects in fishes exposed to suspended sediment pollution. Six sets of thresholds -- for various species, natural histories, and life history phases -- are based on data gleaned by meta-analysis of published literature on the ill effects of suspended sediment pollution. MPE thresholds are based documented ill effects as a function of stress index (SI). SI is the natural logarithm of dose (where dose = concentration x duration and has the units mg x hr/L).

For salmon, trout and grayling (adults and juveniles, but not eggs, not young fry) --fish that bury their eggs, or in the case of grayling, lightly cover their eggs -- the most probable effect thresholds are: behavioural, SI<4; sublethal, SI<9; and lethal, SI>9, (n=165). For juvenile salmon, grayling and trout the most probable effect thresholds are: behavioural, SI<6; sublethal, SI=<11; and lethal, SI>11, (n=94). Although this finding makes it appear that juvenile salmon are more resistant to the ill effects of suspended sediment than adults, this is probably not the case. Most of the work on juvenile salmon focuses on turbidity. Since turbidity is usually created by fine particulate matter the differential effect (adults vs juveniles) probably reflect the diminished impact of smaller particle sizes used in lab and field studies on this life stage. For eggs and young fry the most probable effect thresholds are: behavioural, SI<4; sublethal, SI<6), (n=26).

For larvae and eggs of herring (lake, Pacific, and Atlantic), perch (white and yellow), striped bass and American shad -- fish that do not bury their eggs -- the most probable effect thresholds are: behavioural, SI<4; sublethal, SI<8; and lethal, SI=>8, (n=23). For some adult fishes of the estuary, American shad, Atlantic silverside, bay anchovy, common mummichog, cunner, fourspine stickleback, harlequin, herring, hogchoker, menhaden, oyster toadfish, sheepshead minnow, spot and striped killifish -- the most probable effect thresholds are: behavioural, SI<5; sublethal, SI<7; and lethal, SI =>, (n=66).

And, for non-salmonid fishes (adult fishes; stream and still-water habitats; cold water, temperate, and warm water); the most probable effect thresholds are: behavioural, SI<5; sublethal, SI<10; and lethal, SI =>10, (n=25). Keywords : suspended sediment; sediment; fish effects; turbidity

Newcombe, C.P. and Jensen, J.O.T. 1995. Channel Sediment: Quantitative Impact Assessment for Fisheries. Habitat Protection Branch, Ministry of Environment, Lands and Parks. Victoria, B.C. pp. 1-45+.

This study, which is based on meta-analysis of published reports (n=82), presents six dose-response equations for fishes exposed to pollution by suspended sediment. The data (n=267) are organized according to three biological variables: taxonomic group, life stage, and natural history; and for abiologic variables: [x], [y], and [μ] where,

[x]= duration of exposure expressed as the natural log of hours;

[y]= concentration of sediment expressed as natural log of mg/L;

[z]= severity of ill effect (SE) on a 15-step scale that ranges from 0 to 14. SE=0 represents nil effect, SE=1 to <or= to 3 represents behavioural effects; SE=4 to <or= 9 represents progressively severe sublethal effects; and SE= 10 to <or=14 represents progressively severe lethal effects, or habitat damage, or reduced population size, or all of these; and,

[μ]= particle size. Pooled data for adult salmonids include ill effects caused by exposure to sediment particles that are estimated to range in size from 0.5 to <250 microns (fine clay to medium sand), whilst pooled data for other life history stages include ill effects caused by particles estimated to range in size from 0.5 to <75 microns (fine clay to very fine sand).

Dose-response surfaces based on these data are,

1. Trout, salmon, grayling and Rocky Mountain whitefish (not eggs), particle size range 0.5 to <250 microns, estimated: **$z=1.0642+0.6068x+0.7384y$; $r^2(adj)=0.6009$; n=171;**

2. Adult salmon, grayling and trout (not eggs; not young fry; not fry; not juveniles), particle size range is predominantly 0.5 to <250 microns, estimated:
$z=1.6814+0.4769x+0.7565y$; $r^2(adj) = 0.6173$; n = 63;

3. Under-yearling salmon, grayling and trout (not eggs; not adults), particle size range is predominantly 0.5 to <75 microns, estimated:
$z= 0.7262+0.7034x+0.7144y$; r^2 (adj) = 0.5984; n=108;

4. Eggs and young fry of salmon, trout and grayling; and, larvae and eggs of herring, perch, bass and shad, where particle size range is predominantly 0.5 to <75 microns, estimated: **$z=3.7466+1.0946x+0.3117y$; r^2 (adj) = 0.5516; n=43;**

5. Some adult fishes of the estuary (American shad, Atlantic silverside, bay anchovy, fourspine stickleback, herring, menhaden and spot) where particle size range is predominantly 0.5 to <75 microns, estimated:
$z=3.4969+1.9647x+0.2660y$; $r^2(adj)=0.6200$; n=28; and
6. Some non-salmonid fishes (adult fishes and populations of cold, temperate, and warm waters; stream and still-water habitats, including bass, bluegill, carp, darters, minnow, sunfish and other unspecified fishes), where particle size range is predominantly 0.5 to <75 microns, estimated: **$z=3.2547+0.7461x+0.3861y$; $r^2(adj)=0.7004$; n=25.**

In addition to these equations, the study provides best-available estimates of the onset of sub-lethal effects, based on manual interpolation of the average severity-of-ill-effect scores in the rows and columns of the data-presentation matrixes. Placement of these thresholds on the dose-response continuum is generally consistent with the location of the predicted transitions from behavioural to sub-lethal effects, and from sub-lethal to lethal effects, generated by the dose-response equations. These results lend support to the hypothesis that the onset of a type of ill effect (sub-lethal, or lethal) can begin to occur among susceptible individuals at doses generally associated with a lesser effect.
The research provides new understanding of channel sediment impacts. Discussion includes i) ultrasensitivity in some species and life-stages; ii) potential changes in data collection for law enforcement; iii) examination of meta-analysis as a research method in fisheries habitat impact assessment; and iv) an expression of concem about land use as a source of channel sediment, and the need for better protection of instream, riparian and upland zones.
. Keywords : sediment; fish habitat; fish effects; salmonid; fish eggs; turbidity; suspended sediment

Newcombe, C.P., MacDonald, D.D. 1991. Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management 11:72-82.

Resource managers need to predict effects of pollution episodes on aquatic biota, and suspended sediment is an important variable in considerations of freshwater quality. Despite considerable research, there is little agreement on environmental effects of suspended sediment as a function of concentration and duration of exposure. More than 70 papers on the effects of inorganic suspended sediments on freshwater and marine fish and other organisms were reviewed to compile a data base on such effects. Regression analysis indicates that concentration alone is a relatively poor indicator of suspended sediment effects ($r^2=0.14$, NS). The product of sediment concentration (mg/L) and duration of exposure (h) is a better indicator of effects ($r^2=0.64$, $p<0.01$). An index of pollution intensity (stress index) is calculated by taking the natural logarithm of the product of concentration and duration. The stress index provides a convenient tool for predicting effects for a pollution episode of known intensity. Aquatic biota respond to both the concentration of suspended sediments and the duration of exposure., much as they do for other environmental contaminants. Researchers should, therefore, not only report concentration of suspended sediment but also duration of exposure of aquatic biota to suspended sediments. Keywords : suspended sediment; model; fish effects; sediment; contaminants

Noggle, C.C. 1978. Behavioural, physiological and lethal effects of suspended sediment on juvenile salmonids. University of Washington; 1-87 pp.

Studies were conducted to assess the effects of suspended sediment upon juvenile salmonids in the stream environment. Static bioassay tanks were used to determine 96 hour LC50's, changes in gill histology, and changes in blood physiology. Two experimental stream designs were used to relate sediment concentrations to avoidance behaviour. Results indicate seasonal changes in the tolerance of salmonids to suspended sediment. Bioassays conducted in summer produced LC50's less than 1500 mg/L, while autumn bioassays showed LC50's in excess of 30,000 mg/L. Histological examination of gills revealed structural damage by suspended sediment. Blood chemistry showed elevated blood glucose levels at sublethal suspended sediment

concentrations. Experiments conducted with a turbid artificial stream and clear tributary indicated a reluctance by the fish to leave their established territories. Studies conducted with a Y-shaped stream showed a preference for turbid water at medium concentrations and slight avoidance at high concentrations. Keywords : suspended sediment; salmonids; juvenile fish; behaviour; fish survival; sediment concentrations; sediment

Northwest Hydraulic Consultants Ltd. 1994. Channel morphology, sediment transport and deposition and flushing flows opinion for the Nechako BCUC hearings. Prepared for Fisheries and Oceans Canada, Habitat Management Division. Vancouver, B.C. DFOR-370.

none. Keywords : sediment; sediment transport; flushing flows; flows; Nechako

Novak, M.A. 1988. Impacts of a fire-flood event on physical and biological characteristics of a small mountain stream. Montana State University; 1-110 pp.

A forest fire burned 4811 ha of the lower Beaver Creek drainage and was followed by an intense convectional rainstorm causing extensive soil erosion. Runoff from the event caused physical and biological degradation of the stream. This study evaluated recovery of trout and aquatic macroinvertebrates, use of the stream by spawning adfluvial rainbow trout, emigration of young-of-the-year rainbow trout to the Missouri River, and changes in substrate composition. Two months after the fire and flood, trout populations in the impacted portion of the stream were nearly eliminated; within 2 years, numbers of age-0 to age-III rainbow trout had increased to 5878/ha (68.68 kg/ha), compared to an abundance of 3841/ha (49.34 kg/ha) before the event. The resident brown trout stock did not recover during the period of study. Numbers of adfluvial rainbow trout spawners using Beaver Creek did not differ significantly from pre-event years, however, there was a large increase in recruitment of young-of-the-year rainbow trout to the Missouri River. Fine sediments<0.85 mm increased significantly ($p<0.05$) in riffle areas following the event; fine sediments decreased 7.7% in riffle areas in 2 years. Adult rainbow trout selected spawning sites containing significantly less fine sediments ($p<0.05$) than were measured in randomly sampled riffles. The benthic community was assumed to have been severely reduced by scouring of the substrates during the flood. The benthic community had recovered by fall 1986, however, percent occurrence of several taxa was lower in the impacted area due to greater embeddedness of cobble substrates. Keywords : recovery; trout; rainbow trout; brown trout; erosion; macroinvertebrates; sediment

Olness, A., Smith, S.J., Rhoades, E.D., and Menzel, R.G. 1975. Nutrient and sediment discharge from agricultural watersheds in Oklahoma. J Environ Qual 4(3):331-6.

Seven cropland watersheds and four rangeland watersheds in central Oklahoma were monitored for surface hydrology and discharge of nitrogen, phosphorus, and sediment over a 1 year period. Precipitation and runoff were much above normal during the study. Sediment losses from the continuously grazed rangeland watersheds ranged from 18 to 23 metric tons/ha during the study. None of the sediment losses from the other watersheds exceeded 10 metric tons/ha.
Total nutrients discharged in runoff ranged from 2 to 15 kg/ha of N and 1 to 11.5 kg/ha of P. Flow-weighted mean concentrations ranged from 1 to 6 ppm of total N, 0.2 to 1.9 ppm of nitrate-N, 0.5 to 4.8 ppm of total P, and 0.04 to 0.9 ppm of soluble P. Runoff losses of soluble inorganic nitrogen were generally less than those quantities received in rainfall. Concentrations of soluble phosphorus in runoff from the cropland watersheds were much greater than from the rangeland watersheds. Losses of fertilizer nitrogen and phosphorus did not exceed 5% of the most recent applications, although surface runoff was 4 to 10-fold greater than that observed in previous years. Keywords : sediment; hydrology; agricultural

Olson, W.H., Chase, D.L., and Hanson, J.N. 1973. Preliminary studies using synthetic polymers to reduce turbidity in a hatchery water supply. The Progressive Fish-Culturist 35(2):66-73.

Summary: It has been demonstrated through a pilot treatment system that synthetic polymers worked effectively in reducing turbidity of the hatchery water supply. Two years of monitoring the water and recording the turbidity levels of treated and untreated flows were completed. Growth differences between test fish were measured as well as histological changes in gill structure. No adverse effects were noted in fish reared within treated water while those reared in untreated water of high turbidity lost weight and appeared quite inactive throughout the study. A full scale treatment plant using synthetic polymers to reduce turbidity has been designed for use on the main water supply. A change in water quality as a result of less turbidity would allow the hatchery to operate on a daily feeding schedule without interruption and provide a more efficient operation in terms of production, manpower utilization, and total costs. Keywords : turbidity; methods; fish effects; rainbow trout; monitoring; water quality; flows

Patrick, D.M., Mao, L., and Ross, S.T. 1991. Status Report for the Bayou Darter: The impact of geomorphic change on the distribution of Bayou darters in the Bayou Pierre System. Mississippi Dept. of Wildlife, Fisheries and Parks, Mississippi Museum of Natural Science. Jackson, Mississippi. E-1, segment 6. pp. 1-118.

Channel instability is present throughout the Bayou Pierre basin. Field investigations indicate that streambank erosion occurring on the middle reach and the upper reach of Bayou Pierre has been extensive since 1986 and has caused the loss of agricultural and forest land as well as endangering local highways (547 and 28) and bridges. The width of the channel increased 1 to 3 m, and depth increased approximately 1 m from October 1989 to the spring of 1991. Examination and comparison of historic aerial imagery for the Smyma area for the years 1940, 1964, 1978 and 1985 indicate substantial changes in the stream channel. The knickpoint was located approximately 4,115 m downstream from the Smyrna bridge in 1940 and has since progressed more than 5,000 m upstream to a point approximately 1 km above the Smyrna bridge. Bank erosion caused by the upstream movement of the knickpoint is very extensive. The channel length of this reach was shortened approximately 4,100 m from 1940 to 1985 by the cutting off of meander bends related to the upstream migration of the knickpoint. The widening of the channel was accompanied by decreases in sinuousity and increases in depth and channel gradient. The rate of knickpoint movement increased from 46 m/year for 1940-1964, 124 m/year between 1964 and 1978, and 222 m/year for 1978-1985. The gradient increased approximately 17% to 20% from 1978 to 1985 due to meander cutoffs. Channel width increased from 30 to 57 m in the portion of Bayou Pierre near the Smyrna bridge between 1940 and 1985. Land uses including agriculture, deforestation, urbanization, and gravel mining , are extensive in the basin, especially downstream from Foster Creek, where agricultural land extends beyond the buffer zones along the stream banks.

One of the major causes of erosion is the change in climatic conditions since 1973. Thoroughly wetted bank materials resulted from recent atypical precipitation, and frequent high-peaked floods provided dynamics for the occurrence of erosion in the Bayou Pierre basin. Changes in the gradient of Bayou Pierre resulting from the meander belt migration of the Mississippi River may also influence bank instability. Human activities including agriculture, gravel mining, highway construction, and channelization on the Mississippi River downstream from Bayou Pierre changed morphology directly or indirectly, and induced erosion.

The bayou darter, *Etheostoma rubrum*, which is endemic to the Bayou Pierre system, occurs in the shallow, swift areas having stable gravel beds. The upstream distribution of the bayou darter is largely defined by the uppermost locations of knickpoints on Bayou Pierre and its major tributaries, Foster and Turkey creeks. In Bayou Pierre, the upstream movement of the knickpoint has resulted in formation of riffle habitats which have then been colonized by bayou darters. The downstream distribution of bayou darters is largely defined by overlay of Pleistocene loess deposits. The microhabitats of the bayou darter have been disturbed by the sedimentation of silt and clay from erosion upstream, agricultural activities in the overbank areas and gravel mining in the stream. Keywords : gravel mining; erosion; agricultural; mining

Paustian, S.J., Beschta, R.L. 1979. The suspended sediment regime of an Oregon Coast Range stream. Water Resources Bulletin, American Water Resources Association 15(1):144-54.

Armored stream segments may affect the suspended sediment regime of small mountain streams in western Oregon by the release of fine sediments stored in the bed gravels. Sieve analysis of bed materials indicated that at least 30 percent of the suspended sediment yield for the 1975-76 winter had been stored in the stream bed. Suspended sediment concentration during storm-generated runoff were influenced by stream discharge and hydrograph characteristics. Sediment-discharge relations for individual storms were characterized by hysteresis loops. A seasonal flushing of fines was shown by a progressive decrease in the ratio of suspended sediment to stream discharge during the winter runoff period. Keywords : suspended sediment; winter; sediment concentrations; sediment transport; stormflow; sediment

Peters, J.C. 1967. Effects on a trout stream of sediment from agricultural practices. J Wildl Manage 31(4):805-12.

The effects of sedimentation rates, stream discharge and water temperature were studied in Bluewater Creek, Montana. Trout of all ages were abundant where sediment concentrations or loads were low (range in daily load 0.2-11 tons) and stream discharge stable (range in mean daily discharge 10.0-12.0 cfs). Few trout were found where sediment concentrations or loads were high (range in daily load 2-1,800 tons) and discharge erratic (range in mean daily discharge 4-485 cfs). Water temperatures were higher than desirable for trout (above 80 F for more than 3 hours on summer days) in areas of the stream influenced by irrigation surface return flow. The best survival of trout eggs (97% survival) was found where stream discharge was stable and sediment concentrations were low. Keywords : sedimentation; sediment concentrations; trout; fish eggs

Peterson, G.R., Smith, G.M., and Bodnaruk, L. 1978. Some short-term effects of experimental trenching on two streams in the Caribou River Drainage, Manitoba, 1977. Polar Gas Project.

Experimental trenching was carried out in July 1977 across two streams of the Caribou River drainage in northern Manitoba, and measurements were made of suspended sediments and deposition downstream. The distribution of suspended sediments and settling rates were different in the two streams. A high proportion of sand in the streambed material at Site 1 resulted in rapid deposition and relatively low turbidity downstream, whereas a high proportion of fines at Site 2 resulted in less rapid deposition and greater turbidity downstream. Thicknesses of deposition in the study areas were similar at both sites.
On the basis of information in the literature, suspended sediment loads and thicknesses of deposition might have been expected to be sufficient to cause deleterious effects on stream invertebrates and fish at both sites, at least in the immediate vicinity of the trenching. The sampling techniques used in this study, however, appear to have been too insensitive to prove the extent of such effects, although some sample data were suggestive of such changes. Apparent losses of benthic invertebrates and fish are considered to have been mainly the result of deposition, rather than from suspended sediments per se. Some effects would probably persist at both sites until the spring freshet of 1978.
Measured maximum turbidity levels at Site 1 appeared to be about one-half the recommended maximum given in the report on the Mackenzie Valley Pipeline Inquiry, and at Site 2 they were about 2-1/2 times the recommended maximum. Direct comparisons are, however, difficult because of the discrepancies regarding location of sampling sites.
It was concluded that turbidity (FTU) alone was not a reliable indicator of sediment loading and deposition hence was not the best parameter for indicating the total biological effect of trenching. Direct measurement of suspended sediment concentrations and deposition within the first 200 m below the trench appeared more closely linked to biological effects. It was also concluded that benthic invertebrate sampling, to produce reliable results, would require more physical habitat measurements, a stratified sampling approach, and/or more numerous samples. Invertebrate drift analysis would require the separation of 'catastrophic drift', caused by increased suspended levels and deposition. Because of the low numbers involved, fish sampling would have required

a disproportionate amount of effort to realize statistically reliable results. Effects on fish can probably be adequately determined by measuring changes in their habitats and food supply. Keywords : siltation; benthic invertebrate community; fish effects; silt effects on habitat; suspended sediment; turbidity; sediment

Peterson, L.A., Nyquist, D. 1972. Effects of highway bridge construction on a subarctic stream. The Northern Engineer :18-20.

Study was conducted in central Alaska examining the effects of the construction of a highway bridge on Goldstream Creek. The creek itself has experienced prior disturbances including dredging, placer mining, rerouting and channelization. Noted significant variation in turbidity and TSS above and below construction - values are given in text. States that environmental damage to the aquatic ecosystem was short-lived with recovery noted within one year after construction was initiated. Keywords : highway construction; grayling; benthic invertebrate community; disturbance; turbidity; recovery

Peterson, N.P. 1982. Population characteristics of juvenile coho salmon (*Oncorhynchus kisutch*) overwintering in riverine ponds. Can J Fish Aquat Sci 39:1303-7.

Survival and growth from immigration to smolt outmigration differed substantially between pond populations of juvenile coho salmon (*Oncorhynchus kisutch*). In pond 1 (the deeper, less productive pond) overall survival was 78% but average fish weight increased only 49%, whereas in Pond 2 (the shallow, more-productive pond) survival was only 28% but average fish weight increased 94%. Diet of resident coho in the early spring was characterized by chironomid larvae and newly emerged adults in Ponds 1 and 2, respectively. Manipulation on pond morphometry may have potential for enhancing coho stocks. Keywords : coho; coho salmon; salmon; winter; fish growth; fish habitat

Phillips, R.W., Lantz, R.L., Claire, E.W., and Moring, J.R. 1975. Some effects on gravel mixtures on emergence of coho salmon and steelhead trout fry. Transactions of the American Fisheries Society 3:461-6.

Eight mixtures of sand and gravel were tested in experimental troughs, to simulate hatching conditions in coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*) redds. Fry were released into perforated, open-ended chambers below the gravel surface. An inverse relationship was found between the quantity of fines and emergent survival. Mean emergent survival for coho ranged from 96% in the control mixture to 8% in 70% sand (< 3.3 mm diameter). Mean emergent survival for steelhead ranged from 94% to 18%, respectively. Premature emergence of coho fry was related to higher concentrations of fines. These premature fry were smaller, and retained more yolk than fry emerging at normal times. Keywords : laboratory study; fish survival; coho; steelhead; fry; sediment particle size

Poff, N.L., Allan, J.D. 1995. Functional organization of stream fish assemblages in relation to hydrological variability. Ecology 76(2):606-27.

Stream fish assemblage data for 34 sites in Wisconsin and Minnesota were obtained from archived sources and were used in conjunction with long-term hydrological data to test the hypothesis that functional organization of fish communities is related to hydrological variability. For each of the 106 species present in the data set, six categories of species traits were derived to describe habitat, trophic, morphological and tolerance characteristics. A hierarchical clustering routine was used to identify two functionally similar groups of assemblages defined in terms of species presence/absence. Hydrological factors describing streamflow variability and predictability as well as frequency and predictability, as well as frequency and predictability of high flow and low flow extremes, were derived for each of the 34 sites and employed to explain differences among the functionally defined groups. Canonical discriminant analysis revealed that the hydrological data could clearly separate the two ecologically defined groups of assemblages, which were associated with the hydrologically variable streams (high coefficient of variation of daily flows, moderate frequency of spates) or hydrologically stable streams (high predictability of daily flows, stable baseflow conditions). Discriminant functions based on hydrological information classified the 34 fish assemblages into the correct ecological group with 85% accuracy. Assemblages from hydrologically variable sites had generalized feeding strategies, were associated with silt and general substrata, were characterized by slow-velocity species with headwater affinities, and were tolerant to silt. Proportions of species traits present at the 34 sites were regressed against an index of hydrological stability derived from a principal components analysis to test the hypothesis that functional organization of assemblages varied across a gradient of hydrological stability. Results were complementary with the discriminant analysis. Findings were in general agreement with theoretical predictions that variable habitats should support resource generalists while stable habitats should be characterized by a higher proportion of specialist species. Several species of fish were identified as indicative of the variable-stable hydrological gradient among stream sites. A taxonomic analysis showed strong geographic patterns in species composition of the 34 assemblages. However, zoogeographic constraints did not explain the observed relationship between stream hydrology and functional organization of fish assemblages. The strong hydrological-assemblage relations found in the 34 midwestern sites suggest that hydrological factors are significant environmental variables influencing fish assemblage structure and that hydrological alterations induced by climate change (or other anthropogenic disturbances) could modify stream fish assemblage structure in this region. Keywords : hydrology; disturbance; flows

Porter, T.R., Rosenberg, D.M., and McGowan, D.K. 1974. Winter studies of the effects of highway crossing on the fish and benthos of the Martin River, NWT. Resource Management Branch, Central Region, Environment Canada, Fisheries and Marine Service. CEN/T-74-3. pp. 1-50.

A study of the effects of a highway crossing on the fish and benthos of the Martin River was conducted from November 1972 to April 1973. Physical and chemical parameters were measured at regular intervals at locations upstream and downstream of the crossing. Fish were collected using gillnets and fry driftnets; benthic organisms were collected in benthic driftnets. Suspended sediment concentrations were highest at locations immediately below the highway crossing. In March, at the same locations, dissolved oxygen concentrations were sufficiently low (1.1 and 1.2 mg/L) to be lethal to fish. No significant over-wintering areas were found. A downstream movement of metamorphosed *Lampetra japonica*, juvenile *Lota lota*, *Cottus cognatus, Couesius plumbeus* and *Percopsis omiscomaycus* occurred from mid-November to mid-December. There was no evidence of fish movement 9 January to 3 April 1973. Ephemeroptera were the predominant organisms in the drift followed by Copepoda and Plecoptera. The stomach contents of *C. plumbeus* , *P. omiscomaycus*, *Catostomus catostomus* and *C. cognatus* indicate that these fish are feeding on the bottom benthos rather than drift. Examination of the food preferences of different size classes of *C. cognatus* and *P. omiscomaycus* indicates that Chironomidae decrease while Ephemeroptera and Trichoptera increase in occurrence with and increase in the length of specimens of each species. There was no clear indication that the Martin River highway crossing and related winter activities had any discernible effects on the fish and benthic fauna through the winter of 1972-1973. It is recommended that in-stream construction activities be restricted to the period January to March. Keywords : winter; highway construction; benthic invertebrate community; fish effects; fry; suspended sediment; sediment concentrations; sediment; drift

Powers, C.F., Sanville, W.D., Stay, F.S., and Schuytema, G.S. 1977. Aquatic sediments. Journal WPCF (June):1307-16.

Literature review covering topics including: sediment-water interchange, sampling and analytical methods, chemical and physical characterization, biological considerations, and modelling. 117 references. Keywords : sediment; review; sampling; methods

Redding, J.M., Schreck, C.B., and Everest, F.H. 1987. Physiological effects of coho salmon and steelhead of exposure to suspended solids. Transactions of the American Fisheries Society 116:737-44.

Yearling coho salmon *Oncorhynchus kisutch* and steelhead *Salmo gairdneri* were exposed to high (2-3 g/L) concentrations of three kinds of suspended solids (topsoil, kaolin clay, and volcanic ash) as long as 7-8 days. Such exposure did not cause mortality but plasma cortisol concentrations were temporarily elevated in both species after exposure to 2-3 g/L of suspended topsoil, indicating that such exposure may have been stressful to the fish. Feeding rates of both species were reduced at high exposure concentrations. Exposure of yearling steelhead for 2 d to high or low concentrations of suspended topsoil, kaolin clay, or volcanic ash induced similar elevations of plasma cortisol levels, and, in groups exposed to high concentrations, blood hematocrits were increased. Osmoregulatory performance in fresh water and after transfer to 26% seawater was unaffected and gill tissue appeared normal after exposure to suspended solids. Exposure of yearling steelhead to high concentrations of suspended topsoil reduced the fishes' tolerance of subsequent infection by the bacterial pathogen *Vibrio anguillarum*. These results suggest that coho salmon and steelhead can survive exposure to high concentrations of suspended solids, but may undergo sublethal physiological stress that reduces their performance capacity. Keywords : coho; salmon; steelhead; suspended sediment; fish effects

Reed, G.D. 1981. Evaluation of automatic suspended solids sampling procedures. Journal WPCF 53(10):1481-91.

This paper consists of an evaluation of methods to be used to measure suspended sediments or solids, especially for monitoring programs. The author discusses how to deal with variation by comparing measured levels to background values. He also discusses what would be considered adequate sampling frequency, methods for determining particle size and effects of particle size on recovery of sediment in samples. He also analyzes methodology to determine suitable locations for sampling for suspended solids (ie. in or around the inlet to a waste treatment system) - and suggests that further study is required to determine the relative effectiveness of various types of wastewater sampling methods. Keywords : sampling; monitoring; suspended sediment; methods; recovery; methodology

Reible, D.D., Savant-Malhiet, S.A. 1993. Comparison of physical transport processes in noncohesive river sediments. Journal of Environmental Engineering 119(1):90-102.

In this paper, the sediment-side abiotic mechanisms for contaminant transport across the sediment-water interface of rivers are compared. The transport processes considered include molecular diffusion, colloidal diffusion, pre-water advection between the stream and its associated aquifer, localized advection due to sediment surface roughness, and sediment movement. A simple model for contaminant transport by active bedload transport of noncohesive sediments in triangular dunes is developed and compared to both linearly sorbing and nonsorbing contaminant transport via passive pore-water processes. The model is limited to homogeneous noncohesive sediment beds and specific flow conditions that lead to steady dune-migration rates. The results suggest, however, that advection should normally be the dominant mechanism in stable sediments and nonsorbing contaminants in unstable sediments near the threshold for sediment movement. Sorbing contaminant transport should normally be controlled by the rate of sediment movement. Keywords : sediment; contaminants; model; flows

Reice, S.R. 1977. The role of animal associations and current velocity in sediment-specific leaf litter decomposition. Oikos 29(2):357-65.

Decomposition of white ash leaf packs on four substrates was studied in New Hope Creek, North Carolina, USA. Sediment-specific decomposition rates and animal associations were related. Current velocity did not contribute significantly to the variation in sediment -specific

decomposition. The dynamics of litter decomposition in streams can be more fully understood by simultaneously studying the dynamics of the benthic community.
. Keywords : benthic invertebrate community; flushing flows

Reice, S.R. 1985. Experimental disturbance and the maintenance of species diversity in a stream community. Oecologia 67:90-7.

In order to test the role of disturbance and the effects of disturbance frequency on stream communities, an experiment was conducted in New Hope Creek, North Carolina, USA. Patches of cobbles were tumbled 0, 1 or 2 times in a 6 week span. These tumbling disturbances lasted only 30 seconds. The recovery of the macroinvertebrates was monitored.
Most taxa showed major reductions in population density immediately following the disturbance. The percent reduction of a given taxon in disturbed vs. control patches ranged from 21.4-95%. Recovery to near normal population levels was achieved in about four weeks. A second disturbance caused similar population reductions as the first one and then delayed the recovery. The macroinvertebrate community in cobbles was demonstrated to be resilient in that populations quickly regained their predisturbance densities. Rare taxa did not selectively colonize disturbed patches. The implications of these findings for the intermediate disturbance hypothesis and the structure of stream communities is discussed. Disturbance is a major determinant of lotic community structure and species diversity. Keywords : fish biodiversity; disturbance; recovery; macroinvertebrates

Reiser, D.W., Peters, J.M., and Running, S.K. 1989. Development and application of an intergravel sampling device for quantifying seuiments in streams. EA Engineering, S.A. editor. Pacific Gas and Electric Company. Califomia. 9.4-88.8. pp. 1-51.

The collection of substrate samples is currently accomplished using one of two techniques: grab samples and freeze coring techniques. Both methods involve the removal of a small portion of streambed for later size gradation analysis using sieves. The methods are time consuming, costly and are difficult to use in remote areas and in streams with large substrates. Thus, there is a need for development of a simplified technique for assessing fine sediment accumulation in streams.
This study was conducted to evaluate the use of modified Whitlock-Vibert (W-V) boxes for quantifying sediment deposition in stream gravels and to develop techniques for analyzing W-V box samples in the field. Previous studies have shown a relationship between the amount of sediment contained in W-V boxes and levels determined from McNiel core sampling, one of the most commonly used methods. Recent lab and field studies conducted at the University of Wyoming have shown no significant difference between estimates of fine sediment accumulation in the W-V boxes and the McNeil Sampler.
The study was completed in the Geysers-Calistoga Known Geothermal Resource Area located in northem California and was conducted in conjunction with a sediment monitoring program for Pacific Gas and Electric Company's (PG&E) Unit 16 Geothermal Project. The two Bear Canyon Creek monitoring stations used for that study were also used for the W-V box analysis.
Field studies were initiated on April 16, 1985, and extended to January 1987. The study design consisted of the placement of W-V boxes (clustered in groups of four to eight) in areas of close proximity to McNeil core sampling points used for the sediment monitoring program. Initial tests used empty W-V boxes filled with artificial medium (marbles). Placement of marbles in the boxes served to standardize the volume of voids and weight of each box, which was necessary for development of field analysis procedures.
Five separate methods were assessed for use in analyzing W-V boxes. Two methods proved suitable: gravimetric analysis and saturated weight analysis calibrated to a saturation chamber. The saturation chamber method was the quickest and provided an effective way to analyze boxes in the field. There was a close agreement between predicted percent fines using the saturation chamber and the actual percent fines determined from gravimetric analysis.
Advantages of the W-V box method include 1) provides for rapid, on-site analysis; 2) provides a continuous record since boxes are left in place; 3) can meet sample size requirements for

statistical analysis; 4) the boxes are inexpensive ($1.30 each) and reusable; and 5) use of the boxes is not limited by water depth or substrate size. Many of these advantages relate directly to the cost of sampling. Cost comparisons made between the W-V box, McNeil core and freeze core techniques indicate that the W-V box to the least expensive.
Major disadvantages of the W-V box include: 1) unable to sample high (>35 %) concentrations of sediment; 2) unable to characterize other gravel sizes; and 3) boxes are susceptible to loss and displacement, if not anchored.
Results of the study indicate that the W-V box can serve as an effective and efficient device for quantifying fine sediments in stream gravels. Further, the University of Wyoming study indicates that the W-V box is equal to the McNeil core sampling technique with respect to the fine sediment determination. As a result, it is recommended that the W-V box be considered as an alternative approach to other, more time-intensive sediment sampling methods. Keywords : sampling; sediment; methods

Reiser, D.W., Ramey, M.P., and Lambert, T.R. 1985. Review of flushing flow requirements in regulated streams. Pacific Gas and Electric Company, Dept. of Engineering Research. San Ramon, California. Z19-5-120-84. pp. 1-97 + App.

The regulation of streamflows can alter the natural regime of a system by removing peak flows and reducing the stream sediment transport competency. The net effect can be that sediment which is inputted to the system tends to accumulate rather than being periodically removed (flushed) as during spring runoff. The deposition and aggradation of sediments ultimately becomes a problem when it affects the biotic community. In this case, a release flow (flushing flow) which simulates high runoff events may be periodically needed to remove fine sediments from the stream.
The purpose of this study was to review and summarize existing information on flushing flows and to provide a better understanding of the physical and hydraulic parameters which respond to changes in flow and how they influence the aquatic biota.
Major objectives of this study were to: (1) compile and review information pertaining to flushing flows; (2) review and evaluate existing and proposed methods for recommending flushing flows; (3) evaluate potential techniques useful for determining the need for, timing, magnitude, and effectiveness of flushing flows; (4) develop guidelines for assisting in the determination of flushing flow requirements; and (5) define areas for further research.
Information and data on flushing flows were assembled following a comprehensive review of the literature. This review was supplemented with a detailed mail survey of various state and federal resource agencies and research institutions. The survey forms used were structured to obtain information in four principal areas: awareness and use of methodologies, need for flushing flows, need for standardization of methods, and research activities. A total of 70 survey forms were distributed, of which 46 were completed and returned.
From the review of information, a total of fifteen methods or approaches for assessing flushing flows were identified, reviewed, and presented in summary form. A discussion of the basis for and application of each method, as well as a section on its major constraints and limitations, was included in each summary. Of the fifteen methods, seven were primarily office techniques, three were field based, and the remaining five (including one in a developmental stage) entailed a mixed office and field approach. The majority of methods described were not designed specifically for assessing flushing flows, but rather constituted approaches used for addressing sediment transport problems. The few formal methods that do exist have gone largely untested with respect to their reliability and accuracy, and have only partially addressed the overall needs of a flushing flow (ie. magnitude, timing, duration and effectiveness).
The study further reviewed important parameters and conditions which should be monitored and evaluated when flushing flows are being considered. Emphasis was placed on defining practical techniques useful for assessing flow needs.
Fundamental in the evaluation process is an initial determination of the need for a flushing flow. Specific points which should be considered in this determination include: (1) physical location of the water development project in relation to major sediment sources; (2) topography and geology of the project area; (3) susceptibility of the drainage to catastrophic events; (4) sensitivity of

target fish species and their life history stage to sediment depositional effect; (5) extent of man-induced activities within the drainage; and (6) operational characteristics of the project.
The actual need for a flushing flow should be based on the results of sediment monitoring studies (where possible) using appropriate field techniques. One the need for a flushing flow has been established, it is important to determine the best time for its implementation. Important considerations include: (1) species of fish present in the system; (2) life history functions of important species; (3) historical runoff period; (4) project flow availability; and (5) water temperature.
Ideally, the most effective time for implementing a flushing flow is that which provides the greatest benefits to the biotic communities. Detailed species-life-history charts should be developed and consulted to assist in the determination. The determination of the magnitude of flows is the most important and most difficult aspect of formulating a flushing flow recommendation. No single, standard approach has been developed for this purpose. Until methods are developed, evaluations today will need to utilize an approach tailored to the specific needs and characteristics of each stream and project. This may entail the use of several different office techniques to derive an initial flow estimate, followed by detailed field studies to refine and finalize the recommendation.
The most reliable method for establishing required flushing-flow rates is to observe various test flow releases. Field observations such as the sampling and tagging of bed material, should be made before and after each release to determine the actual effectiveness. Flow releases may not be feasible on all streams. However, where feasible, they provide the best results of all methods. Where test flow releases cannot be made, the use of methods based on sediment transport mechanics may be the most reliable approach for determining flushing flow rates.
An evaluation of the effectiveness of a recommended discharge for removing sediments should be a logical part of every flushing flow study. Through this process, actual, versus desired results can be compared and refinements made. This study reviewed 24 different techniques which could be used for assessing the effectiveness of the flows.
The study resulted in the development of the following guidelines for conducting flushing flow studies: (1) flushing flow studies should utilize an interdisciplinary team approach; team members should include at a minimum a hydrologic engineer and a fisheries biologist; (2) an initial determination of the actual need for the flushing flow should precede detailed assessments; (3) the assessment approach should be tailored to the specific needs and characteristics of each stream and project; office and field techniques both may be required; (4) for comparative purposes, more than one method should be used for deriving flow recommendations; (5) flushing flow recommendations should be stated in terms of magnitude, timing and duration; (6) follow-up studies should be conducted to evaluate the effectiveness of the flow and allow for adjustments.
From the review of literature, data and results of the survey, important areas of research relating to flushing flows are identified. Keywords : methodology; dam; fish effects; silt effects on habitat; salmonid; recovery; sediment transport; flushing flows; sediment; flows

Resh, V.H., Brown, A.V., Covich, A.P., Gurtz, M.E., Li, H.W., Minshall, G.W., Reice, S.R., Sheldon, A.L., Wallace, J.B., and Wissmar, R.C. 1988. The role of disturbance in stream ecology. Journal of the North American Benthological Society 7(4):433-55.

We define disturbance in stream ecosystems to be: any relatively discrete event in time that is characterized by a frequency, intensity, and severity outside a predictable range, and that disrupts ecosystem, community, or population structure and changes resources or the physical environment. Of the three major hypotheses relating to lotic community structure, the dynamic equilibrium hypothesis appears to be generally applicable, although specific studies support the intermediate disturbance hypothesis and the equilibrium model. Differences in disturbance frequency between lentic and lotic systems may explain why biotic interactions are more apparent in lakes than in streams.
Responses to both natural and anthropogenic disturbances vary regionally, as illustrated by examples from the mid-continent, Pacific northwest , and southeastern United States. Based on a generalized framework of climatic-biogeochemical characteristics, two features are considered

to be most significant in choosing streams for comparative studies of disturbance: hydrologic regimes and comparable geomorphology. A method is described for quantifying predictability of the hydrologic regime based on long-term records of monthly maximum and minimum stream flows. Different channel forms (boulder and cobble, alluvial gravelbed, alluvial sandbed) have different responses to hydrologic disturbance from spates. A number of structural and functional components for comparing disturbance effects within regions and across biomes are presented. Experimental approaches to studying disturbance involve spatial-scale considerations, logistic difficulties, and ethical questions. General questions related to disturbance that could be addressed by stream ecologists are proposed. Keywords : disturbance; model; lake; hydrology

Rice, R.M., Rothacher, J.S., and Megahan, W.F. 197. Erosional consequences of timber harvesting: an appraisal. National Symposium on Watersheds in Transition. 321-329.

This paper summarizes our current understanding of the effects of timber harvesting on erosion. Rates of erosion on mountain watersheds vary widely but the relative importance of different types of erosion and the consequences of disturbances remain fairly consistent. Therefore these conclusions seem to be valid for most circumstances: Most of man's activities will increase erosion to some extent in forested watersheds; erosion rarely occurs uniformly; sediment production declines rapidly following disturbance; landslides and creep are the chief forms of natural erosion in mountainous regions; cutting of trees does not significantly increase erosion, but clearcutting on steep unstable slopes may lead to increased mass erosion; accelerated erosion is a possible undesirable side effect of use of fire in conjunction with logging; the road system built for timber harvesting far overshadows logging or fire as a cause of increased erosion; and potentially hazardous areas can be identified in advance of the timber harvest. Keywords : forestry; highway construction; erosion; landslide sediment input; disturbance; sediment; logging

Rice, R.M., Tilley, F.B., and Datzman, P.A. 1979. A watershed's response to logging and roads: South Fork of Caspar Creek, California, 1967-1976. Pacific Southwest Forest and Range Experiment Station. Berkeley, California. pp. 1-12.

This study examines the long term effects of logging on a watershed in California. He models streamflow and suspended sediment volume and examines debris basin accumulation. Effects of road construction are separated from effects from logging and sedimentation over time is presented. Water quality is discussed and logging techniques are compared.

Conclusions: The study of roading and selective timber harvest in the watershed of the South Fork of Caspar Creek suggests that: (1) the watershed appears representative of other harvested areas investigated in northwestern California; (2) the information gained in this study applies most directly to tractor-yarded, partially cut second-growth redwood and old-growth timber of other species; (3) disturbances from roadbuilding and logging changed the sediment/discharge relationship of the South Fork from one which was supply dependent to one which was stream power dependent, resulting in substantial increases in suspended sediment discharges; (4) although roadbuilding and logging apparently increased debris basin deposits as well, the nature of the increase is much less clear. Lags in the movement of bed material through the stream system may be the confusing element; (5) the overall effect on site quality, as estimated by erosion or sedimentation, does not appear to be a cause for concern; (6) road construction and logging appear to have resulted in increases in average turbidity levels (as inferred from suspended sediment increases) above those permitted by Regional Water Quality Regulations. Keywords : logging; suspended sediment; erosion; model; sedimentation; water quality; sediment

Richards, C., Bacon, K.L. 1994. Influence of fine sediment on macroinvertebrate colonization of surface and hyporheic stream substrates. Great Basin Naturalist 54(2):106-13.

Colonization of macroinvertebrates was assessed in a stream impacted by inputs of fine sediments. Colonization was examined at the stream surface and within the hyporheos with Whitlock-Vibert (W-V) boxes. Hyporheic areas accumulated much greater amounts of all size categories of sediment. No significant difference was observed in the amounts of organic matter accumulated at either depth. Only 150um sediment had significant effects on macroinvertebrate total numbers and number of taxa. Total numbers of invertebrates at 30 cm were only 20% of those at the surface. Canonical Correspondence analysis indicated that the strongest influence on macroinvertebrates colonizing W-V boxes at the surface was stream size and secondarily fine sediments. Within the hyporheos, abundance of sedimentation on hyporheic environments can have significant and persistent impacts on streams. Keywords : sediment; macroinvertebrates; hyporheos; sedimentation

Ringler, N.H., Hall, J.D. 1996. Effects of logging on water temperature and dissolved oxygen in spawning beds. Amer Fisheries Soc Trans

The temperature and dissolved oxygen content of intragravel water were measured in three Oregon coastal streams between June 1968 and June 1969. In 1966, the watershed of one stream had been completely clearcut, and that of a second stream partially clearcut in staggered settings. A third watershed was left unlogged.
Clearcut logging resulted in increased temperature of intragravel water in salmon and trout spawning beds and decreased concentrations of dissolved oxygen. The changes were related largely to reduced forest cover over the stream surface and to deposition of fine sediment in the gravel.
No serious reduction in survival to emergence of coho salmon occurred along with the observed changes in temperature or dissolved oxygen. A decrease in the resident population of cutthroat trout after logging may have been related to these changes. Keywords : logging; coho salmon; cutthroat trout; forestry; temperature

Ritchie, J.C. 1972. Sediment, fish, and fish habitat. Journal of Soil and Water Conservation 27:124-5.

A short literature review covering the physiological effects of turbidity on fish, damage to aquatic ecosystems and fish population changes which have been noted by various studies. The author concludes that sediment does have an effect on fish and shellfish. Under most conditions the ecological effect of sediment on aquatic ecosystems is probably greater than the physiological effect of sediment on fish. But the combination of ecological and physiological effects creates an additional stress on fish populations which tends to change these populations either in number of in dominant fish species, thereby altering original aquatic ecosystems. Keywords : fish habitat; instream sediment; turbidity; fish survival; review; sediment

Rood, K.M. 1987. The effects of regulation of flow in the Nechako River on channel morphology, sediment transport and deposition and flushing flows. Expert Report for the Nechako River Court Action. Prepared for the Department of Fisheries and Oceans. Reid Crowther and Partners Ltd. North Vancouver, B.C. DFOR-370. pp. 1-13.

none. Keywords : flows; sediment; sediment transport; flushing flows

Rood, K.M. and Neill, C.R. 1987. A study of some aspects of the geomorphology of the Nechako River. Reid Crowther and Partners Ltd. Prepared for Fisheries and Oceans Canada. Vancouver, B.C.

Keywords : sediment transport; flushing flows; Nechako

Rose, K.A., Brenkert, A.L., Schohl, G.A., Onishi, Y., Hayworth, J.S., Holly, F., Perkins, W., Beard, L., Cook, R.B., and Waldrop, W. 1995. Multiple model analysis of sediment transport

and contamination distribution in the Clinch River/Watts Bar Reservoir, Tennessee, U.S.A. Wat Sci Tech 28(8-9):65-78.

Three models of sediment transport and contaminant distribution (CHARIMA, HEC-6, and TODAM) are being applied to the Clinch River/Watts Bar Reservoir system as a part of a CERCLA remedial investigation. Planned uses of model results are to identify high deposition areas of the river, forecast the effects of various remedial actions and climatic events on contaminant distribution, and aid in the design of future data collection efforts. The three models share some similarities but also differ in several important details. All three models are one-dimensional and include similar processes for sediment deposition and resuspension. Differences among the models include steady-state versus unsteady flow, the complexity of the channel network permitted, and the level of detail of contaminant-related fate processes represented. As part of our multiple model strategy, some aspects of the three models are configured using common information on the system (e.g. spatial geometry), while other aspects of the models, including some modeler decisions and calibration methods, are allowed to differ. Comparison of results among the three models can lead to increased confidence in predictions and in recommendations for future data collection. The general approach of using multiple models is described and preliminary results of the Clinch River/Watts Bar application are presented to illustrate the utility of using a multiple model approach for complex environmental assessments. Keywords : model; sediment transport; contaminants; sediment deposition; methods; sediment

Rosenberg, D.M. and Snow, N.B. 197. A design for environmental impact studies with special reference to sedimentation in aquatic systems in the MacKenzie and Porcupine River drainages. BEAK.

The first major environmental impact study to be done in Canada's north was carried out under the auspices of the Environmental-Social Committee, Task Force on Northern Oil Development. Our involvement in this study led to the development of what we consider to be a suitable approach to future environmental impact studies. This approach consists of eight steps which we have illustrated with data from our physical and biological studies on sedimentation in the Mackenzie and Porcupine River drainages. We suggest that the most important function of an environmental impact study is prediction of the effects of an impact before it occurs and recommendation of mitigation procedures. Settled sediment is likely more important than suspended sediment with respect to zoobenthos communities. The amount of sediment that settles depends on the carrying capacity of the river for sediment and/or the amount of sediment added. The magnitude of the effect will depend on the amount of sediment that settles. The duration of the effect will depend on whether the annual maximum discharge period is capable of removing the added sediment from the substrates and, if it is capable, the length of time until the removal occurs. Therefore, verification that a river is capable of removing an increased supply of sediment originating from a technological disturbance should be sought. Failing the river's capability to do that, sediment addition should be reduced as much as possible and verification sought that the annual maximum discharge can remove the added sediment from the river substrate. Addition of sediment to rivers in which annual maximum discharge cannot remove the added sediment should be avoided or long-term changes in the biota will result.
Attempts to set *a priori* tolerance levels for controlling the amount of sediment unnaturally added to systems with natural sediment transport rates as diverse as those in the Mackenzie and Porcupine drainages are unsuitable. Keywords : sedimentation; suspended sediment; disturbance; sediment

Rosenberg, D.M. and Snow, N.B. 1975. Ecological studies of aquatic organisms in the MacKenzie and Porcupine River drainages in relation to sedimentation. Department of the Environment, Fisheries and Marine Service, Research and Development Directorate. Winnipeg, Manitoba. 547. pp. 1-86.

A review of recent literature on the effects of increased sedimentation on aquatic biota is presented. Timber harvesting, forest fires, road construction and operation, and channelization of rivers and streams were identified as the major possible sources of unnatural increases in suspended and settled sediments in northern watersheds. Detrimental effects of increased suspended and settled sediments can result, singly or in combination from, a reduction in light penetration, mechanical abrasion, toxicants adsorbed to sediment particles, and changes in substrate. Specific detrimental effects, due to a variety of watershed disturbances, on flora and fauna are discussed. Recovery rates of flowing waters from increased sedimentation vary from a few days to not at all and depend, basically, on characteristics of the river or stream, the severity of sediment addition, and availability of undamaged areas as sources of recolonization. It would appear from the literature that unnatural increases in suspended sediment concentrations of most flowing waters should not result in a concentration of >80 mg/L to ensure protection of aquatic life. A flowing-water habitat should always be able to carry away an increased sediment load to prevent permanent sedimentation of the substrate. Future research needs on the effects of unnatural increases of sediment on aquatic biota include a standardization of measurements and methods used, quantification of terms such as "adverse" , " detrimental", "deleterious" , and "damage", and laboratory experimentation complementary to descriptive and experimental field data.

A natural retrogressive-thaw flow slide on Caribou Bar Creek, northern Yukon, added an estimated 2000-2600 metric tons of sediment to the Creek. Standing crop of benthic invertebrates was reduced immediately by 70% and qualitative changes in proportions of benthic-invertebrate taxa were evident. Recovery of benthic invertebrate populations occurred within a month. Although the mudslide was intermittently active during the following year, no apparent effect on the benthic invertebrate fauna resulted. The difficulties in using all but the most specialized forms of Chironomidae as indicators of unnatural increases in sedimentation are discussed.

Crossings of the Martin River by the Mackenzie Highway right-of-way slash, winter road, and temporary bridge resulted in no significant effects on benthic invertebrate and fish populations, and physical and chemical parameters of the water in the first year after construction activities began. The study is continuing. The Dempster Highway crossing of Campbell Creek NWT, appeared to have prevented upstream migration by northern pike and broad whitefish in spring of 1973. From visual observations, the site has received increased sediment supply, likely from roadfill and erosion of adjacent disturbed terrain. However, physical and chemical parameters of the water showed no major differences above and below the crossing and bottom substrates had only slightly higher proportion of fine sediments at the downstream stations than those upstream of the crossing. Benthic invertebrate populations downstream of the crossing tended to be typical of the areas disturbed by sedimentation. However, these data were not conclusive. This could have been due to differences in substrate above and below the crossing which made the area difficult to sample adequately. Also the full effect of hydrologic complexity of the Campbell Creek watershed on benthic invertebrate populations is unknown.

Experimental as well as descriptive approaches to the study of the effects of suspended and settled sediments on aquatic biota are necessary. To this end, the drift responses of invertebrates in the Harris River, NWT to additions of known amounts of bankside sediment were studied. River invertebrates were categorized into macrobenthos, zooplankton, and total (=macrobenthos + zooplankton) invertebrates in order to measure response to the added sediment. Macrobenthos showed a positive percent increase in drift at all intended concentrations of suspended sediment used (10-500mg/L) but zooplankton and total invertebrates did not. No relation existed between percent increase of macrobenthos drifting and suspended sediment concentration, total weight of sediment added, or theoretical weight of sediment added per unit area of stream bottom. Analyses of variance done for the macrobenthos showed a significant difference between numbers drifting during control and sediment addition periods and among sediment loads. No relationship could be found between sediment loads and numbers of macrobenthos drifting. Similar results were obtained from analysis of the percent increase data. Preliminary results have shown that individual taxa of macrobenthos showed different responses to sediment addition. Analysis of variance done for zooplankton and total invertebrates showed a significant difference in numbers drifting among

sediment loads but not significant difference between numbers drifting during control and sediment addition periods or the interaction between sediment load and numbers drifting. Separation of the river invertebrates into three types revealed the sensitivity of the macrobenthos to increased sedimentation.
Maximum numbers of macrobenthos leaving per m^2 of experimental channel bottom as a result of sediment addition over a 15 min period in the Harris River ranged from 25.5 and 129.6. The minimum number per m^2 was 1.9 for a 15 min sediment addition period. The maximum percent of the resident macrobenthos population caused to drift by sediment addition was estimated to be 2.6 while the minimum was estimated to be 0.04%. Based on a number of assumptions, depletion of 50% of the standing crop of macrobenthos would occur in 7 hours at the maximum rate of exit and 18 days at the minimum. A model illustrating drift dynamics for an undisturbed section of river and one affected by sediment addition is presented. Keywords : sedimentation; review; disturbance; recovery; suspended sediment; sediment concentrations; methods; sediment; light penetration; model; road construction; river; laboratory

Rosenberg, D.M., Wiens, A.P. 1975. Experimental sediment addition studies on the Harris River, N.W.T., Canada: the effect on macroinvertebrate drift. Verh Internat Verein Limnol Bd 19:1568-74.

No abstract. Study dealt with the response of benthic macroinvertebrates, as measured by numbers of animals in the drift, to additions of predetermined amounts of river bank sediment. Keywords : benthic invertebrate community; sediment concentrations; model; macroinvertebrates; drift; sediment

Rosenberg, D.M., Wiens, A.P. 1978. Effects of sediment addition on macrobenthic invertebrates in a northern Canadian river. Water Research 12:753-63.

Two channels built into the Harris River, Northwest Territories, were used to study responses of invertebrates to sediment addition. Sediment was added to one channel continuously for approximately 5 h. The other channel was used as a control. In August, 28.27 kg of sediment or 1.38 kg/m^2 of channel bottom were added. Values for September were 35.88 kg or 1.53 kg/m^2.
As a result of sediment addition, numbers of macrobenthos drifting from the sediment addition channel (S) increased significantly over those drifting in the control (C) in August (=summer) and September (=fall). Total drift from S was > 3 times higher in August and > 2 times higher in September than from C. Significantly higher numbers of macrobenthos drifted in fall than in summer. Numbers of macrobenthos drifting during sediment addition were significantly related to time in September but not in August, indicating a seasonal difference in temporal response to sediment addition. Two explanations are proposed from the response of the September community, as indicated by shape of a polynomial regression curve, to sediment addition. No significant difference existed in standing crops of macrobenthos in the substrate in C and S after sediment addition.
Sediment addition caused (1) higher numbers of Oligochaeta and Simuliidae to drift in August and September; (2) higher numbers of Plecoptera and Ephemeroptera to drift in September but not in August; and (3) higher numbers of Hydracarina and Chironomidae to drift in August but not September.
We suggest that future work try to relate amounts of settled rather than suspended sediments to quantitative responses of stream macrobenthos. We recommend that highway and pipeline construction undertaken in watersheds of Mackenzie Valley streams during the open-water period, resulting in sediment addition to these streams, should be done during summer rather than spring or fall, providing river discharge is adequate to transport the added sediment. Keywords : benthic invertebrate community; silt effects on habitat; model; sediment concentrations; invertebrate community changes; suspended sediment; sediment; river

Rosenberg, D.M., Wiens, A.P. 1978. Responses of chironomidae (Diptera) to short-term experimental sediment additions in the Harris River, Northwest Territories, Canada. Acta Universitatis Carolinae - Biologica 12:181-92.

Significantly higher numbers of Chironomidae drifted during sediment addition to the Harris River, Northwest Territories Canada in August 1974 but numbers drifting were apparently unaffected during sediment addition in September 1974. Higher water temperatures in August than September in the Harris River may have increased sensitivity to the chironomid community to sediment addition.
Numbers of drifting *Cricotopus bicinctus* (Meig.) and *Corynoneura* grp. pupae increased during the August sediment addition. *Stempellinella* pupae were unaffected. Sediment addition in September apparently depressed numbers of *Constempellina* sp. 2 and *Stempellinella* sp. 1 larvae drifting. *Thienemanniella* sp. n. larvae, and *Corynoneura* grp. pupae were unaffected. Responses of these taxa to sediment addition can be related to differences in microhabitats occupied. Keywords : instream sediment; benthic invertebrate community; sediment

Rosenthal, H., Alderdice, D.F. 1976. Sublethal effects of environmental stressors, natural and pollutional, on marine fish eggs and larvae. J Fish Res Bd Canada 33:2047-65.

Sublethal effects of environmental changes on marine fish eggs and larvae are reviewed within a framework of concepts supplied by Bartholomew (1964), Sprague (1971), and Selye (1952). Such effects are those a) elicited through application of stress at one level of organization or development, b) recognized through the appearance of altered structure or function at a later stage in development, and c) whose significance is fully manifested as lower survival potential at a further stage of development. A number of sublethal effects are marshalled in terms of type of biological response and inferred consequences. Data suggest that a variety of stress-stressor systems may trigger a limited number of organismic responses, often appearing to involve the same physiological and biochemical mechanisms. Most sublethal effects appear to be biochemical in origin, elicited through physical or chemical changes, and expressed in terms of histological, morphological, physiological or ethological response. A need is expressed for an expanded and more unified inquiry into the origin, recognition, and significance of sublethal effects. Keywords : fish eggs; review; fish survival; behaviour; contaminants

Ryan, P.A. 1991. Environmental effects of sediment on New Zealand streams: a review. New Zealand Journal of Marine and Freshwater Research 25:207-21.

Literature pertaining to sediment in stream ecosystems is reviewed. Suspended sediment can alter the water chemistry, and cause temperature decreases and turbidity increases. Deposition of sediment may change the character of the substrate, block interstices, and reduce interstitial volume. Turbidity levels as low as 5 NTU can decrease primary productivity by 3-13%. An increase of suspended sediment levels increases the drift fauna and may reduce benthic densities as well as alter community structure. Fish are not so obviously affected, although death resulting from clogging of the gills may occur in sensitive species. Suspended and deposited sediment may alter fish community composition, both by interference with run-riffle-pool sequences and by favouring olfactory feeders over visual feeders. In many situations aesthetic reactions to suspended sediment may be of more concern than biological ones. In already turbid water, a 20-50% reduction in clarity may not be detectable whereas in normally clear water a clarity reduction of 10-15% is distinguishable. Recovery from the effects of suspended sediment and sediment deposition is usually rapid, once the source of contamination is removed and as long as the stream is prone to regular spates; the aesthetic recovery may only take days whereas biological recovery may take months. Keywords : review; suspended sediment; turbidity; recovery; sediment; drift; sediment deposition

Sallenave, R.M., Barton, D.R. 1990. The distribution of benthic invertebrates along a natural turbidity gradient in Lake Temiskaming, Ontario-Quebec. Hydrobiologia 206:225-34.

Lake Temiskaming, a rift valley lake on the Ontario-Quebec border, exhibits a permanent gradient of turbidity due to tributary streams which cut through clay deposits to the north of the lake. Concentrations of total phosphorus (TP) also decreased from north to south, with values suggesting mesotrophic conditions. Concentrations of chlorophyll a were characteristic of oligotrophic lakes and showed little relationship to either turbidity or TP. Large numbers of Tubificidae were found at our northernmost sampling station at a depth of 50 m, probably reflecting the localized impact of allochthonous organic matter introduced by a tributary stream. Numerical abundance of the benthic fauna was much lower and did not vary significantly among the six more southerly 50 m station, but biomass declined from north to south as *Heterotrissocladius oliveri* replaced *Pontoporeia hoyi*. Numerical abundance did not differ significantly among stations at depths of 10 m, but biomass decreased from north to south reflecting the distributions of the largest species , *Hexagenia* sp. and *P. hoyi*. Intensive sampling on two transects showed that maximum numbers of invertebrates occurred in the profundal zone. While these results are consistent with the correlation between TP and zoobenthic biomass reported by other investigators, size selective predation by fish may also be important in controlling the distribution of benthic invertebrates in Lake Temiskaming. Keywords : turbidity; lake; sampling; benthic invertebrate community; suspended sediment

Saunders, J.W., Smith, M.W. 1965. Changes in a stream population of trout associated with increased silt. J Fish Res Bd Canada 22(2):395-404.

Low standing crops of brook trout (*Salvelinus fontinalis*) were closely associated with silting in Ellerslie Brook, Prince Edward Island, and appeared to result from the destruction of hiding places. Spawning was also curtailed by silting. Following scouring, trout stocks soon increased. The remarkable adaptability of trout to silting , in a habitat with favourable flow and water temperature was illustrated. Keywords : trout; brook trout; silt effects on habitat; recovery; flushing flows

Saunders, J.W., Smith, M.W. 1965. Changes in a stream population of trout associated with increased silt. Journal of Fisheries Research Board of Canada 22(2):396-404.

Low standing crops of brook trout, *Salvelinus fontinalis*, were closely associated with silting in Ellerslie Brook, Prince Edward Island, and appeared to result from the destruction of hiding places. Spawning was also curtailed by silting. Following scouring, trout stocks soon increased. The remarkable adaptability of trout to silting, in a habitat with favourable flow and water temperature, was illustrated. Keywords : silt effects on habitat; brook trout; trout

Scannell, P.O. 1988. Effects of elevated sediment levels from placer mining on survival and behavior of immature arctic grayling. University of Alaska, Fairbanks; 1-93 pp.

The effect of placer mining effluents on arctic grayling fingerling and egg survival was tested in mined and unmined streams in interior Alaska. Also the influence of turbidity on arctic grayling reactive distance and avoidance behavior was tested in a laboratory choice chamber. Arctic grayling fingerlings suffered less than 1% mortality during a 96 hr toxicity test in both clear (mean NTU = 1.4) and mined (mean NTU = 445) streams. Arctic grayling eggs did not show significantly ($p>0.1$) higher mortality in mined streams than in unmined streams. In a laboratory choice chamber test, arctic grayling avoided water with a turbidity above 20 NTU. Arctic grayling reactive distance diminished proportional to the natural logarithm of turbidity. Keywords : grayling; suspended sediment; behaviour; turbidity; fish eggs; immature fish

Schreiber, J.D., Rausch, D.L. 1979. Suspended sediment-phosphorus relationships for the inflow and outflow of a flood detention reservoir. J Environ Qual 8(4):510-4.

Callahan Reservoir, located in an agricultural area near Columbia, Missouri, was studied for 3 years to determine the inflow and outflow of suspended sediment phosphorus (P) and solution P relationships. During the study, the mean inflow solution ortho-P concentration was 0.085 mg/L as compared with 0.041 mg/L for the outflow. Concentrations of ortho-P were highest in both the inflow and outflow during the fall and winter. As yearly suspended sediment concentrations decreased in both the inflow and outflow, due to lower runoff and sediment yields, solution ortho-P (mg/L), as well as sediment total, inorganic, organic, and exhangeable P concentrations (μg/g), increased. Similarly, as a result of coarse sediment deposition within the reservoir during individual storm events, outflow sediments were enriched in clay and had higher concentrations (μg/g) of total, inorganic, organic, and exhangeable P than inflow sediments. However, because of sediment deposition within the reservoir, outflow volume concentrations (mg/L) of sediment total P decreased fourfold as compared with inflow sediments. Keywords : reservoir; agricultural; suspended sediment; sediment; winter; sediment concentrations; sediment deposition

Schubel, J.R., Auld, A.H., and Schmidt, G.M. 1974. Effects of suspended sediment on the development and hatching success of yellow perch and striped bass eggs. Chesapeake Bay Institute, The Johns Hopkins University. Maryland. 35. pp. 1-12.

Yellow perch and striped bass eggs were incubated in suspensions of different concentrations of natural, fine-grained sediments. The results showed that in the laboratory concentrations of up to 500 mg/L did not significantly affect the hatching success of yellow perch or striped bass eggs, but that concentrations of 1000 mg/L did significantly affect their hatching success. Keywords : suspended sediment; perch; bass; fish eggs; laboratory study; sediment

Schubert, J.P. and Vinikour, W.S. 1987. Effects on suspended and substrate sediments in two streams resulting from different gas-pipeline installation techniques. Fourth Symposium on Environmental Concerns in Rights-of-way Management. 25 October 1987; Indianapolis, Illinois. 491-502.

The effects of gas-pipeline construction projects on suspended solids (SS) and streambed sediments were investigated at two stream sites. The Little Miami River in Ohio was crossed using the wet-ditching techniques. Concentrations of SS were elevated up to 400 m downstream during the two days of trenching operations and fine sediment was deposited on the stream bed up to 200 m downstream of the crossing. The SS decreased rapidly after trenching was completed and the fine sediment was removed from the streambed by high stream flows two to eight months after construction. Canada Creek in Michigan was crossed using a plow method, The time duration of stream disturbance was much less for the plow method, and the effects on suspended solids and streambed sedimentation were minimal. For both installation methods, the impacts were reversible, and no long-term impacts on the stream environments were detectable. Keywords : pipeline; suspended sediment; recovery; methods; disturbance; sedimentation; sediment

Schubert, J.P., Vinikour, W.S., and Gartman, D.K. 1985. Effects of gas-pipeline construction on the Little Miami aquatic ecosystem. Gas Research Institute, NTIS. Chicago, Illinois. GRI-86/0024. pp. 1-104.

A study was conducted to quantify the effects of a pipeline construction project on the physical, chemical and biological characteristics of the Little Miami River in Glen Helen Nature Preserve near Yellow Springs, Ohio. Suspended-solids concentrations, generally less than 25 mg/L for one month prior to construction, rose to a maximum of 1461 mg/L during construction (October 17-18 1983). Suspended-solids concentrations then decreased to less than 50 mg/L within 12 h following trenching activities. Silt and fine sand were found on the streambed within 175 m downstream of the crossing site one month after construction. No detrimental alterations of water chemistry were observed as a result of pipeline construction. Postconstruction collections indicated that complete benthic recolonization of the affected areas occurred within two to seven months, while the silver shiner (the numerically predominant fish species) became reestablished in the affected stream reach within one month. However, densities and size distributions were decreased at and below the crossing. Collections taken within one year of construction revealed that fish community characteristics were similar to those that existed prior to construction.

Overall, impacts on benthos and fish associated with construction were minimal and short-term. Keywords : pipeline; fish effects; sediment deposition; turbidity; water quality; river

Servizi, J.A., Martens, D.W. 1987. Some effects of suspended Fraser River sediments on sockeye salmon (*Oncorhynchus nerka*). Can Spec Publ Fish Aquat Sci 96:254-64.

The lethality of natural Fraser River sediments to underyearling sockeye salmon increased with particle size. Fine sediments typical of those in suspension in the river were found to lodge in the gills of underyearlings and cause gill trauma at 3,148 mg/L or 0.2 of the 96 h LC50 value. Sockeye smolts suffered a slight impairment in hypoosmoregulatory capacity when exposed 96h to 14,407 mg/L of fine sediment. Plasma glucose levels of adult sockeye increased 150 and 39% as a result of exposures to 1500 and 500 mg/L respectively, of fine sediment. Suspended solids levels equal to those causing a stress response among adults have been recorded in the Fraser River during spawning migrations. Keywords : sediment particle size; suspended sediment; salmon; underyearling

Servizi, J.A., Martens, D.W. 1991. Effect of temperature, season, and fish size on acute lethality of suspended sediments to Coho salmon (*Oncorhynchus kisutch*). Can J Fish Aquat Sci 48:493-7.

Tolerance of underyearling coho salmon to Fraser River suspended sediments (SS) at 7C was independent of season of the year. However, coho of 0.52 g (4.0 cm) possessed only 35% tolerance of larger specimens. Tolerance to SS was temperature dependent, with 96-h LC50 at 1 and 18C being 47 and 33% respectively, of the value at 7C. Tolerance was further reduced among underyearling coho which were later found to have a viral kidney infection. Cough reflex, oxygen transfer, oxygen saturation levels, metabolic rates, and capacity to do work all probably affect the relationship between SS tolerance and temperature. Keywords : suspended sediment; coho; salmon; laboratory study; fish effects; underyearling; coho salmon; Fraser River; river; sediment; temperature

Servizi, J.A., Martens, D.W. 1995. Effect of temperature, season, and fish size on acute lethality of suspended sediments to Coho Salmon (*Oncorhynchus kisutch*). Can J Fish Aquat Sci 48:493-7.

Tolerance of underyearling coho salmon (*Oncorhynchus kisutch*) to Fraser River suspended sediments (SS) at 7 C was independent of season of the year. However, coho of 0.52 g (4.0 cm) possessed only 35% of the tolerance of larger specimens. Tolerance to SS was temperature dependent with 96-h LC50 at 1 and 18 C being 47 and 33% respectively, of the value at 7 C. Tolerance was further reduced among underyearling coho which were later found to have a viral kidney infection. Cough reflex, oxygen transfer, oxygen saturation levels, metabolic rates, and capacity to do work all probably affect the relationship between SS tolerance and temperature. Keywords : suspended sediment; underyearling; coho; coho salmon; salmon; sediment

Shapley, S.P., Bishop, D.M. 1965. Sedimentation in a salmon stream. J Fish Res Bd Canada 22(4):919-28.

Sediment was artificially added to a small southeastern Alaskan salmon stream. Observations in sedimented and control riffles indicate that the amount of sediment settling to the stream bottom decreases exponentially with distance downstream. The dissolved oxygen content of intragravel stream water remained high in sedimented riffles. The added sediment was removed from streambed gravels by fall freshets and floods. Keywords : sedimentation; salmon; instream sediment; silt effects on habitat; sediment transport; sediment deposition; recovery

Sheehan, R.J., Lewis, W.M., and Bodensteiner, L.R. 1990. Project Completion Report: Winter habitat requirements and overwintering of riverine fishes. Fisheries Research Laboratory, Southern Illinois University. Carbondale, Illinois. F-79-R.

Only recently it has been recognized that overwinter survival of young-of-the-year (YOY) fish is an important determinant of ultimate recruitment for many lentic fish populations. The relationship between recruitment and overwinter survival of YOY fish may be of even greater significance in large rivers. Although lentic fishes have 4C habitat available to them throughout the winter due to stratification, temperatures of 0C prevail in river channels for extended periods of time. The channel habitat appears even more inhospitable to life when one considers that not only must fish somehow manage minimal physiological function at a freezing temperature, they also face the challenge of maintenance of position in a flowing environment.
Survival of YOY freshwater drum in the upper Mississippi River (UMR) appears to be dependent on the availability of suitable winter habitat/microhabitat (Lewis and Bodensteiner 1986). Laboratory studies showed that water temperatures (0-1C) that exist for extended periods of time during the winter in the UMR main channel are lethal to freshwater drum, and it appeared that swimming ability was severely impaired at 1C. This indicated that main channel flows are probably inimical to freshwater drum survival during winter and early spring. Although YOY freshwater drum appear to be intolerant to winter temperatures and flows in the main channel, backwaters (under certain conditions) can provide winter refuges from the harsh environment of the river channel. We recorded temperatures under the ice in deeper areas of backwaters in excess of 5C at times when the main channel was 0C (Lewis and Bodensteiner 1986). The absence of water currents in backwaters would also seem to facilitate overwinter survival.
Backwaters may be essential winter habitat for other UMR species as well. High numbers of dead, moribund, or incapacitated bluegill, channel catfish, gizzard shad, and pumpkinseed sunfish have been found drifting in the main channel during late winter and early spring (Lewis and Bodensteiner 1986). As was the case for freshwater drum, the majority of these fish were in the smallest size classes. Healthy specimens of these same species were found in backwaters during the same time periods. This suggested that a number of important fishes have winter habitat requirements similar to those of the freshwater drum.
Existing backwater habitats in major rivers are rapidly aggrading and disappearing. The formation of new backwater habitats through natural hydrological processes has been largely precluded due to bank stabilization and channelization of the river. The Mississippi River Environmental Management Program (MR EMP), to be implemented over the next ten years, may represent one of the few remaining opportunities to significantly enhance fish habitat in backwaters. Thus, it is imperative that the winter habitat requirements of YOY fishes be delineated as soon as possible so that they can be taken into consideration in MR EMP Habitat Restoration and Enhancement Projects (Bodensteiner and Sheehan 1988).
PROJECT GOAL: The overall goal of this study was to examine the possible use of backwaters as refuges by temperate latitude river fishes during winter. The specific objectives were to: 1) describe winter habitat requirements and habitat use of a number of river fishes; 2) determine the physicochemical, geomorphological, and hydrological characteristics of backwaters suitable for overwintering fish; and 3) examine the seasonal movements of fishes into backwaters.
Keywords : winter; fish habitat; river; temperature

Sheridan, W.L., McNeil, W.J. 1968. Some effects of logging on two salmon streams in Alaska. Journal of Forestry Feb:128-33.

Sedimentation of spawning beds and density of pink salmon (*Oncorhynchus gorbuscha*) were observed before and after logging in two streams in southeastern Alaska. The study lasted seven years (1958-1964). Although the amount of fine particles in spawning beds increased temporarily, the amount in 1964 (five years after logging began) was not significantly greater than in 1959. Densities of salmon spawners and fry increased in the sampling areas during the period of this study. The increases were probably due to the abolition in 1959 of salmon traps (formerly the primary means of catching salmon). Keywords : logging; salmon; recovery; siltation; sedimentation; fry; sampling

Sherk, J.A., O'Connor, J.M., and Neumann, D.A. 1973. Effects of suspended and deposited sediments on estuarine environments. Estuarine Research :541-58.

Static bioassays conducted with fuller's earth suspensions on white perch, spot, silversides, bay anchovies, mummichogs, striped killifish and menhaden, showed that significant mortality in five of the seven species could be caused by concentrations of natural suspended solids typically found in estuarine systems during flooding, dredging, and spoil disposal. Lethal concentrations ranged from a low of 0.58 g/L fuller's earth (24 hr LC10) for silversides to 24.5 g/L fuller's earth (24 hr LC10) for mummichogs. Fishes were classified as either tolerant (24 hr LC10>10 g/L), sensitive (24 hr LC10<10>1.0 g/L), or highly sensitive, (24 hr LC10<1.0 g/L) to fuller's earth. Generally, bottom-dwelling species were most tolerant to suspended solids; filter feeders were most sensitive. Early life stages were more sensitive to suspended solids than adults.
Exposure to sublethal fuller's earth concentrations significantly increased hematocrit value, hemoglobin concentration, and erthrocyte numbers in the blood of white perch, hogchokers, and striped killifish, but not of spot and striped bass. Evidence of O_2-CO_2 transfer interference during exposure to sublethal concentrations of fuller's earth was exhibited by the gills of white perch, which showed tissue disruption and increased mucous production. Suspensions of fuller's earth, fine sand, and Patuxent River silt (>250 mg/L) caused significant reductions in ingestion of radio-labelled ($NaHC^{14}O_3$) *Monochrysis luteri* by the copepods *Eurytemora affinis* and *Acartia tonsa*. Differences in uptake between the two species may have been related to their different life habitats, although both are non-selective suspension feeders. Keywords : adult fish; suspended sediment; fish survival; perch

Shields, F.D., Jr., Sanders, T.G. 1986. Water quality effects of excavation and diversion. Journal of Environmental Engineering 112(2):211-28.

Water quality data collected from Yellow Creek in northeast Mississippi before and during construction of the Divide Cut of the Tennessee-Tombigbee Waterway provide information regarding the water quality effects of stream channelization and large-scale construction projects. Simple graphical and statistical procedures for detecting changes in stream water quality are demonstrated. Data analysis was hindered by missing data, inconsistencies in the list of variables monitored, and changes in sampling frequency. Observed water quality changes were evidently due to increased inputs of sediment and reduced shade. Statistically significant changes in variances and means were observed for most grab-sample variables. Mean values of specific conductance, turbidity, color, COD and total alkalinity hardness, ammonia, phosphorus, sulfate, iron, lead, and manganese were 50-100% greater during construction than before construction. Estimated average daily loadings of total metals, nutrients, and dissolved solids were greater during construction. Average daily suspended sediment load was slightly less during construction, probably because the preconstruction suspended sediment record was brief and influenced by high flow event. Average daily maximum stream temperature was 4C greater and coliform densities and phenol concentrations decreased. Total organic nitrogen, phosphorus, iron manganese and zinc were significantly correlated with turbidity during construction but only total phosphorus was correlated with turbidity before construction. Keywords : water quality; sampling; turbidity; suspended sediment; Tombigbee; sediment; flows; temperature

Sigler, J.W., Bjornn, T.C., and Everest, F.H. 1984. Effects of chronic turbidity on density and growth of steelheads and coho salmon. Transactions of the American Fisheries Society 113:142-50.

Chronic turbidity in streams during emergence and rearing of young anadromous salmonids could affect the numbers and quality of fish produced. We conducted laboratory tests to determine the effect of chronic turbidity on feeding of 30-65 mm long steelheads *Salmo gairdneri* and coho salmon *Oncorhynchus kisutch* in straight and oval channels. Fish subjected to continuous clay turbidities grew less well than those living in clear water, and more of them emigrated from channels during the experiments. Keywords : turbidity; steelhead; coho; salmon; salmonid; fish effects; laboratory study

Simmons, R.C. 1984. Effects of placer mining sedimentation on arctic grayling of interior Alaska. University of Alaska, Fairbanks; 1-75 pp.

During summer 1982 and 1983, the author assessed the effects of placer mining sedimentation on arctic grayling in the headwaters of the Birch Creek and Chatanika River drainages, northeast of Fairbanks, Alaska. In each drainage compared the differences between two streams near their confluence, one that was undisturbed and one with mining activity upstream. Although many age-0 and adult grayling used unmined streams for summer habitat, found no grayling in the mined streams except during periods of migration. Apparently, grayling consistently chose clearwater streams for summer residence. Caged fish studies demonstrated that if grayling could not escape from streams carrying mining sediments, they would suffer direct, chronic effects, including gill damage, dietary deficiencies, and slowed maturation. The indirect effects of sedimentation on grayling populations, through loss of summer habitat for feeding and reproduction, are more severe than the direct ones. Keywords : sedimentation; grayling; adult fish; immature fish; field study

Singleton, H.J. 1985. Water quality criteria for particulate matter. Technical Appendix. Resource Quality Section, Water Management Branch, Ministry of Environment, Province of British Columbia. Victoria, B.C. pp. 1-81.

Keywords : water quality; suspended sediment

Smith, S.B. and Seidner, R.T. 1978. The effects of sedimentation on aquatic biota. Alberta Environment and Environment Canada. editors. Alberta Oil Sands Environmental Research Program. Edmonton. AF 4.9.1. pp. 1-85.

A review of the effects of sedimentation on aquatic biota is presented. The detrimental effects of increased suspended and settled sediments on fish, bottom invertebrates, and primary productivity are documented. It is shown that the upper tolerance level for suspended sediment is between 80-100 mg/L for fish, and as low as 10-15 mg/L for bottom invertebrates. Recovery of the aquatic biota from increased sedimentation is dependent on the severity of sediment additions and the discharge level of the rivers or streams. Recovery from short term additions of sediment is usually complete within one year.

The use of remote sensing and biomonitoring to locate sources of sedimentation is discussed. Remote sensing can generally be used to identify point sources of sedimentation, define flow patterns, choose sampling stations, interpret ground survey data, and maintain permanent records of changes in water quality. Biomonitoring can be used to monitor water quality, especially with regard to sedimentation, since alterations in the environment are reflected by indigenous biota.

The sedimentation characteristics in the Alberta Oil Sands Environmental Research Program (AOSERP) study are presented and observations are made on the potential for erosion and sediment production. The AOSERP study area is divided into twelve hydrological zones and each zone is classified for erosion potential. The zones having high potential are 1) lower Ells basin and eastern slopes of Birch Mountains (Zone 1); 2) tributaries immediately north of Ft. McMurray (Zone 6); 3) Christina River basin (Zone 7); 4) Hangingstone and Horse River basins (Zone 8); 5) MacKay River basin (Zone 9); 6) Dunkirk River basin (Zone 10); and 7) upper Ells River basin (Zone 11).

Road construction, pipeline construction, general construction (urban and industrial sites), vegetation removal, overburden removal, and pit excavation, tailings pods, settling ponds, and diversion channels were identified as possible sources of unnatural increases in suspended and settled sediments in the AOSERP study area. The effect of development activities on the hydrological regime and the aquatic biota is shown. The scale of the disturbance and the length of the recovery period are also predicted. Development activities such as road building and pipeline construction will affect a number of the watershed basins; therefore, they were classified as having regional effect and were considered to be of greatest concern. Keywords : sedimentation; review; sediment; suspended sediment; recovery; highway construction; pipeline

Smits, M.P.e. 1994. Effects of PGT - PG & E Gas Pipeline Construction on the Moyie River, Boundary County, Idaho: PGT - PG & E Pipeline Expansion Project.

A study was conducted to determine the effects of the PGT - PG & E Pipeline Expansion Project on the physical and biological characteristics of the Moyie River in Boundary County, Idaho and to determine the effectiveness of flow control structures installed to mitigate potential effects of construction. Construction occurred from July to September, 1992 for eight wet river crossings. The construction activities have changed the depth profile at the river crossings, caused high embeddedness at two crossings, and caused sediment deposits in low flow areas. No long term effects were found on the biota due to embeddedness. The flow control structures have had a damming effect on the river, decreasing velocity and increasing widths upstream of their placement. The structures have also had a centralizing effect on the river flow at the pipeline and further downstream of the structures. The structures effectively reduced the velocity at pipeline transects, prevented long - term scour, provided cover over the pipeline, and created fish habitat areas. The structures were not effective in preventing high turbidity and TSS levels. The water quality of the river was not affected by the construction activities. The spring runoff had little or no effect on removal of the sediment from the low flow areas. Keywords : pipeline; fish habitat; turbidity; water quality; sediment

Sommarstrom, S., Kellogg, E., and Kellogg, J. 1990. Scott River Watershed granitic sediment study. Klamath River Basin Fisheries Task Force, USFWS.

The extent of the decomposed granitic (DG) sediment problem is examined in the Scott River watershed of Siskiyou County, California. This sand-sized sediment was previously identified to cause spawning habitat impacts for salmon and steelhead and to be an important factor constraining anadromous fish production in the Scott River, a large tributary of the Klamath River. Data was collected during 1989-90 within the 215,000 acre study area, which also included the Scott Valley portion of the Scott River and several tributaries. Analysis focuses on three aspects of the problem; (1) sources of granitic sediment production; (2) granitic sediment storage and transport in the Scott River; and (3) extent of impact of granitic sediment on salmon and steelhead spawning habitat in the Scott River and selected tributaries.
To help analyze the large quantity of data, a GIS database was developed of the study area of which 57,000 acres (26%) are granitic soils. Soils developed from granitics are recognized as some of the most erodible. Total upland decomposed granitic erosion is estimated to be about 340,450 tons per year. Road cuts constitute 40% of the amount, streambanks 23%, road fills 21%, skid trails 13%, and the balance from road surfaces, other sheet and rill erosion, and landslides. For most years, sediment production in the study area is stored in the upper watershed. A delivery ratio of 0.21 is preferred for estimating annual sediment yield to the Scott River, based on results of a recent reservoir study in a similar area. An average yield of 71,500 tons of decomposed granitic sediment is therefore predicted to be delivered to the Scott River each year.
Although the low gradient reaches of the river in Scott Valley represent a natural area of sediment deposition, considerable channel alteration of the Scott River over the years has changed its sediment storage and transport capacities. The greatest amount of sand in channel storage is in the reach between Oro Fino Creek and the State Highway 3 bridge near Fort Jones. Portions of this reach were affected by a diversion dam which acted as a sediment trap from 1958 until its removal in 1987-89. Adjustments in slope and transport capacity will continue to occur both upstream and downstream until a new equilibrium is established. Sediment transport equations, while very limited, in accuracy, were useful in identifying relative sediment transport between reaches and possible contributing factors. The Engelund-Hansen and Ackers-White transport equations appeared the most comparable to actual stream conditions. Prevention and rehabilitation of DG erosion in the uplands of the Scott River watershed would serve to decrease

the input side of the local sediment budget and allow more of the DG sand in channel storage to get moved out over the long term.
Existing and potential spawning areas were sampled for grain size composition using 238 McNeil sampler cores at 11 sites in the Scott River, and 55 cores at 6 sites in lower Etna, French and Sugar Creeks. Core samples were sieved into 7 size categories for analysis. Four quality indices were applied to the field data: percentage fines, geometric mean, fredle index, and visual substrate score. For percentage fines less than 6.3 mm, the three worst sites had amounts ranging from 82.1% to 92.7%, amounts which were greater than any reported for the literature. The relative ratings of the various indices for each site are quite consistent except for the fredle index. Quality indices best serve as relative measurements between sites and between years rather than as accurate predictors of emergent survival. The spawning gravel data developed for this study serves as a good baseline for monitoring changes in streambed composition of the Scott River and several tributaries. Keywords : salmon; steelhead; sediment

Statzner, B., Gore, J.A., and Resh, V.H. 1988. Hydraulic stream ecology: observed patterns and potential applications. Journal of the North American Benthological Society 7(4):307-60.

Although it is well known that metabolism, feeding and behaviour of lotic organisms is influenced by various flow characteristics, hydraulic variables usually are not accurately measured in lotic ecology studies. Using 'hydraulic stream ecology' approach - link organismic responses to a more comprehensive treatment of the physical environment.
Since a unified analytical solution for all important hydraulic variables in running waters does not exist at the moment, we advocate a simpler view of the physical system. We demonstrate methods for estimating complex hydraulic key characteristics, like turbulence in the free flow, turbulence close to the stream bottom and the force of flow prevailing at the bottom. Calculations of these complex key characteristics require measurement of simple hydraulic characteristics like mean velocity, water surface slope, depth, bottom roughness, kinematic viscosity, and density of the water. They hydraulic environment shows characteristic patterns within whole catchments or within reaches of different types of running waters (eg, high gradient mountain stream, lowland stream, mid-order river). Examples from lotic macroinvertebrates, in particular original data on the water bug... demonstrate how organismic responses are linked to the hydraulic environment....abst. continues... Keywords : stream hydraulics; behaviour; methodology; stream ecology; flows

Stigliani, W.M. 1988. Changes in valued 'capacities' of soils and sediments as indicators of nonlinear and time-delayed environmental effects. Environmental Monitoring and Assessment 10:245-307.

This paper discusses the buffering, oxygen-donating, and sorption capacities of soils and sediments as inter-connected system for regulating the retention and release of chemical pollutants. In this context, the author discusses the chemical conditions under which sediments may serve as a source or a sink for toxic materials, and conditions under which soils may retain or release them. It is demonstrated that nonlinear, time-delayed ecological transformations in soils and sediments often can be understood in terms of the interlinked system. The author discusses some possible future long-term environmental problems that might beset Europe, and some implications for a monitoring strategy for forseeing such problems. Because the release of adsorbed toxic chemicals from heavily polluted sediments and soils can occur suddenly owing to changes in oxygen status (ie redox potential) or acidity, strategies for preventing the long-term release of such materials should not only consider current conditions of pH and redox potential, but also how those conditions might change in the future. Keywords : monitoring; suspended sediment; contaminants; model; sediment

Swanston, D.N. 1980. Influence of forest and rangeland management on anadromous fish habitat in western North America: impacts of natural events. Meehan, W.R. editor. Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Dept. of Agriculture. Portland, Oregon. PNW-104. pp. 1-27. USDA Forest Service, General Technical Report.

Natural events affecting vegetative cover and the hydrology and stability of a stream and its parent watershed are key factors influencing the quality of anadromous fish habitat. High intensity storms, drought, soil mass movement, and fire have the greatest impacts. Wind, stream icing, and the influence of insects and disease are important locally. Keywords : fish habitat; hydrology; winter; disturbance

Taylor, B.R., Roff, J.C. 1986. Long-term effects of highway construction on the ecology of a southern Ontario stream. Environmental Pollution (Series A) 40:317-44.

Long-term sampling of a small stream revealed changes up to 6 years after completion of a major highway crossing. Suspended solids and rates of sedimentation declined below the construction site as silt was flushed downstream. Upstream conditions were not re-established for 5 years; incomplete recovery occurred downstream.
Complex changes in invertebrate communities occurred; for 2.5 years after construction, populations increased downstream, and diversity declined. Trichoptera and Diptera proliferated, while Plecoptera and Ephemeroptera remained unchanged, or declined. Five years after construction diversity had rebounded, as flushing of silt allowed repopulations, and silt-tolerant Diptera declined. Few species were lost or gained, but a restructuring of invertebrate communities was evident, especially among the Trichoptera.
Blacknose dace and creek chub increased disproportionately for 2 years, but bottom-feeding species rebounded when sedimentation rates declined. The creek is apparently still changing in response to nutrients and sediments introduced by erosion, and elevated production appears to be relatively persistent. Keywords : logging; salmon; highway construction; sampling; sedimentation; recovery

Tebo, L.B., Jr. 1955. Effects of siltation, resulting from improper logging on the bottom fauna of a small trout stream in the southern Appalachians. The Progressive Fish-Culturist April:64-70.

Summary: 1. From 1942 to 1948, a 212 acre watershed on the Coweeta Experimental Forest, Macon County, North Carolina, was logged by a local contractor. Roads and skid trails were built parallel and adjacent to the stream channel. No surfacing material and no drains were used. 2. They physical and chemical characteristics of Shope Creek, a small trout stream which receives the stream from the logged watershed are described. 3. During storm periods the turbidity of Shope Creek was appreciably increased by the highly turbid waters from the logged area. The accumulation of sand and silt in Shope Creek below the mouth of the stream from the logged watershed is described. 4. Roads and skid trails proved to be the major source of turbidity. From April 1951 to March 1953, an average of 5.34 cubic feet of soil per lineal foot of road surface was eroded from the logging road. 5. From October 1952 to June 1953, 108 sq. foot bottom samples were collected at monthly intervals in Shope Creek at stations above and below the mouth of the stream from the logged watershed. 6. From October 1952 through January 1953, the period of maximum accumulation of sediment in the affected section of Shope Creek, there was a significantly lower standing crop of bottom organisms at the station below the mouth of the logged watershed. 7. A flood on Feb 21, 1953, removed the accumulation of sand and silt in Shope Creek below the mouth of the logged watershed and reduced the bottom fauna at the lower station to 7.3 organisms per sq ft., as compared with 25.5 organisms per sq ft at the upper station, which had not been subject to siltation from the logged watershed. 8. The Feb flood exposed and excellent bottom of rubble and gravel at the lower station; from Feb through May , spring rains and high stream flow prevented the reaccumulation of sand and silt at the lower station on Shope Creek. During this period there was o significant difference in the standing crop of bottom fauna at the control and treated stations. During June, when silt had begun to reaccumulate, the control section again produced a larger standing crop of bottom organisms. The difference was not significantly different. Keywords : siltation; logging; turbidity; recovery; trout; sediment

TERA Environmental Consultants (ALTA.) LTD. 1983. A study on pipeline water crossing methods. Prepared for the Canadian Petroleum Association, Environmental Research Advisory Committee. Alberta. pp. 1-132.

The Canadian Petroleum Association, Environmental Research Advisory Committee has sponsored this report on Pipeline Water Crossing Methods. The objective has been to describe, in a concise set of construction procedures, guidelines for pipeline stream crossings which acknowledge high standards of environmental protection. The study first examines the existing stream classification systems related to stream morphology, aquatic habitat, and pipeline construction methods. From this, four size categories of streams are presented and are used throughout the report as a basis for describing construction procedures. The study has also included a comprehensive review of the literature relating to pipeline stream crossings. While there are several potential environmental impact resulting from pipeline construction, the temporary disturbance or alteration of fish habitat is clearly the dominant one. Measure taken to protect fish habitat will also mitigate other concerns.
Most pipeline stream crossings are constructed "in the wet" by excavation of a ditch across the stream channel. All authors recognize that this method leads to a temporary increase in the sediment load of the stream. However, the extent of this resulting sedimentation is small compared to other types of in-stream construction and, for most small streams, would only continue for two or three days.
This study acknowledges that the conventional open-cut crossing procedure will continue to be the most common method of pipeline stream crossing method and has found no evidence to recommend against this procedure on a broad basis. There are alternatives to this procedures for avoiding wet work are the pump-around procedure and the fluming procedure. Both are fully described and can be used where downstream sedimentation is a serious concern.
Sedimentation during construction results from ditch excavation and from construction equipment crossing the stream. Alternative procedures for vehicle crossings are also addressed.
This study recommends that environmental surveys during route selection and planning identify, not only which streams are environmentally sensitive, but also why: what is the primary objective of the environmental protection measures. For example, it may be to minimize siltation, allow fish passage, maintain stream flow or minimize the disturbance to the bed and banks. With this knowledge, the crossing procedure can be modified to respond to these specific objectives.
In many cases, route surveys and environmental studies are undertaken well before construction. This study recommends that the regulatory body approving stream crossings not attempt to specify the exact construction procedure but rather should approve the standard procedures that may be used and allow the field inspection staff the final decision during construction. The construction procedures set out in the summary of this report show how the environmental impact of pipeline stream crossing can be minimized. Keywords : pipeline; methods; stream morphology; review; disturbance; fish habitat

The technical staff of the Environmental Quality Unit, S.O. 1973. Pipeline construction guide. Dept. of the Environment, Fisheries and Marine Service, Pacific Region. TR-1973-2. pp. 1-8.

Keywords : pipeline; methods

Thomann, R.V., Mueller, J.A. 1987. Principles of surface water quality modeling and control. ; Robichaud, C. editor. Harper and Row, Publishers, Inc. New York, N.Y. 0-06-046677-4.

Toneys, M.L., Coble, D.W. 1979. Size-related, first winter mortality of freshwater fishes. Transactions of the American Fisheries Society 108:415-9.

To determine if first winter mortality were greater for small than for large freshwater fish, we conducted eight experiments in lakes and hatchery ponds during which fish were measured in late fall and early spring. Overwinter increase in mean length of the bluegill (*Lepomis macrochirus*) in one lake and largemouth bass (*Micropterus salmoides*) in another could have been caused by higher mortality of smaller fish Size-related mortality was not detected in six other populations - two of bluegill and one each of largemouth bass, green sunfish (*Lepomis cyanellus*), fathead minnow (*Pimephales promelas*), and white crappie (*Pomoxis annularis*). Available evidence indicates that size-related mortality is probably not a common phenomenon for bluegill and largemouth bass, but it may be important for walleye (*Stizostedion vitreum*) and sander (*Stizostedion lucioperca*). Keywords : winter; lake; bluegill; bass

Tsui, P.T.P., McCart, P.J. 1981. Effects of stream-crossing by a pipeline on the benthic macroinvertebrate communities of a small mountain stream. Hydrobiologia 79:271-6.

Aquatic environmental impact associated with stream-crossing by a pipeline was monitored at Archibald Creek, B.C. for two years. Water chemistry and benthic macroinvertebrates were used as monitoring tools. Results indicated that impacts arising from stream-crossing were short-term and non-residual. Keywords : pipeline; benthic invertebrate community; silt effects on habitat; macroinvertebrates; monitoring

US Forest Service. 1974. Trout biology and population ecology: Effects of sand and sediment on brook trout in Hunt Creek. US Forest Service, North Central Forest Experiment Station. Michigan. F-30-R-8. pp. 1-8.

This is a progress report - consists of one large summary. Keywords : brook trout; suspended sediment

van Boetzelaer, M.E., van Geldermalsen, L.A., Vrijling, J.K., and Prins, J.E. 1991. Chapter 2. Relating hydraulics and ecological processes. Journal of Hydraulic Research 29(extra):8-19.

Any major modification of the hydraulic system results with some retardation in a response of the ecosystem trying to adapt to the new conditions. It is difficult to imagine situations where hydraulics and ecosystems are not related. Thus, harmonizing hydraulics with ecology means to identify alternative hydraulic measures which yield simultaneously economic benefits and improvement, preservation or at least a best fit of the environmental situation. Often, these objectives are subjected to an inherent conflict and therefore harmonizing is dependent on the preference structure of the modem society, which is inclined to sustainable development. The objective of this chapter is to develop a framework (methodology) which might assist in relating hydraulics and ecology with respect to specific goals under site and problem dependent constraints. Keywords : methodology; hydrology

Ventling-Schwank, A.R., Livingstone, D.M. 1994. Transport and burial as a cause of whitefish (*Coregonus* sp.) egg mortality in a eutrophic lake. Can J Fish Aquat Sci 51:1908-19.

Predictions based on the Shields diagram and confirmed by experiments conducted in eutrophic Lake Sempach imply that bottom currents associated with winter storm events are responsible for the simultaneous transport of coregonid eggs and fine silt and clay (grain size <=10 um) from the spawning grounds into deeper lake regions. The critical shear stress required to initiate egg transport is estimated to lie in the range of 0.02-0.04 N/m^2, corresponding to mean current speeds of 10-15 cm/s at a reference height of 0.5 m above the sediment surface. On settling out, egg burial is likely. This will increase egg mortality not only by physically hindering oxygen transport to the egg, but also, in POC-rich eutrophic lake sediment, by relocating the egg in a zone of steep oxygen gradients and low mean oxygen concentrations. Microelectrode measurements and computation of the thickness of the oxygen diffusive boundary layer over the sediment reveal that even eggs that escape interment are likely to be subjected to ambient oxygen concentrations insufficient for development to hatching. It is suggested that transport and burial may in general be important factors determining coregonid egg mortality in eutrophic lakes. Keywords : winter; fish survival; whitefish; lake; silt effects on habitat; sediment

Villamere, J. 1982. An evaluation of the effectiveness of instream silt control devices in controlling siltation during construction activities. Hatfield Consultants Ltd., for Supply and Services Canada and Fisheries and Oceans Canada. Vancouver, B.C. pp. 1-22.

This study was undertaken to evaluate the effectiveness of five in-stream silt control devices in collecting silt created during in-stream activities. The silt control studies were carried out in Chinamans Creek, a small fast-flowing mountain stream typical of many west coast salmon streams. Four of the five silt control devices tested were manufactured silt screen products. Straw bales were also tested. The tests were carried out during mock pipeline crossing construction activities and during stream diversion activities.
The results obtained were not encouraging. Two banks of the most successful silt screen, operating downstream of a mock pipeline crossing, resulted in only a 40.7% reduction in suspended solids. Straw bales utilized during stream diversion activities removed only 10.7% of the suspended solids loading. The other three silt screens tested did not have the required permeability to function effectively under the hydraulic conditions existing in the stream.
The project resulted in a great deal of first-hand knowledge and experience with respect to maximizing the effectiveness of the silt screens through the selection of the most efficient operating procedures. Testing indicated that two banks of screens were more effective than a single bank, and that silt screen maintenance during operating periods was essential. The procedures followed during silt screen removal (i.e. upon completion of construction activities) were found to be very important. The importance of a structurally sound support fence (i.e. able to with stand the pressure resulting from a head of water across the fence) was also apparent. Keywords : sedimentation; logging; salmon; trout; siltation; pipeline

Vinikour, W.S. and Schubert, J.P. 1987. Effects of gas pipeline construction on the aquatic ecosystem of Canada Creek, Presque Isle County, Michigan. Gas Research Institute, NTIS. Chicago, Illinois. GRI-87/0027. pp. 1-82.

A study was conducted to quantify the effects of pipeline construction on the biological , physical and chemical characteristics of Canada Creek in Presque Isle County, Michigan. The plow method was used to install the pipeline. Shoreline ramp construction, rather than the actual installation of the pipeline by the plow, resulted in the greatest increases in suspended sediment. During ramp excavation, suspended-solids concentrations increased from <= 50 mg/L to as high as 1105 mg/L three meters downstream from the crossing site; during actual pipeline installation, suspended-solids concentrations did not exceed 77 mg/L. Streambed particle-size distribution was not appreciably affected by excavation and installation activities, and no effects on water chemistry were detected. Additionally, no impacts on benthic macroinvertebrates or the prevalent fish species (American brook lamprey and mottled sculpin) occurred, Minor, short-term effects on macroinvertebrate drift during ramp excavation were indicated by increased drift densities and diversities as well as by the increased occurrence of terrestrial species. The short installation time required, in combination with the minimal amount of instream disturbance caused by the plow accounts for the lack of major installation impacts. Keywords : pipeline; suspended sediment

Vinyard, G.L., O'Brien, W.J. 1976. Effects of light and turbidity on the reactive distance of bluegill (*Lepomis macrochirus*). J Fish Res Bd Canada 33:2845-9.

Changes in the reactive distance of bluegill to various sizes of *Daphnia pulex* were measured at light intensities ranging from 0.70 to 215.3 1x(0.065-20.0 ft-c) and at turbidities ranging from 1 to 30 JTUs. Both reduced illumination and increased turbidity caused substantial reduction in the reactive distance of bluegill for all prey sizes, and particularly for large prey. This result should be considered in efforts to determine fish feeding rates in lakes, and may be particularly relevant to vertically migrating zooplankton, or those inhabiting more turbid waters. Keywords : turbidity; lake; zooplankton; bluegill; behaviour; suspended sediment

Vogel, B. 1980. The impacts of pipelines on fish and wildlife: an annotated bibliography. The Northern Pipeline Agency. pp. 1-77.

No abstract. Series of references with short discussions given of each. Keywords : highway construction; pipeline

Wagener, S.M. 1984. Effects of gold placer mining on stream macroinvertebrates of interior Alaska. University of Alaska, Fairbanks; 1-100 pp.

Placer gold mining is an economically and politically important industry in Alaska which can have major impacts on the water quality of streams. To determine the effect of placer mining on benthic macroinvertebrates we determined water quality characteristics and samples benthic invertebrates in nine hydrologically similar and proximally located streams. Sampled streams ranged from unmined control streams to heavily mined streams. Placer mining caused increases in turbidity, settleable solids, percent substrate embeddedness, nonfilterable residue, and total recoverable arsenic, lead, zinc, and copper. Placer mining decreased invertebrate density and biomass. Substrate embeddedness and turbidity were the best predictive descriptors of reduced invertebrate density and biomass. Invertebrate communities in mined streams usually contained higher proportions of collector-gatherers, and lower proportions of crawlers, shredders, filter-feeders, predators, and oligochaetes compared to unmined streams. Keywords : water quality; turbidity; settleable solids; benthic invertebrate community

Wagener, S.M., LaPerriere, J.D. 1985. Effects of placer mining on the invertebrate communities of interior Alaska streams. Freshwat Invertebr Biol 4(4):208-14.

To determine the effect of placer mining on benthic macroinvertebrates we determined selected water quality characteristics and sampled benthic invertebrates in nine hydrologically similar and proximally located streams, ranging from unmined to heavily mined streams. Placer mining caused increased turbidity, and increased amounts of settleable solids and suspended sediment (nonfilterable residues). Sediment from placer mining was associated with decreased density and biomass of invertebrates. In a stream where mining began in mid-August, Orthocladiini (Diptera: Chironomidae) and Chloroperlid stoneflies decreased in abundance while they were not decreased in a nearby unmined stream. Water mites seemed to be the organism most affected by placer mining. Keywords : water quality; turbidity; settleable solids; suspended sediment; benthic invertebrate community

Ward, N. 1992. The problem of sediment in water for fish. Northwestern Ontario Boreal Forest Management Technical Notes TN-21:1-8.

This paper reviews the effects of sediment on fish in freshwater. The following notes summarize the main points of the paper.

Soils that are high in silt and fine sand and low in clay and organic matter are generally the most erodible - well grained sandy and rocky soils are the least erodible (Goldman et al. 1986). Sediment is classified by particle size: 3 mj. classes 1) sand, 2) silt, and 3) clay. The size of particles and water velocity determine how the particle is transported (large particles such as sand and gravel tend to roll along the stream bottom as part of the bedload; small particles, ie. silt and clay, are usually transported in suspension - concentrations are generally uniformly distributed throughout the water column (Culbertson 1977). TSS = total suspended solids mg/L or ppm = turbidity.
High turbidity can limit photosynthesis of algae and macrophytes - this limits the production of food for aquatic life - can also cause changes in fish feeding behaviour, because prey is less visible - can also harm incubating eggs and fry (Cedarholm et al. 1982), reduce the abundance

of insect larvae (fish food) (Hynes 1973) and high levels of suspended sediment can cause fish mortality if lasting for many days (200-300 mg/L) (Phillips 1971).
The impact to aquatic organisms from suspended sediment is a function of duration and concentration (Newcombe and MacDonald 1991).
Total suspended solids <25 mg/L shouldn't harm fish or fish habitat (EIFAC 1965, USEPA 1973, DFO and DOE 1983). However, low levels of SS shouldn't last longer than several weeks as rubble/gravel areas will rapidly become silted, even in flows with low concentrations of SS (Carling 1984).
Instream construction activities should be restricted during spawning/egg incubation periods to prevent SS from attaching to the adhesive surface of fish eggs. South Dakota study found that a deposit of 1 mm of silt per day during pike egg incubation caused egg mortality of 97% or more (Hassler 1970).
Bedload Sediment: if water velocity is less than the soil particle's settling velocity, then the particle becomes bedload sediment as it slides, rolls or bounces along the bottom. This sediment may fill in the interstitial spaces or crevices between rock rubble/gravel spawning areas suffocating eggs or fry if present (Hall and Lantz 1969). There is an inverse relationship between sediment concentration and %fish fry emergence (see fig 2). Interstitial spaces also act as hiding areas for eggs from predators. Sediment also adversely affects invertebrates by filling up their crevice homes, muddying over their attachment surfaces, and eliminating interstitial spaces which act as a storehouse for organic silt on which many other invertebrates feed (Hynes 1973). Some invertebrates like mud/silt but this community is a quite different community ie. get worms or midge larvae vs mayflies and caddisflies.
Walleye egg survival was reduced by 2/3 when eggs were deposited on sand vs clean gravel/rubble substrate and was 1/10 of the clean substrate when laid on silt or muck/detritus bottom (Johnson 1961) (see fig 3). Flushing flows in spring may not have enough velocity to clean out silt from surfaces and from between rocks (Milhous 1982). Keywords : instream sediment; fish effects; review; sediment

Waters, T.F. 1995. Sediment in Streams: Sources, biological effects and control. 1st. ed. American Fisheries Society;Bethesda, Maryland. 0-913235-97-0. 1-251.

Monograph produced by the American Fisheries Society. Introduction deals with the extent of sediment pollution, early studies, biotic stream communities, and previous publications on sediment. Chapters cover physical characteristics of stream sediments, sources of sediment (principally agriculture, forestry, mining, urban development, streambank erosion as well as miscellaneous sources), effects of suspended sediment, effects of deposited sediment on benthic invertebrates, effects of sediment on fish, control of sediment, and a summary is given. Keywords : sediment; forestry; erosion; suspended sediment; mining

Way, J.G. and Thorne, G.A. 1978. Reconnaissance of polar gas route river crossings in the Keewatin District, NWT. Water Survey of Canada, Inland Waters Directorate, Fisheries and Environment Canada. Ottawa, Ontario. AI-16. pp. 1-145.

This report summarizes the work carried out during 1976 by the FP-1-76-3 Project of the Hydrologic Regimes component of the Freshwater Program of the Arctic Islands Pipeline Program. The objective of this project was to obtain an overview of hydrology along the pipeline corridor from Churchill to Spence Bay, in order to provide data for an adequate assessment of the proponent's application as it concerns river crossings. To achieve the objective, broad spatial coverage of hydrologic events through a "quick look" reconnaissance was performed, similar to that of Wedel and Way (1976). Due to the vastness of the geographic area involved, the large number of lakes and rivers found within it, and the fact that studies of hydrologic events are time-dependent, additional information is required before quantitative assessments can be made. However, an attempt has been made to relate hydrologic, fluvio-morphometric and climatic data to support subjective approximations of hydrologic parameters. Appended to this report is a survey equipment, listing a detailed stream catalogue and a listing of water quality parameters analyzed by the Water Quality Branch, Inland Waters Directorate, Western and

Northern Region. Within the reconnaissance area - and as part of the Freshwater Program - three separate reports have been submitted by the Glaciology Division of the Inland Waters Directorate, Environment Canada dealing with hydrologic regimes in the district of Keewatin. Two major recommendations result from these investigations: one being the need for a user-oriented centralized hydrologic data bank, which was originally proposed by Wedel and Way (1976); and the other the need for the establishment of a continuous hydrologic and fluvio-morphometric network rather than a hydrometric network alone. Keywords : pipeline; hydrology; lake; water quality

Weaver, T.M., Fraley, J.J. 1993. A method to measure emergence success of westslope cutthroat trout fry from varying substrate compositions in a natural stream channel. North American Journal of Fisheries Management 13:817-22.

This study developed a field method to examine emergence success of fry of westslope cutthroat trout in relation to varying levels of fine substrate materials in a natural stream environment. We attempted to simulate natural incubation conditions in a stream by constructing cells with particle sizes and egg pockets characteristic of antural westslope cutthroat trout redds. We found a significant inverse relationship (r^2=0.72, p<0.005, N=17) between fry emergence success, as measured by fry emergence traps, and the percentage of substrate materials less than 6.35 mm in diameter. Mean fry emergence success was 76, 55, 39, 34, 26, and 4%, respectively, in cells containing 0, 10, 20, 30, 40, and 50% substrate materials less than 6.35 mm. There were no significant differences in length or weight of fry emerging from the six gravel mixtures. Using the methods and results presented in this study, as well as previous laboratory results, resource managers could develop substrate quality guidelines for westslope cutthroat trout reproduction in streams affected by land management practices. Keywords : methods; cutthroat trout; fry; fish habitat; trout; laboratory; reproduction; management

Whitehead, V.M. 1978. Stream crossing design and construction: implication to Manitoba fisheries. Fisheries Research, Fisheries Management Branch, Manitoba Dept of Northern Affairs, Renewable Resources, and Transportation Services. 78-10. pp. 1-171.

This report has attempted to review the criteria for protection of the fisheries resource from the impacts of stream crossing. Manitoba's fisheries resource will not be protected unless the foregoing recommendations are consistently carried out on each stream crossing project. Written specifications in the contract plus consultation with Manitoba regional fisheries biologists will help guarantee meeting the desired objectives. It is hoped that this report will generate additional studies on swimming capabilities of fish and the hydraulic analysis of fish passage structures specific to Manitoba's needs. Further evaluation of the effectiveness of existing stream crossing installations is needed in Manitoba for improved management of our fisheries resource.
Chapter include a discussion of properties of streams and stream flow, stream sensitivities, hydrology of streams, effects of spates, sensitivity of fish, behavioural effects and physiological effects, design of fish facilities, mitigation and minimization of impacts including routing, scheduling, gravel removal, cuts and clearing, slope stabilization, drainage, etc... Keyword : review

Wiederholm T. 1984. 17, Responses of aquatic insects to environmental pollution. ; Resh VH, Rosenberg DM, editors. The Ecology of Aquatic Insects. Praeger Scientific, New York: pp. 508-557.

Keywords : benthic invertebrate community; contaminants; recovery; review

Wilber, C.G. 1983. Turbidity in the Aquatic Environment. Charles C. Thomas. Springfield, Illinois. 1057. pp. 1-132.

This publication consists of a review of the ecological and biological effects of turbidity in aquatic ecosystems. It includes a review of the means of measuring turbidity, the dynamics of suspended particles, effects of turbidity in estuaries, a review of studies examining turbidity and its effects worldwide and means for mitigation. Keywords : turbidity; review; aquatic environment

Williams, D.D., Hynes, H.B.N. 1976. The recolonization mechanisms of stream benthos. Oikos 27(2):265-72.

The animals recolonizing an area of denuded stream substrate are thought to come from four main sources. These are drift, upstream migration within the water, migration from within the substrate, and aerial sources, e.g. oviposition. An experiment in a Canadian stream showed drift to be the most important source of recolonizing animals, contributing 41.4% of the total number that settled on an area of 1800 c^{m2}. This compares with 28.2% from aerial sources while upstream migration and movement up from within the substrate contributed about equally (18.2% and 19.1% respectively). Clearly then, all four directions are important in repopulating bare areas. Further, many groups of organisms were found to have preferred directions from which they recolonize and this, it is argued, may lead to the establishment of separate and distinct faunal assemblages if the other directions are excluded. Keywords : benthic invertebrate community; biomass changes; disturbance; flushing flows; invertebrate community changes; drift

Wohl, N.E. 1993. An ecological assessment of sediment loads from three streams in the Spring Creek basin, Centre County, Pennsylvania. Pennsylvania State University; 1-130 pp.

Eroded streambanks are common in agricultural areas where farm animals have ready access to streams. Deposition of eroded streambank soil onto the streambed during storm events may reduce fish density and recruitment, and affect macroinvertebrate community density and diversity. The main objective of this study was to determine if there is a relation between the amount of sediment being eroded from agricultural areas and the densities and diversities of fish and aquatic macroinvertebrates. Cedar Run and Slab Cabin Run, two of three major tributaries in the Spring Creek watershed, Centre County Pennsylvania, transport elevated levels of suspended sediment in proportion to the length of eroded stream banks adjacent to grazed areas along each stream. The main stem of Spring Creek receives the runoff from these two agricultural streams. The headwaters of Spring Creek proper have little agricultural sediment loading, and served as a reference for comparing sediment loading to the other two streams. Sediment loading, substrate composition, water temperatures, fish and aquatic macroinvertebrates were assessed at nine sites. Sediment yield was estimated to be 0.234, 0.698, and 1.221 tonnes per square kilometer of watershed area per million cubic meters of discharge per year in Spring Creek, Cedar Run and Slab Cabin Run, respectively. Spring Creek had significantly higher quality trout spawning substrate and habitat than the other two streams. Water temperatures below 5C were found most often in the Slab Cabin Run, sometimes in Cedar Run, and never in Spring Creek. Aquatic macroinvertebrate densities were also significantly different among streams with Spring Creek at 15,293/m^2, Cedar Run at 7,241/m^2, and Slab Cabin Run at 5,000/m^2. Aquatic macroinvertebrate diversities were not significantly different, due to substitution of pollution tolerant taxa in place of pollution intolerant taxa. Adult and age-0 brown trout (*Salmo trutta*) populations were also significantly different among streams. Spring Creek has 1,000/km and 1,967/km, Cedar Run had 214/km and 173/km, and Slab Cabin had 15/km and 20/km adult and age-0 brown trout, respectively. Temperature and flow variation play a role in brown trout population dynamics. Although these two variables were more closely linked to ground water entry into the stream than to the loss of riparian vegetation in grazed area, sediment loads were also inversely related to age-0 brown trout and aquatic macroinvertebrate densities. The data suggest that while the degree of sediment deposition and the status of aquatic communities are a function of the degree of disturbance in the riparian zone, the amount of ground water entering the stream may also significantly influence aquatic community structure. Keywords : suspended sediment; brown trout; disturbance; agricultural; macroinvertebrates; sediment; trout; sediment deposition

Young, M.K., Hubert, W.A., and Wesche, T.A. 1991. Selection of measures of substrate composition to estimate survival to emergence of salmonids and to detect changes in stream substrates. North American Journal of Fisheries Management 11:339-46.

Biologists have attempted to link intragravel survival of juvenile salmonids to changes in stream substrate quality caused by land management, but the failure to standardize measures of substrate composition has hindered this effort. We compared 15 such measures in laboratory tests that evaluated survival to emergence of Colorado River cutthroat trout *Oncorhynchus clarki pleuriticus* in substrates of different composition. We also evaluated the sensitivity of three measures of substrate composition to the modification of stream substrates by spawning brook trout *Salvelinus fontinalis* and the deposition of sediment in former redds of Colorado River cutthroat trout. Different estimates of the geometric mean particle size accounted for the greatest proportion of the variation in survival to emergence in laboratory tests, but the percentage of substrate less than 0.85 mm in diameter was the most sensitive measure of known changes in substrate composition in the field. We concluded that a single measure of substrate composition may be inadequate to both assess the potential survival to emergence in a substrate and detect changes in substrate composition caused by land use. Keywords : sediment particle size; fish habitat; fish survival; salmonids; cutthroat trout; trout; sediment; management; laboratory; river

Young, R.J. 1986. The effect of winter oil pipeline construction on the benthic macroinvertebrate community structure of Hodgson Creek, N.W.T. University of Guelph; 1-78 pp.

Studies were conducted during the ice-free seasons of 1984 and the winter and summer of 1985 to determine the effect of winter oil pipeline construction on the benthic macroinvertebrates of Hodgson Creek, NWT. Effects of winter in-stream construction were determined by assessing changes in drift densities and short-term effects were determined in the ice-free periods by examining changes in benthic density and community structure.
Downstream of the construction site, total suspended sediment (TSS) concentrations increased from 2 mg/L prior to construction, to over 300 mg/L during the construction period, with peak concentrations over 3000 mg/L during the concentration period, with peak concentrations over 3000 mg/L being recorded. Silt deposition ranged from 15 to 78 g/m^2/day before construction, but increased to over 1500 g/m^2/day downstream of the construction site. Drift densities were significantly higher at the two stations receiving the highest silt deposition. *Capnia* sp. and *Alloperla* spp. numerically dominated the drift during this period. TSS concentrations returned to pre-construction values within five days of construction at all stations and the silt deposition rate decreased to 280 g/m^2/day downstream of the right-of-way five weeks following construction. Drift densities increased at the control station in late winter as *Capnia* sp. nymphs matured, while significantly lower drift densities were observed at two downstream stations. Densities of *Capnia* sp. apparently did not recover to pre-construction levels by the end of the winter study period.
TSS and nutrient concentrations were similar among stations in all ice-free sampling periods. Comparison of downstream and control stations prior to construction demonstrated no significant differences in species composition or community structure. Following ice scouring and spate events in the spring of 1985 (after construction), macroinvertebrate densities at all stations were approximately 100/m^2. The substrate was quickly colonized by *Similium* sp. and *Prosimilium* sp. and densities increased exponentially to over 1000/m^2 within 50-d of flooding. It appears that pipeline construction did not contribute to changes in habitat that would result in significant changes in community structure or benthic densities.
A benthic recolonization pathway experiment showed similar benthic densities were reached from the drift, upstream, aerial, and vertical-migration pathways after 28-d. However, Plecoptera and Ephemeroptera predominated in the drift pathway and Chironomidae were numerically dominant in the aerial, upstream, and vertical migration-pathways. Control traps, allowing colonization from all pathways, had significantly greater invertebrate densities than did Surber samples. Also, control traps had proportionately more Chironomidae and fewer Plecoptera and

Ephemeroptera. It is suggested that colonizing organisms in Hodgson Creek originate from upstream tributaries and areas less affected by spate events.
. Keywords : winter; pipeline; recovery; benthic invertebrate community

Young, R.J., Mackie, G.L. 1991. Effect of oil pipeline construction on the benthic invertebrate community structure of Hodgson Creek, Northwest Territories. Can J Zool 69:2154-60.

During the ice-free seasons of 1984 and the winter and summer of 1985, we determined the effect of winter oil pipeline construction on benthic invertebrates of Hodgson Creek, Northwest Territories. Total suspended sediments increased from <2mg/L to >300 mg/L at sampling stations downstream of the pipeline right-of-way during construction, with peak concentrations exceeding 3000 mg/L. A concurrent increase in benthic invertebrate drift density from 2.6 to 37.6/100 m^3 was observed downstream of construction. The effects of pipeline installation were observed up to 5 weeks following the end of construction. Following the spring snowmelt in 1985, no significant difference in standing crop, species richness, or functional group composition between stations upstream and downstream of the pipeline right-of-way was observed. We concluded that the negative impact of pipeline construction was limited to the period between construction and spring ice breakup. The frequency and magnitude of spate events were sufficient to remove accumulated sediment. Thus, the impact of natural perturbations in Hodgson Creek was greater than the effect of pipeline construction on benthic community structure. Keywords : pipeline; sediment concentrations; benthic invertebrate community

Zallen, M. 199. Effects of pipeline construction on juveniles and incubating eggs of mountain whitefish (*Prosopium williamsoni* Girard) in the Moyie River, British Columbia.[Unpublished]

The effects of construction and installation of a 914 mm O.D. (36 in) natural gas pipeline on the incubating eggs and juveniles of mountain whitefish (*Prosopium williamsoni*) were investigated at two crossings of the Moyie River, British Columbia. During November, 1980, prior to the pipeline installations, recently deposited whitefish eggs were quantitatively sampled in transects across the river at several locations upstream and downstream of the ROW crossings to a distance of 1 km. In addition, seining in pools below the crossings indicated that numerous young-of-the-year mountain whitefish were also present downstream of the ROW. Installation of the pipeline occurred during January, 1981, and involved ditching directly across the river. At each crossing, instream construction activities occurred intermittently during 5-6 days and maximum observed suspended sediment levels in the river were 1000-3000 ppm, decreasing rapidly after several hours after construction. Approximately one month after the completion of the stream crossings, a re-examination of habitats containing whitefish eggs revealed no significant increase in mortality of eggs downstream of the crossing sites compared to control areas, while juvenile whitefish continued to utilize most pool habitats downstream of the ROW. Keywords : pipeline; whitefish; suspended sediment; winter; fish survival; fish eggs; juvenile fish; British Columbia; sediment; river

APPENDIX 2

DOSE/RESPONSE RELATIONSHIPS SUMMARY

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

Organism: i. Common Name; ii. Habitat (f = fresh; e = estuarine); iii. Life-History Phase

Exposure: Concentration and Duration; Stress Index (SI) — Natural log of mg.hr/L

Nature of Ill Effect (NE): all organisms; and, Severity of Ill Effect (SE): fishes only.

i.	ii.	iii.	mg/L	hr	SI (mg.hr/L)	SE	NE	Reference
					SI <0			
zooplankton	f	I	1	0.08	-2.48	n	Feeding rate (ingestion + incorporation) slightly reduced.	Arruda and others 1983
whitefish	f	A	0.66	1.00	0.00	3	Pattern of swimming behavior changed.	Lawrence and Scherer 1974
zooplankton	f	I	10	0.08	-0.18	n	Efficiency of incorporation of food reduced.	Arruda and others 1983
salmon (coho)	f	J	53.5	0.02	-0.11	1	Alarm reaction.	Berg 1983
					SI =>0			
salmon (coho)	f	U	20	0.05	0.00	1	Cough frequency not increased.	Servizi and Martens 1992
salmon (coho)	f	J	88	0.02	0.38	1	Alarm reaction.	Bisson and Bilby 1982
oysters (1)	e	I	100	0.02	0.51	n	Change in filtering rate.	Loosanoff and Tommers 1948
oysters (2)	e	I	100	0.02	0.51	n	Change in pattern of shell movements.	Loosanoff and Tommers 1948
zooplankton	f	I	24.5	0.08	0.71	n	Feeding rate (ingestion + incorporation) reduced by 10 %.	Arruda and others 1983
zoobenthos	f	I	10	0.25	0.92	n	Increased invertebrate drift.	Rosenberg and Snow 1980

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
SI =>1								
zooplankton	f	I	24	0.17	1.39	n	Reduced efficiency of food assimilation.	McCabe and O'Brien 1983
copepod	e	I	50	0.08	1.43	n	Ingestion of food drastically reduced.	Sherk and others 1975
macrobenthos	f	I	23	0.25	1.75	n	Increased drift of macrobenthos.	Rosenberg and Snow 1975
salmon (coho)	f	J	88	0.08	1.99	3	Avoidance behavior.	Bisson and Bilby 1982
SI =>2								
zooplankton	f	I	100	0.08	2.12	n	Efficiency of incorporation of food greatly reduced.	Arruda and others 1983
trout (rainbow)(1)	f	A	100	0.10	2.30	3	Fish avoid turbid water (avoidance behaviour).	Suchanek and others 1984a, and 1984b; from Lloyd 1985
grayling (arctic)(2)	f	A	100	0.10	2.30	3	Fish avoid turbid water (avoidance behavior).	Suchanek and others 1984a, and 1984b; from Lloyd 1985
bluegill	f	A	15	1	2.71	4	Reduced capacity to locate prey.	Vinyard and O'Brien 1976
SI =>3								
zooplankton	f	I	245	0.08	3.02	n	Feeding rate (ingestion + incorporation) reduced by ~90%.	Arruda and others 1983
bluegill	f	A	423	0.05	3.05	4	Rate of feeding reduced.	Gardner 1981
trout (rainbow)	f	A	100	0.25	3.22	5	Rate of coughing increased. (Particle Size 0.01 to 0.07 mm).	Hughes 1975
salmon (coho)	f	J	25	1	3.22	4	Rats of feeding declines.	Noggle 1978
herring	e	L	10	3	3.40	3	Change in depth preferendum of larvae in holding tank.	Johnson and Wildish 1982
grayling (arctic)	f	J	86	0.42	3.58	3	>78 per cent of test fish avoid turbid water. (NTU >20).	Scannell 1989
shad (American)	e	A	150	0.25	3.62	3	Change in swimming preferendum.	Dadswell and others 1983
invertebrates	f	I	7.6	5.00	3.64	n	Increased drift of macrobenthic invertebrates.	Rosenberg and Wiens 1978
copepod species	f	I	250	0.17	3.73	n	Maximum rate of food ingestion reduced.	Sherk and others 1975

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
salmon (coho)	f	U	300	0.17	3.91	3	Avoidance behaviour manifest within minutes.	Servizi and Martens 1992
				SI = >4				
salmon (chinook)	f	A	350	0.17	4.07	7	Home water preference disrupted.	Whitman and others 1982
herring	e	A	20	3.00	4.09	4	Reduced feeding rate.	Johnson and Wildish 1982
trout (rainbow)	f	A	250	0.25	4.14	5	Increased rate of coughing.	Hughes 1975
trout (rainbow)	f	A	66	1.00	4.19	3	Avoidance behaviour manifest part of the time.	Lawrence and Scherer 1974
trout (cutthroat)	f	A	35	2.00	4.25	4	Feeding ceases, and fish seek cover.	Cordone and Kelly 1961
bass (striped)	e	L	200	0.42	4.42	4	Rate of feeding reduced 40 per cent.	Breitburg 1988
management (of fish)	f	n/a	4	24	4.56	n	Turbidity hinders aerial survey techniques for fish habitat.	Ott 1984; from Lloyd 1985
grayling (arctic)(1)	f	U	100	1	4.61	4	Catch rate reduced. (Unfamiliar prey species: Tubificids).	McLeay and others 1987
grayling (arctic)(2)	f	U	100	1	4.61	4	Catch rate reduced. (Unfamiliar prey species: Drosophila).	McLeay and others 1987
salmon	f	A	25	4	4.61	4	Feeding activity reduced.	Phillips 1970
salmon (coho)	f	J	100	1	4.61	4	Feeding rate decreases to 55 percent of maximum.	Noggle 1978
salmon (coho)	f	U	2460	0.05	4.81	5	Coughing behaviour manifest within minutes.	Servizi and Martens 1992
				SI = >5				
zooplankton	f	I	2451	0.08	5.32	n	Feeding rate (ingestion + incorporation) reduced by 99.2%.	Arruda and others 1983
salmon (coho)	f	J	250	1	5.52	4	Feeding rate decreases to 10 percent of maximum.	Noggle 1978
grayling (arctic)	f	U	300	1	5.70	4	Catch rate reduced. (Unfamiliar prey species: Drosophila).	McLeay and others 1987
salmon (coho)	f	J	300	1	5.70	4	Feeding ceased.	Noggle 1978
herring (lake)	f	L	16	24	5.95	3	Change in preferred swimming depth.	Swenson and Matson 1976
trout (1)	f	A	16.5	24	5.98	4	Feeding behavior apparently reduced.	Townsend 1983; and Ott 1984;

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
								both from Lloyd 1985
salmon (2)	f	A	16.5	24	5.98	4	Feeding behavior apparently reduced.	Townsend 1983; and Ott 1984; both from Lloyd 1985
SI = >6								
grayling (arctic)	f	U	20	24	6.17	3	Fish avoid parts of the stream.	Birtwell and others 1984
trout (lake)(1)	f	A	3.5	168	6.38	3	Fish avoid turbid areas.	Swenson 1978; from Gradall and Swenson 1982
smelt (rainbow)(2)	f	A	3.5	168	6.38	7	Increased vulnerability to predation.	Swenson 1978; from Gradall and Swenson 1982
grayling (arctic)	f	SF	25	24	6.40	10	Mortality rate of sac fry was 5.7 per cent.	LaPerriere 1988
salmon (coho)(1)	f	J	53.5	12	6.46	3	Changes in territorial behavior.	Berg 1983; also Berg and Northcote 1985
salmon (coho)(2)	f	J	53.5	12	6.46	6	Increase in physiological stress.	Berg 1983; also Berg and Northcote 1985
trout (rainbow)	f	A	665	1	6.50	3	Fish attracted to turbidity.	Lawrence and Scherer 1974
trout (brook)	f	A	4.5	168	6.63	3	Fish were more active and less dependent on cover.	Gradall and Swenson 1982
grayling (arctic)	f	U	1000	1	6.91	4	Feeding rate reduced. (Unfamiliar prey: Tubificids).	McLeay and others 1987
grayling (arctic)	f	U	1000	1	6.91	4	Feeding rate reduced. (Unfamiliar prey: Drosophila).	McLeay and others 1987
herring (Pacific)	e	L	500	2	6.91	n	Larval herring able to feed at a greater rate.	Boehelert and Morgan 1985
grayling (arctic)	f	SF	22.5	48	6.98	10	Mortality rate of sac fry was 14.0 per cent.	LaPerriere 1988
SI = >7								
grayling (arctic)	f	U	100	12	7.09	6	Reduced ability to tolerate high temperatures.	McLeay and others 1987
minnow (fathead)(1)	f	A	50	24	7.09	6	Fish's swimming performance reduced. (Wood Fibre).	MacLeod and Smith 1966

APPENDIX 2

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
minnow (fathead)(2)	f	A	50	24	7.09	6	Changes in the fish's "active metabolism." (Wood Fibre).	MacLeod and Smith 1966
silverside (Atlantic)	e	A	58	24	7.24	10	Mortality rate was 10 per cent. (Fuller's Earth).	Sherk and others 1975.
trout (steelhead)	f	A	500	3	7.31	5	Signs of sublethal stress. (Volcanic Ash).	Redding and Schreck 1982
grayling (arctic)	f	SF	65	24	7.35	10	Mortality rate of sac fry was 15.0 per cent.	LaPerriere 1988
grayling (arctic)	f	SF	21.7	72	7.35	10	Mortality rate of sac fry was 14.7 per cent.	LaPerriere 1988
invertebrates (macro)	f	I	72.5	24	7.46	n	Increased drift.	Gammon 1970
invertebrates (macro)	f	I	72.5	24	7.46	n	Silt-intolerant species less abundant.	Gammon 1970
grayling (arctic)	f	SF	20	96	7.56	10	Mortality rate of sac fry was 13.4 per cent.	LaPerriere 1988
stickleback (fourspine)	e	A	100	24	7.78	10	Mortality rate was <1 per cent. (Incinerator Ash).	Rogers 1969
perch (winter)	e	E	100	24	7.78	9	Hatching delayed.	Schubel and Wang 1973; from Morgan and others 1983
bass (striped)	e	E	100	24	7.78	9	Hatching delayed.	Schubel and Wang 1973; from Morgan and others 1983
salmon (coho)	f	U	2460	1	7.81	6	Cough frequency greatly increased.	Servizi and Martens 1992
					SI = >8			
toadfish (oyster)	e	A	3360	1	8.12	6	Oxygen consumption in pre-stressed fish, more variable.	Neumann and others 1975
invertebrates (benthic)	f	I	1700	2	8.13	n	Temporary changes in community structure.	Fairchild and others 1987
zoobenthos (1)	f	I	5	720	8.19	n	Fewer taxa in lakes flooded with turbid water.	Rosenberg and Snow 1977
zoobenthos (2)	f	I	5	720	8.19	n	Reduced standing crop in lakes flooded with turbid water.	Rosenberg and Snow 1977
menhaden	e	A	154	24	8.22	10	Mortality rate was 10 per cent. (Fuller's Earth).	Sherk and others 1975
herring (Pacific)	e	L	2000	2	8.29	4	Feeding rate reduced.	Boehlert and Morgan 1985
algae (benthic)	f	P	90	48	8.37	n	Mean productivity reduced by approximately half.	Van Nieuwenhuyse 1983
trout (steelhead)	f	A	500	9	8.41	8	Blood cell count, and blood chemistry change.	Redding and Schreck 1982
trout (rainbow)	f	A	200	24	8.48	10	Test fish began to die on the first day. (Wood Fibre).	Herbert and Richards 1963

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
salmon (1)	f	A	210	24	8.53	10	Fish abandoned their traditional spawning habitat.	Hamilton 1961
trout (sea)(2)	f	A	210	24	8.53	10	Fish abandoned their traditional spawning habitat.	Hamilton 1961
spot	e	A	114	48	8.61	10	Mortality rate was 10 per cent. (Fuller's Earth).	Sherk and others 1975
anchovy (bay)	e	A	231	24	8.62	10	Mortality rate was 10 per cent. (Fuller's Earth).	Sherk and others 1975
salmon (coho)	f	U	240	24	8.66	6	Cough frequency increased more than 5-fold.	Servizi and Martens 1992
menhaden	e	A	247	24	8.69	12	Mortality rate was 50 per cent. (Fuller's Earth).	Sherk and others 1975
silverside (Atlantic)	e	A	250	24	8.70	12	Mortality rate was 50 per cent. (Fuller's Earth).	Sherk and others 1975
salmon (coho)	f	J	6000	1	8.70	3	Avoidance behavior.	Noggle 1978
grayling (arctic)	f	SF	142.5	48	8.83	11	Mortality rate was 26 per cent.	LaPerriere 1988
stickleback (fourspine)	e	A	300	24	8.88	12	Mortality rate was ~50 per cent. (Incinerator Ash).	Rogers 1969
perch (white)	e	A	305	24	8.90	10	Mortality rate was 10 per cent. (Fuller's Earth).	Sherk and others 1975
perch (white)	e	L	155	48	8.91	12	Mortality rate was 50 per cent.	Morgan and others 1973
trout (rainbow)	f	E	6.6	1152	8.94	11	Mortality rate was 40 per cent.	Slaney Halsey and Tautz 1977
					SI =>9			
salmon (chinook)	f	J	6	1440	9.06	9	Growth rate reduced. (Neutral Ferric Hydroxide	MacKinlay and others 1987
perch (white)	e	L	373	24	9.10	12	Mortality rate was 50 per cent.	Morgan and others 1973
zoobenthos	f	I	12.5	720	9.10	n	Decrease in size of zoobenthic population.	Rosenberg and Snow 1977
spot	e	A	189	48	9.11	12	Mortality rate was 50 per cent. (Fuller's Earth).	Sherk and others 1975
menhaden	e	A	396	24	9.16	14	Mortality rate was 90 per cent. (Fuller's Earth).	Sherk and others 1975
zooplankton	f	I	50	192	9.17	n	Zooplankton eat fewer algae and could starve.	Arruda 1983
sunfish (green)	f	A	9600	1	9.17	5	Rate of ventilation increased.	Horkel and Pearson 1976
shad (American)	e	L	100	96	9.17	10	Mortality rate was 18 per cent (controls 5 per cent).	Auld and Schubel 1978
anchovy (bay)	e	A	471	24	9.33	12	Mortality rate was 50 per cent. (Fuller's Earth).	Sherk and others 1975
bass (striped)	e	L	485	24	9.36	12	Mortality rate was 50 per cent. (Natural Sediment).	Morgan and others 1973

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
stickleback (fourspine)	e	A	500	24	9.39	14	Mortality rate was 100 per cent.	Rogers 1969
trout (1)	f	A	75	168	9.44	7	Reduced quality of rearing habitat.	Slaney Halsey and Tautz 1977
salmon (1)	f	A	75	168	9.44	7	Reduced quality of rearing habitat.	Slaney Halsey and Tautz 1977
insects (benthic)	f	I	75	168	9.44	n	Abundance of benthic insects markedly reduced.	Slaney Halsey and Tautz 1977
trout (rainbow)(1)	f	A	18	720	9.47	10	Abundance reduced.	Peters 1967
trout (brown)(2)	f	A	18	720	9.47	10	Abundance reduced.	Peters 1967
grayling (arctic)	f	SF	185	72	9.50	12	Mortality rate of sac fry was 41.3 per cent.	LaPerriere 1988
perch (white)	e	L	280	48	9.51	12	Mortality rate was 50 per cent. (Natural Sediment).	Morgan and others 1973
sauger (1)	f	E	28	504	9.55	n	Catch of three-year olds linked to turbidity at age zero.	Doan 1941
sauger (2)	f	L	28	504	9.55	n	Catch of three-year olds linked to turbidity at age zero.	Doan 1941
spot	e	A	317	48	9.63	14	Mortality rate was 90 per cent. (Fuller's Earth).	Sherk and others 1975
trout (rainbow)	f	J	171	96	9.71	8	Particles penetrate the cells of the branchial epithelium.	Goldes 1983
cladocera (1)	e	I	273	72	9.89	n	Survival reduced.	Robertson 1957; from Alabaster and Lloyd 1980
cladocera (2)	e	I	273	72	9.89	n	Reproduction reduced.	Robertson 1957; from Alabaster and Lloyd 1980
bass (striped)(1)	e	E	800	24	9.86	9	Rate of egg development slowed significantly.	Morgan II and others 1983
perch (white)(2)	e	E	800	24	9.86	9	Rate of egg development slowed significantly.	Morgan II and others 1983
grayling (arctic)	f	Y*	140	144	9.91	n	No observed ill effects.	Simmons 1982
invertebrate (1)	f	I	29	720	9.95	n	Conditions unsuitable for Trichoptera.	M.P. Vivier, pers. comm.; from Alabaster and Lloyd 1980
invertebrate (2)	f	I	29	720	9.95	n	Conditions unsuitable for Ephemeroptera.	M.P. Vivier, pers. comm.; from Alabaster and Lloyd 1980
invertebrate (3)	f	I	29	720	9.95	n	Conditions unsuitable for Crustacea.	M.P. Vivier, pers. comm.; from Alabaster and Lloyd 1980

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
invertebrate (4)	f	I	29	720	9.95	n	Conditions unsuitable for Mollusca.	M.P. Vivier, pers. comm.; from Alabaster and Lloyd 1980
					SI =>10			
grayling (arctic)	f	SF	230	96	10.00	12	Mortality rate of sac fry was 47 per cent.	LaPerriere 1988
zooplankton	f	I	104	220	10.04	n	Reproduction severely curtailed. (Glacial Particle SS).	Edmunsdon and Koenings 1985
zooplankton	f	I	104	220	10.04	n	Mortality rate of zooplankters, 85 per cent (controls 55 %).	Edmunsdon and Koenings 1985
anchovy (bay)	e	A	960	24	10.04	14	Mortality rate was 90 per cent.	Sherk and others 1975
perch (white)	e	A	985	24	10.07	12	Mortality rate was 50 per cent.	Sherk and others 1975
invertebrates	f	I	16	1488	10.08	n	Standing crop of benthic invertebrates reduced.	Slaney Halsey and Smith 1977
trout (rainbow)	f	E	20.8	1152	10.08	13	Mortality rate was 72 per cent.	Slaney Halsey and Smith 1977
silverside (Atlantic)	e	A	1000	24	10.09	14	Mortality rate was 90 per cent. (Fuller's Earth).	Sherk and others 1975
herring (Pacific)	e	L	1000	24	10.09	8	Mechanical damage to epidermis.	Boehlert 1984
zoobenthos (1)	f	I	17.6	1488	10.17	n	Species diversity of zoobenthic communities reduced.	McCart 1979
zoobenthos (2)	f	I	17.6	1488	10.17	n	Species equitability in zoobenthic communities reduced.	McCart 1979
zoobenthos (3)	f	I	17.6	1488	10.17	n	Taxonomic diversity in zoobenthic communities reduced.	McCart 1979
cladocera (1)	e	I	400	72	10.27	n	Gills and gut clogged.	Stephan 1953; from Alabaster and Lloyd 1980
copepoda (2)	e	I	400	72	10.27	n	Gills and gut clogged.	Stephan 1953; from Alabaster and Lloyd 1980
zooplankton	f	I	150	192	10.27	n	Zooplankton eat fewer algae and may starve.	Arruda 1983
hogchoker	e	A	1240	24	10.30	8	Increase in rate of energy utilization.	Sherk and others 1975
fish (1)	f	A	620	48	10.30	10	Fish kills occurred downstream from source of sediment.	Hesse and Newcomb 1982
invertebrates (2)	f	I	620	48	10.30	n	Catastrophic loss of many invertebrate species.	Hesse and Newcomb 1982

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
spot	e	A	1309	24	10.36	10	Mortality rate was 10 per cent. (Fuller's Earth).	Sherk and others 1975
trout (steelhead)(1)	f	J	102	336	10.44	9	Growth rate reduced. (Fire Clay and Bentonite Clay).	Sigler and others 1984
salmon (coho)(2)	f	J	102	336	10.44	9	Growth rate reduced. (Fire Clay and Bentonite Clay).	Sigler and others 1984
bass (striped)	e	L	500	72	10.49	12	Mortality rate was 42 per cent (controls 17 per cent).	Auld and Schubel 1978
perch (white)	e	A	305	120	10.51	8	Structure of gill tissue may be damaged.	Sherk and others 1975
trout (rainbow)(1)	f	˜Y	90	456	10.62	10	Mortalities ranged from 0 to 15 per cent. (Kaolin SS).	Herbert and Merkens 1961
trout (rainbow)(2)	f	˜Y	90	456	10.62	10	Mortality rate 0 to 20 per cent. (Diatomaceous Earth).	Herbert and Merkens 1961
herring (lake)	f	A	28	1488	10.64	n	No observable effect on survival or growth.	Swenson and Matson 1976
bass (largemouth)(1)	f	A	62.5	720	10.71	9	Weight gain reduced ˜50 per cent.	Buck 1956
bluegill (2)	f	A	62.5	720	10.71	9	Weight gain reduced ˜50 per cent.	Buck 1956
sunfish (redear)(3)	f	A	62.5	720	10.71	9	Weight gain was reduced ˜50 per cent.	Buck 1956
trout (rainbow)	f	E	120	384	10.74	13	Mortality was ˜60-70 per cent (controls 38.6 per cent).	Erman and Lignon 1988
invertebrates (1)	f	I	120	384	10.74	n	Reductions in numbers and taxa of invertebrates.	Erman and Lignon 1988
fish (2)	f	A	120	384	10.74	10	Reduction in density of fish.	Erman and Lignon 1988
salmon (chinook)	f	S	488	96	10.75	12	Mortality rate was 50 per cent.	Stober and others 1981
invertebrate (benthic)	f	I	32	1488	10.77	n	Standing crop reduced.	Slaney Halsey and Smith 1977
shad (American)	e	L	500	96	10.78	11	Mortality rate was 36 per cent (controls 4 per cent).	Auld and Schubel 1978
trout (rainbow)	f	A	50	960	10.78	9	Rate of weight gain reduced. (Coal Washery Solids).	Herbert and Richards 1963
trout (rainbow)	f	A	50	960	10.78	9	Rate of weight gain reduced. (Wood Fibre).	Herbert and Richards 1963
perch (yellow)	e	L	500	96	10.78	11	Mortality rate was 37 per cent (controls 7 per cent).	Auld and Schubel 1978
salmon (sockeye)	f	A	500	96	10.78	8	Plasma glucose levels increased 39 per cent.	Servizi and Martens 1987
spot	e	A	2034	24	10.80	12	Mortality rate was 50 per cent.	Sherk and others 1975

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
salmon (coho)	f	S	509	96	10.80	12	Mortality rate was 50 per cent.	Stober and others 1981
moss (aquatic)	f	P	100	504	10.83	n	Leaves of aquatic plants severely abraded.	Lewis 1973
salmon (chinook)(1)	f	J	1400	36	10.83	12	Mortality rate was 50 per cent.	Newcomb and Flagg 1983
salmon (sockeye)(2)	f	J	1400	36	10.83	12	Mortality rate was 50 per cent.	Newcomb and Flagg 1983
salmon (coho)	f	U	530	96	10.84	6	Blood glucose levels increased.	Servizi and Martens 1992
trout (rainbow)	f	E	46.6	1152	10.89	14	Mortality rate was 100 per cent.	Slaney Halsey and Tautz 1977
trout (steelhead)	f	E	37	1488	10.92	12	Hatching success: 42 per cent (controls 63 per cent).	Slaney Halsey and Tautz 1977
mummichog (common)	e	A	2447	24	10.98	10	Mortality rate was 10 per cent. (Fuller's Earth).	Sherk and others 1975
salmon (coho)	f	U	2460	24	10.99	8	Fatigue of the cough reflex.	Servizi and Martens 1992
SI = >11								
salmon (Atlantic)	f	A	2500	24	11.00	10	Increased risk of predation.	Gibson 1933; from Alabaster and Lloyd 1980.
grayling (arctic)	f	Y*	1250	48	11.00	8	Moderate levels of damage to gill tissue.	Simmons 1982
grayling (arctic)	f	U	660	96	11.06	n	No gill pathology in underyearlings.	McLeay and others 1983
zoobenthos	f	I	100	672	11.12	n	Standing crop reduced.	Rosenberg and Snow 1977
salmon (chinook)	f	S	943	72	11.13	8	Tolerance to stress reduced. (Volcanic Ash).	Stober and others 1981
bass (striped)	e	L	1000	68	11.13	11	Mortality rate was 35 per cent (controls 16 per cent).	Auld and Schubel 1978
trout (brook)	f	FF	12	5880	11.16	9	Growth rates declined.	Sykora and others 1972
trout (brown)	f	A	100	720	11.18	11	Population reduced.	Scullion and Edwards 1980
grayling (arctic)	f	U	100	756	11.23	7	Fish moved out of the test channel.	McLeay and others 1987
perch (white)	e	A	3181	24	11.24	14	Mortality rate was 90 per cent. (Fuller's Earth).	Sherk and others 1975
perch (white)(1)	e	A	650	120	11.26	6	Haematocrit increased.	Sherk and others 1975
perch (white)(2)	e	A	650	120	11.26	6	Erythrocyte count increased.	Sherk and others 1975
perch (white)(3)	e	A	650	120	11.26	6	Haemoglobin concentration increased.	Sherk and others 1975

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
perch (white)	e	A	650	120	11.26	8	Histological evidence of damage to gill tissue.	Sherk and others 1975
killifish (striped)	e	A	3277	24	11.27	10	Mortality rate was 10 per cent. (Fuller's Earth).	Sherk and others 1975
grayling (arctic)	f	U	100	840	11.34	9	Fish respond less rapidly to food drifting on the surface.	McLeay and others 1987
moss (aquatic)	f	P	500	168	11.34	n	Leaves severely damaged by abrasion of coal dust.	Lewis 1973
trout	f	A	270	312	11.34	8	Gill tissue damaged.	Herbert and Merkens 1961
trout (rainbow)	f	E	57	1488	11.35	12	Mortality of eggs 47 per cent (controls 32 %).	Slaney and others 1977
killifish (striped)	e	A	3819	24	11.43	12	Mortality rate was 50 per cent.	Sherk and others 1975
trout (brook)	e	FF	50	1848	11.43	9	Growth rates decline. (Lime-neutralized Iron Hydroxide).	Sykora and others 1972
mummichog (common)	e	A	3900	24	11.45	12	Mortality rate was 50 per cent. (Fuller's Earth).	Sherk and others 1975
herring (Pacific)	e	L	4000	24	11.47	8	Epidermis punctured, and microridges less distinct.	Boehlert 1984
shad (American)	e	L	1000	96	11.47	11	Mortality rate was 34 per cent (controls 5 per cent).	Auld and Schubel 1978
perch (yellow)	e	L	1000	96	11.47	11	Mortality rate was 38 per cent (controls 7 per cent).	Auld and Schubel 1978
grayling (arctic)	f	U	100	1008	11.52	9	Rate of growth reduced.	McLeay and others 1984
grayling (arctic)(1)	f	A	100	1008	11.52	9	Reduced growth.	McLeay and others 1984
grayling (arctic)(2)	f	A	100	1008	11.52	9	Impaired feeding.	McLeay and others 1984
grayling (arctic)(3)	f	A	100	1008	11.52	8	Decreased resistance to environmental stresses.	McLeay and others 1984
bass (largemouth)(1)	f	A	144.5	720	11.55	9	Growth retarded.	Buck 1956
bluegill (2)	f	A	144.5	720	11.55	9	Growth retarded.	Buck 1956
sunfish (redear)(3)	f	A	144.5	720	11.55	9	Growth retarded.	Buck 1956
bass (largemouth)(4)	f	A	144.5	720	11.55	12	Fish unable to reproduce.	Buck 1956
bluegill (5)	f	A	144.5	720	11.55	12	Fish unable to reproduce.	Buck 1956
sunfish (redear)(6)	f	A	144.5	720	11.55	12	Fish unable to reproduce.	Buck 1956
salmon (chinook)	f	A	650	168	11.60	7	Homing behavior normal, but fewer test fish returned.	Whitman and others 1982

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
salmon (chinook)	f	A	650	168	11.60	5	No histological signs of damage to olfactory epithelium.	Brannon and others; from Martin and others 1984
trout (1)	f	E	117	960	11.63	10	Mortality of trout eggs; deterioration of spawning gravel.	Cederholm and others 1981
salmon (2)	f	E	117	960	11.63	10	Mortality of salmon eggs; deterioration of spawning gravel.	Cederholm and others 1981
killifish (striped)	e	A	960	120	11.65	8	Haematocrit increases.	Sherk and others 1975
salmon (coho)	f	J	1200	96	11.65	12	Mortality rate was 50 per cent.	Noggle 1978
salmon (coho)	f	S	1217	96	11.67	12	Mortality rate was 50 per cent. (Volcanic Ash).	Stober and others 1981
trout (brookl	f	F*	100	1176	11.68	9	Test fish weigh 16 per cent of controls. (L-N Iron Hydroxide).	Sykora and others 1972
salmon (sockeye)	f	S	1261	96	11.70	8	Body moisture content reduced.	Servizi and Martens 1987
trout (rainbow)	f	¯Y	270	456	11.72	11	Mortality rate was 10 to 35 per cent. (Kaolin).	Herbert and Merkens 1961
trout (rainbow)	f	¯Y	270	456	11.72	12	Mortality rate 25 to 80 per cent. (Diatomaceous Earth).	Herbert and Merkens 1961
trout (brook)	f	FF	24	5208	11.74	9	Growth rate reduced. (Lime-neutralized Iron Hydroxide).	Sykora and others 1972
trout (rainbow)	f	A	59	2232	11.79	10	Habitat damage: reduced porosity of gravel.	Slaney Halsey and Tautz 1977
grayling (arctic)	f	Y*	1388	96	11.80	8	Hyperplasia and hypertrophy of gill tissue.	Simmons 1982
salmon (sockeye)	f	U	1465	96	11.85	8	Hypertrophy, necrosis of gill tissue. (C SS, 180-740 um).	Servizi and Martens 1987
salmon (coho)	f	U	1547	96	11.91	n	No mortality.	Noggle 1978
salmon (coho)	f	U	3000	48	11.88	8	Manifestation of high level sublethal stress: avoidance.	Servizi and Martens 1992
salmon (sockeye)	f	A	1500	96	11.88	8	Plasma glucose levels increased 150 per cent.	Servizi and Martens 1987
trout (rainbow)	f	E	101	1440	11.89	14	Mortality rate was 98 per cent (controls 14.6 per cent).	Turnpenny and Williams 1980
killifish (striped)	e	A	6136	24	11.90	14	Mortality rate was 90 per cent.	Sherk and others 1975
salmon (coho)	f	J	1547	96	11.91	8	Gill damage.	Noggle 1978

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
invertebrate	f	I	62	2400	11.91	n	Invertebrate POPULATIONS reduced 77 per cent (density).	Wagener and LaPerriere 1985
invertebrate	f	I	62	2400	11.91	n	Invertebrate BIOMASS reduced.	Wagener and LaPerriere 1985
hogchoker (1)	e	A	1240	120	11.91	8	Erythrocyte count increased.	Sherk and others 1975
hogchoker (2)	e	A	1240	120	11.91	8	Hematocrit increased.	Sherk and others 1975
invertebrates (macro-)	f	I	17	8760	11.91	n	Many taxa eliminated. (Coal particles).	Learner and others 1971
mummichog (common)	e	A	6217	24	11.91	14	Mortality rate was 90 per cent.	Sherk and others 1975
SI =>12								
salmon (sockeye)	f	U	1700	96	12.00	12	Mortality rate was 50 per cent. (C SS, 180-740	Servizi and Martens 1987
spot	e	A	6875	24	12.01	10	Mortality rate was 10 per cent.	Sherk and others 1975
salmon (coho)	f	S	5000	36	12.10	n	Survival of smolts probably not affected during migration.	Martin and others 1981
perch (white)	e	E	1000	168	12.03	10	Reduced hatching success.	Auld and Schubel 1978
bass (striped)	e	E	1000	168	12.03	10	Reduced hatching success.	Auld and Schubel 1978
invertebrates	f	I	77	2400	12.13	n	Invertebrate populations reduced 50 per cent.	Wagener and LaPerriere 1985
invertebrates	f	I	77	2400	12.13	n	Invertebrate biomass 1.9 mg per 0.1 m2 (controls 3.4 mg).	Wagener and LaPerriere 1985
algae (1)	f	P	570	336	12.16	n	Algal growth decreased as a function of increasing turbidity.	Wang 1974
plants (vascular)(2)	f	P	570	336	12.16	n	Plant growth decreased as a function of increasing turbidity.	Wang 1974
fish (warm-water)	f	A	22	8760	12.17	12	Fish populations destroyed.	Menzel and others 1984
salmon (sockeye)	f	U	2100	96	12.21	10	None of the test fish died in medium-fine sediment.	Servizi and Martens 1987
salmon (chinook)(1)	f	A	207000	1	12.24	14	Mortality rate was100 per cent in volcanic ash.	Newcomb and Flagg 1983
salmon (sockeye)(2)	f	A	207000	1	12.24	14	Mortality rate was 100 per cent in volcanic ash.	Newcomb and Flagg 1983
spot	e	A	8800	24	12.26	12	Mortality rate was 50 per cent.	Sherk and others 1975
trout	f	A	300	720	12.28	12	Decrease in the size of a trout population.	Peters 1967

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
fish (warm-water)	f	A	200,000	1.125	12.32	10	Fish died: opercular cavities and gill filaments clogged.	Wallen 1951
grayling (arctic)	f	U	300	756	12.33	10	Fish displaced from their habitat.	McLeay and others 1987
killifish (striped)	e	A	9720	24	12.36	10	Mortality rate was 10 per cent.	Sherk and others 1975
fauna (benthos)	f	I	325.5	720	12.36	n	Numbers of organisms per unit area reduced 75 per cent.	Tebo 1955
stickleback (fourspine)	e	A	10000	24	12.39	10	No mortality. (Kingston Silt, 10-12 Degrees C).	Rogers 1969
whitefish (rm)	f	A	10,000	24	12.39	10	Rocky Mountain whitefish died: silt-clogged gills.	Langer 1980
grayling (arctic)	f	U	300	840	12.44	8	Serious impairment of feeding behavior.	McLeay and others 1987
trout (rainbow)	f	EE	1750	144	12.44	10	Eggs: mortality rate greater than controls (controls 6 %).	Campbell 1954
salmon (sockeye)	f	U	2688	96	12.46	8	Gill tissue: hypertrophy and necrosis. (MC SS, 150-295 uml.	Servizi and Martens 1987
spot	e	A	11263	24	12.51	14	Mortality rate was 90 per cent.	Sherk and others 1975
salmon (coho)	f	E	157	1728	12.51	14	Mortality rate was100 per cent (controls 16.2 per cent).	Shaw and Maga 1943
salmon (chum)	f	E	97	2808	12.51	13	Mortality rate was 77 per cent (controls 6 per cent).	Langer 1980
invertebrates (benthic)	f	I	390	720	12.55	n	The density of benthic invertebrates decreased.	Tebo 1955
fish (warm-water)	f	A	400	720	12.57	n	An inferred water quality standard of Maryland (USA).	Earhart 1984
salmon (sockeye)	f	U	3143	96	12.62	8	Hypertrophy and necrosis of gill tissue. (Fine SS, <74 um).	Servizi and Martens 1987
grayling (arctic)	f	U	300	1008	12.62	8	Rate of respiration (O2 consumption) increased. (Fine SS).	McLeay and others 1987
grayling (arctic)	f	U	300	1008	12.62	8	Fish less able to tolerate toxicity of pentachlorophenol.	McLeay and others 1987
grayling (arctic)	f	U	300	1008	12.62	9	Rate of weight gain reduced.	McLeay and others 1987
grayling (arctic)	f	U	300	1008	12.62	4	Rate of feeding reduced.	McLeay and others 1987
grayling (arctic)	f	U	300	1008	12.62	n	Test fish became slightly paler than the controls.	McLeay and others 1987
killifish (striped)	e	A	12820	24	12.64	12	Mortality rate was 50 per cent.	Sherk and others 1975

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
trout (1)	f	A	525	588	12.64	10	No mortality (other end-points not investigated).	Griffin 1938; from Alabaster and Lloyd 1980
salmon (Pacific)(2)	f	A	525	588	12.64	10	No mortality (other end-points not investigated).	Griffin 1938; from Alabaster and Lloyd 1980
salmon (chinook)(1)	f	J	9400	36	12.73	12	Mortality rate was 50 per cent.	Newcomb and Flagg 1983
salmon (sockeye)(2)	f	J	9400	36	12.73	12	Mortality rate was 50 per cent.	Newcomb and Flagg 1983
trout (rainbow)(1)	f	~Y	810	456	12.82	12	Mortality ranged from 5 to 80 per cent. (Kaolin).	Herbert and Merkens 1961
trout (rainbow)(2)	f	~Y	810	456	12.82	12	Mortality rate: 35 to 85 per cent. (Diatomaceous Earth).	Herbert and Merkens 1961
steelhead (1)	f	A	1650	240	12.89	7	Loss of habitat caused by excessive sediment transport.	Coats and others 1985
salmon (2)	f	A	1650	240	12.89	7	Loss of habitat caused by excessive sediment transport.	Coats and others 1985
killifish (striped)	e	A	16930	24	12.91	13	Mortality rate was 90 per cent.	Shark and others 1975
trout (rainbow)(1)	f	A	810	504	12.92	10	Some of the fish died.	Herbert and Merkens 1961
trout (rainbow)(2)	f	A	810	504	12.92	8	Gills of fish that survived had thickened epithelium.	Herbert and Merkens 1961
invertebrates (macro-)	f	I	46.8	8760	12.92	n	Species diversity reduced; some species absent. (Sand).	Nuttall 1972
stickleback (fourspine)	e	A	18000	24	12.98	12	Mortality rata was 50 per cent. (15.0 to 16.0 Degrees C).	Rogers 1969

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
					SI = >13			
salmon (sockeye)	f	U	4850	96	13.05	12	Mortality rate was 50 per cent. (MC SS, 150-295 um).	Servizi and Martens 1987
fish (warm water)	f	A	20000	24	13.08	n	Threshold of observable effects in the fish's behavior.	Wallen 1951; from Cordone and Kelley 1961
salmon (chinook)(1)	f	A	82400	6	13.11	12	Mortality rate was 60 per cent. (Volcanic Ash, <5 - 100 um).	Newcomb and Flagg 1983
salmon (sockeye)(2)	f	A	82400	6	13.11	12	Mortality rate was 60 per cent. (Volcanic Ash, <5 - 100 um).	Newcomb and Flagg 1983
Warm-water Streams	f	n/a	57	8760	13.12	9	Moderately severe habitat degradation.	Menzel and others 1984
bass (striped)(1)	e	A	1500	336	13.13	8	Haematocrit increased. (Fuller's Earth).	Sherk and others 1975
bass (striped)(2)	e	A	1500	336	13.13	8	Plasma osmolality increased. (Fuller's Earth).	Sherk and others 1975
grayling (arctic)(1)	f	Y*	3810	144	13.22	4	Food intake severely limited.	Simmons 1982
grayling (arctic)(2)	f	Y*	3810	144	13.22	8	Fish display many signs of poor condition.	Simmons 1982
grayling (arctic)(3)	f	Y*	3810	144	13.22	8	Mucus and sediment accumulated in the gill lamellae.	Simmons 1982
Warm Water Fish	f	A	66	8760	13.27	7	Habitat degradation.	Barkman and Rabeni 1987
fish (fresh-water)(UK)	f	A	900	720	13.38	12	Fish are absent or markedly reduced in abundance.	Herbert and Richards 1963
Invertebrates	f	I	278	2400	13.41	n	Invertebrate populations reduced by 80 per cent.	Wagener and LaPerriere 1985
Invertebrates	f	I	278	2400	13.41	n	Invertebrate biomass reduced.	Wagener and LaPerriere 1985
Cunner	e	A	28000	24	13.42	12	Mortality rate was 50 per cent. (20.0-25.0 Degrees C).	Rogers 1969
salmon (sockeye)	f	S	7447	96	13.48	8	Plasma chloride levels increased slightly.	Servizi and Martens 1987
fish (1)	e	A	3000	240	13.49	10	Fish died.	Kemp 1949; from Cordone and Kelley 1961
oysters (2)	e	I	3000	240	13.49	n	Severe damage to oyster beds.	Kemp 1949; from Cordone and Kelley 1961
crab (dungeness)	e	I	1800	420	13.54	n	Sublethal effects. (Contaminated Sediment).	Petticord 1980

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
salmon (coho)	f	U	8000	96	13.55	10	One per cent of the under-yearling fish died.	Servizi and Martens 1991
salmon (coho)	f	F*	8100	96	13.56	12	Fry died: mortality rate was 50 per cent.	Servizi and Martens 1991
salmon (sockeye)	f	U	8200	96	13.58	12	Mortality rate was 50 per cent. (MF SS, 75-149 um).	Servizi and Martens 1987
toadfish (oyster)	e	A	11090	72	13.59	9	Latent ill effects manifested in test at low SS concentration.	Neumann and others 1975
grayling (arctic)	f	U	1000	840	13.64	4	Reduced rate of feeding.	McLeay and others 1987
trout (rainbow)	f	FF	1750	480	13.64	12	Mortality rate was 57 per cent (controls 5 per cent).	Campbell 1954; from Cordone and Kelley 1961
salmon (sockeye)	f	U	9000	96	13.67	10	No mortality.	Servizi and Martens 1987
trout (rainbow)	f	A	270	3240	13.68	10	Rate of survival reduced.	Herbert and Merkens 1961
shrimp (spottailed sand)	e	I	2500	360	13.71	10	Mortality rate was 5 per cent.	Petticord 1980
salmon (chinook)(1)	f	A	39300	24	13.76	10	No mortality. (Volcanic Ash, <5 - 100 um; median <15 um).	Newcomb and Flagg 1983
salmon (sockeye)(2)	f	A	39300	24	13.76	10	No mortality. (Volcanic Ash, <5 - 100 um; median <15 um).	Newcomb and Flagg 1983
salmon (sockeye)	f	U	9850	96	13.76	10	Gill hyperplasia, hypertrophy, separation, necrosis. (MFSS).	Servizi and Martens 1987
salmon (sockeye)	f	U	9851	96	13.76	8	Hypertrophy and necrosis of gill tissue. (MC SS, 150 295 um).	Servizi and Martens 1987
grayling (arctic)	f	U	10000	96	13.77	3	Fish swim near the surface.	McLeay and others 1987
harlequin	e	A	40000	24	13.77	10	Fish died. (Bentonite Clay).	J.S. Alabaster, personal comm; fr. Alabaster and Lloyd 1980
harlequin	e	A	6000	168	13.82	10	Fish survived. (Bentonite Clay).	J.S. Alabaster, personal comm; fr. Alabaster and Lloyd 1980
grayling (arctic)	f	U	1000	1008	13.82	4	Fish failed to consume all prey.	McLeay and others 1987
grayling (arctic)(1)	f	U	1000	1008	13.82	4	Fish responded very slowly to prey.	McLeay and others 1987
grayling (arctic)(2)	f	U	1000	1008	13.82	4	Fish had frequent mis-strikes while feeding.	McLeay and others 1987
grayling (arctic)	f	U	1000	1008	13.82	9	Amount of weight gained was reduced by 33 per cent.	McLeay and others 1987

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
toadfish (oyster)	e	A	14600	72	13.87	8	Fish largely unaffected, but developed latent ill effects.	Neumann and others 1975
salmon (chinook)	f	S	11000	96	13.87	12	Mortality rate was 50 per cent.	Stober and others 1981
tunicate	e	I	2100	504	13.87	n	One tunicate died.	Petticord 1980
invertebrates (stream)	f	I	130	8760	13.95	n	Species diversity reduced.	Nuttall and Bielby 1973
stickleback (fourspine)	e	A	50000	24	14.00	12	Mortality rate was 50 per cent. (Kingston Silt).	Rogers 1969
SI = >14								
salmon (sockeye)	f	U	13000	96	14.04	14	Mortality rate was 90 per cent. (Medium-Fine SS, 75-149 um).	Servizi and Martens 1987
shrimp (black-tailed)	e	I	2500	504	14.05	n	Mortality rate of Black-tailed Sand Shrimp: ~15 per cent.	Petticord 1980
stickleback (fourspine)	e	A	53000	24	14.06	12	Mortality rate was 50 per cent. (10-12 Degrees C).	Rogers 1969
salmon (sockeye)	f	U	13900	96	14.10	10	Mortality rate was 10 per cent. (Fine SS, <74 microns, um).	Servizi and Martens 1987
shrimp (black-tailed)	e	I	19700	72	14.17	10	Mortality rate of Spot-tailed Sand Shrimp: 5 per cent.	Petticord 1980
salmon (chinook)(1)	f	J	39400	36	14.17	14	Mortality rate was 90 per cent. (Volcanic Ash).	Newcomb and Flagg 1983
salmon (sockeye)(2)	f	J	39400	36	14.17	14	Mortality rate was 90 per cent. (Volcanic Ash).	Newcomb and Flagg 1983
trout (rainbow)	f	Y	2120	672	14.17	14	Mortality rate was 100 per cent.	Herbert and Wakeford 1962
whitefish	f	A	16613	96	14.28	12	Mortality rate was 50 per cent. (Inert Drilling Mud).	Lawrence and Scherer 1974
cunner	e	A	133000	12	14.28	12	Mortality rate was 50 per cent. (15 Degrees C).	Rogers 1969
ecosystem	f	n/a	189	8760	14.32	n	Severe habitat degradation in warm water ecosystems.	Menzel and others 1984
rivers in flood	f	n/a	4000	420	14.33	n	Typical concentrations and durations for such rivers.	Alabaster and Lloyd 1980
salmon (sockeye)	f	U	17560	96	14.34	8	Hypertrophy of gill tissue. (Fine SS, <74 microns, um).	Servizi and Martens 1987
salmon (sockeye)	f	U	17560	96	14.34	12	Mortality rate was 50 per cent. (Fine SS, <74 microns, um).	Servizi and Martens 1987

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
invertebrates	f	I	743	2400	14.39	n	Invertebrate populations reduced 85 per cent.	Wagener and LaPerriere 1985
invertebrates	f	I	743	2400	14.39	n	Invertebrate biomass reduced.	Wagener and LaPerriere 1985
salmon (coho)	f	PS	18672	96	14.40	12	Mortality rate of pre-smolts was 50 per cent.	Stober and others 1981
salmon (chinook)	f	S	19364	96	14.44	12	Mortality rate was 50 per cent.	Stober and others 1981
trout (rainbow)(1)	f	J	4887	384	14.44	8	Parasitic infection of gill tissue.	Goldes 1983
trout (rainbow)(2)	f	J	4887	384	14.44	8	Hyperplasia of gill tissue.	Goldes 1983
fish	f	A	20000	96	14.47	13	Most of the test fish died. (Wood Fibre SS).	Cole 1935; from Alabaster and Lloyd 1980
trout (rainbow)	f	A	80000	24	14.47	10	No mortality.	Herbert, pers. comm.; from Alabaster and Lloyd 1980
shrimp (sand)	e	I	4300	456	14.49	n	Mortality rate of Spot Tailed Sand Shrimp: 5 per cent.	Petticord 1980
crab (dungeness)	e	I	9200	216	14.50	n	Mortality rate was ~5 per cent. (Contaminated SS).	Petticord 1980
salmon (coho)	f	U	22700	96	14.59	12	Mortality rate was 50 per cent.	Servizi and Martens 1991
salmon (sockeye)	f	U	23900	96	14.65	14	Mortality rate was 90 per cent. (Fine SS, <74 microns, um).	Servizi and Martens 1987
salmon (sockeye)	f	U	23790	96	14.64	8	Hypertrophy and necrosis of gill tissue. (Fine SS, <74 um).	Servizi and Martens 1987
cunner	e	A	100000	24	14.69	12	Mortality rate was 50 per cent. (15 Degrees C).	Rogers 1969
minnow (sheepshead)	e	A	100000	24	14.69	14	Mortality rate was 90 per cent. (19 Degrees C).	Rogers 1969
trout (rainbow)	f	A	4250	588	14.73	12	Mortality rate was 50 per cent. (Calcium sulphate SS).	Herbert and Wakeford 1962
salmon (coho)(1)	f	F	28000	96	14.80	n	No observable ill effects. (Contaminated SS).	LeGore and Des Voigne 1973; fr. Alabaster and Lloyd 1980
stickleback (2)	e	A	28000	96	14.80	n	No observable ill effects. (Contaminated SS).	LeGore and Des Voigne 1973; fr. Alabaster and Lloyd 1980
salmon (chum)	f	J	28000	96	14.80	12	Mortality rate was 50 per cent. (Natural Sediment).	Smith 1939
salmon (coho)	f	S	28184	96	14.81	12	Mortality rate was 50 per cent. (Volcanic ash).	Stober and others 1981

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
salmon (coho)	f	S	29580	96	14.86	12	Mortality rate was 50 per cent. (Mud Flow Sediments).	Stober and others 1981
trout (rainbow)	f	Y	4250	672	14.86	12	Mortality rate was 50 per cent.	Herbert and Wakeford 1962
trout (rainbow)	f	A	17500	168	14.89	8	Fish survived; gill epithelium proliferated and thickened.	Slanina 1962; from Alabaster and Lloyd 1980
SI = >15								
salmon (coho)	f	J	35000	96	15.03	12	Mortality rate was 50 per cent.	Noggle 1978
cunner	e	A	72000	48	15.06	12	Mortality rate was 50 per cent. (15 Degrees C).	Rogers 1969
mussel (coast)	e	I	15500	240	15.13	n	Mortality rate low. (Sediment NOT contaminated).	Petticord 1980
trout (rainbow)	f	A	160000	24	15.16	14	Mortality rate was 100 per cent.	Herbert, pers. comm.; from Alabaster and Lloyd 1980
trout (rainbow)	f	A	49838	96	15.38	12	Mortality rate was 50 per cent. (Non-toxic Drilling Mud).	Lawrence and Scherer 1974
minnow (sheepshead)	e	A	200000	24	15.38	10	Mortality rate was 10 per cent. (15 Degrees C).	Rogers 1969
stickleback (fourspine)	e	A	200000	24	15.38	14	Mortality rate was 95 per cent. (Kingston silt).	Rogers 1969
algae (1)	f	P	570	8760	15.42	n	Reduced distribution.	Wang 1974
plants (vascular)(2)	f	P	570	8760	15.42	n	Reduced distribution.	Wang 1974
trout (rainbow)	f	Y	7433	672	15.42	11	Mortality rate was 40 per cent. (Calcium sulphate SS).	Herbert and Wakeford 1962
trout (rainbow)	f	A	3500	1488	15.47	13	Catastrophic reduction in population size.	Herbert and Merkens 1961
salmon (chum)	f	J	55000	96	15.48	12	Mortality rate was 50 per cent. (Winter: cold water).	Smith 1939
crab (dungeness)	e	I	9200	600	15.52	n	Mortality rate was 38 per cent. (Contaminated sediment).	Petticord 1980
mummichog (common)	e	A	300000	24	15.79	10	No mortality. (15 Degrees C).	Rogers 1969
minnow (sheepshead)	e	A	300000	24	15.79	11	Mortality rate was 30 per cent. (10 Degrees C).	Rogers 1969
mussel (coast)	e	I	15500	504	15.87	n	Mortality rate was 35 per cent.	Petticord 1980

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
stickleback (fourspine)	e	A	330000	24	15.88	12	Mortality rate was 50 per cent. (9.0-9.5 Degrees C).	Rogers 1969
goldfish (1)	f	A	25000	336	15.94	10	Some mortality. (Montmorillonite clay).	Wallen 1951; from Alabaster and Lloyd 1980
carp (common) (2)	f	A	25000	336	15.94	10	Some mortality. (Montmorillonite clay).	Wallen 1951; from Alabaster and Lloyd 1980
SI = >16								
trout (brown)	f	A	1040	8760	16.02	14	Population one-seventh of expected size. (River Fal).	Herbert and others 1961
shrimp (spottailed sand)	e	I	19700	504	16.11	n	Mortality rate of Spottailed Sand Shrimp was 15 per cent.	Petticord 1980
tunicate	e	I	20000	504	16.13	n	Mortality rate was 87 per cent. (Contaminated SS).	Petticord 1980
Invertebrates	f	I	5108	2400	16.32	n	Invertebrate populations reduced: 94 per cent of expected.	Wagener and LaPerriere 1985
invertebrates	f	I	5108	2400	16.32	n	Invertebrate biomass reduced: 56 per cent of control site.	Wagener and LaPerriere 1985
grayling (arctic)	f	U	100000	168	16.64	5	No changes in gill histology.	McLeay and others 1983
darters (1)	f	A	2045	8760	16.70	14	Darters absent.	Vaughan 1979; also Vaughan and others 1982
fish (2)	f	A	2045	8760	16.70	12	Habitat destruction: fish populations smaller than expected.	Vaughan 1979; also Vaughan and others 1982
diatoms (3)	f	I	2045	8760	16.70	n	Smaller populations of diatoms.	Vaughan 1979; also Vaughan and others 1982
trout (brown)	f	A	1040	17520	16.72	8	Gill lamellae thickened. (VF SS; prob. <20 microns, um).	Herbert, Alabaster, Dart, and Lloyd 1961
trout (brown)	f	A	1210	17520	16.87	8	Some gill lamellae become fused. (VF SS; prob. <20 μm).	Herbert, Alabaster, Dart, and Lloyd 1961

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii.	iii.	mg/L	hr	L	SE	NE	Reference
SI =>17								
fish (warm water)	f	A	100000	252	17.04	10	Some fish died, but most survived.	Wallen 1951; from Cordone and Kelley 1961
trout (brown)	f	A	5838	8760	17.75	14	Fish numbers one-seventh of expected. (River Par).	Herbert, Alabaster, Dart, and Lloyd 1961
SI =>19								
invertebrates	f	I	25000	8760	19.20	n	Macrofauna absent.	Nuttall and Bielby 1973

Footnotes to Table 4:

Numbers in brackets	(x)	Multiple entries based on one précis are numbered sequentially, as shown: (1), (2), (3) ... (6). Refer to the Précis Section for details and cross references.
Severity-of-Effect Scale	SE	Severity of Effect for Fish (Examples are provided for each level of severity in the Footnote Table, below.)
	n	Severity-of-Effect scale not applicable (the Severity-of-Effect scale for invertebrates has not been developed as of July 1994. There are, however, sufficient data in this database to begin the process.)
Suspended Sediments	SS	Suspended sediments.
	C SS	Coarse suspended sediment (diameter range: 180-740 microns, um).
	MC SS	Medium-coarse suspended sediments (diameter range: 150-295 microns, um).
	MF SS	Medium-fine suspended sediments (diameter range: 75-149 microns, um).
	F SS	Fine suspended sediments (diameter range: <75 microns, um).
	VF SS	Very-fine suspended sediments (diameter range <5 to 100 microns, um; most of the particles have a diameter
	L-N	Lime-Neutralized (e.g., Lime-neutralized Iron Hydroxide particles).
	um	micron (one millionth of a metre).
Life-history Phases	E	egg
	EE	eyed eggs
	SF	sac fry
	F*	swim-up fry
	L	larvae
	F	fry
	J	juvenile

ADVERSE EFFECTS OF SUSPENDED SEDIMENT AS A FUNCTION OF CONCENTRATION AND DURATION OF EXPOSURE: SUMMARY

i.	ii. iii.	mg/L	hr	L	SE	NE	Reference

	FF	fingerling (in Sykora and others 1972, relatively young fingerlings: less than 30 weeks in this life-history phase.
	FF*	fingerling (in Sykora and others 1972, relatively old fingerlings: 30 to 35 weeks in this life-history phase. See R
	PS	pre-smolt
	S	smolt
	U	underyearling
	~Y	approximately a year old
	Y*	young-of-the-year
	A	adult
Type of Organism (other than fish)	P	plant
	I	invertebrate
Habitat	f	fresh water fish; or, fresh-water phase of anadromous species.
	e	estuarine fish species.

APPENDIX 3

TOLERANCE OF FISH TO TURBIDITY

APPENDIX 3

TSS TOLERANCES OF RIVERINE FISH SPECIES*

TSS Tolerances of 106 fish species from 34 riverine sites in Wisconsin and Minnesota, and the total number of sites from which each species was collected.
Also shown are the proportional occurrences of each species at hydrologically variable or stable sites. TSS tolerances categories are (1) high (2) medium (3) low (from Poff and Allan 1995. Ecol. 76 (2): 606-627).

Family	Species	Total Sites	Variable Sites	Stable Sites	Silt Tol.
Acipenseridae	Acipenser fulvescens	1	0	0.056	
Amiidae	Amia calva	2	0.125	0	
Anguillidae	Anguilla rostrata	1	0.062	0	1
Atherinidae	Labidesthes sicculus	4	0.125	0.111	3
Catastomidae	Carpoides carpio	5	0.125	0.167	2
Catastomidae	Carpoides cyprinus	10	0.375	0.222	2
Catastomidae	Carpoides velifer	3	0.062	0.111	2
Catastomidae	Catastomus commersoni	33	0.938	1	1
Catastomidae	Erimyzon sucetta	1	0.062	0	3
Catastomidae	Hypentelium nigricans	16	0.188	0.722	3
Catastomidae	Ictiobus bubalus	2	0.125	0	2
Catastomidae	Ictiobus cyprinellus	5	0.188	0.111	2
Catastomidae	Moxostoma anisurum	18	0.438	0.611	3
Catastomidae	Moxostoma carinatum	1	0	0.056	3
Catastomidae	Moxostoma erythrurum	19	0.438	0.667	3
Catastomidae	Moxostoma macrolepidotum	21	0.312	0.889	3
Catastomidae	Moxostoma valenciennesi	3	0.062	0.111	3
Centrarchidae	Ambloplites rupestris	15	0.375	0.5	3
Centrarchidae	Lepomis cyanellus	18	0.625	0.444	1
Centrarchidae	Lepomis gibbosus	11	0.5	0.167	2
Centrarchidae	Lepomis humilis	9	0.375	0.167	1
Centrarchidae	Lepomis macrochirus	17	0.562	0.444	1
Centrarchidae	Micropterus dolomieu	20	0.312	0.833	3
Centrarchidae	Micropterus salmoides	11	0.438	0.222	2
Centrarchidae	Pomoxis annularis	5	0.25	0.056	1
Centrarchidae	Pomoxis nigromaculatus	12	0.375	0.333	2
Clupeidae	Dorosoma cepedianum	4	0.25	0	1
Cottidae	Cottus bairdi	6	0.125	0.222	3
Cyprinidae	Campostoma anomalum	8	0.375	0.111	2
Cyprinidae	Campostoma oligolepis	10	0.125	0.444	
Cyprinidae	Clinostoma elongatus	1	0	0.056	3
Cyprinidae	Couesisus plumbeus	5	0.312	0	1
Cyprinidae	Cyprinella spiloptera	23	0.688	0.667	1
Cyprinidae	Cyprinus carpio	24	0.812	0.0611	1
Cyprinidae	Hybognathus nuchalis	1	0	0.056	3
Cyprinidae	Luxilus chrysocephalus	1	0.062	0	2
Cyprinidae	Luxilus cornutus	34	1	1	2
Cyprinidae	Lythurus umbratilis	2	0.125	0	1
Cyprinidae	Margariscus margarita	4	0.25	0	

APPENDIX 3

TSS TOLERANCES OF RIVERINE FISH SPECIES*

Family	Species	Total Sites	Variable Sites	Stable Sites	Silt Tol.
Cyprinidae	Macrohybopsis aestivalis	1	0	0.056	3
Cyprinidae	Macrohybopsis storeriana	1	0	0.056	3
Cyprinidae	Nocomis biguttatus	26	0.688	0.833	3
Cyprinidae	Notemigonsus crysoleucas	8	0.5	0	1
Cyprinidae	Notropis atherinoides	14	0.5	0.333	2
Cyprinidae	Notropis blennius	6	0.188	0.167	
Cyprinidae	Notropis dorsalis	20	0.562	0.611	
Cyprinidae	Notropis heterolepis	6	0.25	0.111	3
Cyprinidae	Notropis hudsonius	7	0.25	0.167	3
Cyprinidae	Notropis nubilus	1	0	0.056	
Cyprinidae	Notropis rubellus	14	0.188	0.611	3
Cyprinidae	Notropis stramineus	21	0.688	0.556	2
Cyprinidae	Notropis texanus	1	0	0.056	
Cyprinidae	Notropis volucellus	5	0.062	0.222	3
Cyprinidae	Phenacobius mirabilis	8	0.125	0.333	7
Cyprinidae	Phoxinus eos	5	0.188	0.111	2
Cyprinidae	Phoxinus erythrogaster	9	0.25	0.278	3
Cyprinidae	Phoxinus neogaeus	1	0.062	0	
Cyprinidae	Pimephales notatus	30	0.938	0.8333	1
Cyprinidae	Pimephales promelas	24	0.938	0.5	1
Cyprinidae	Pimephales vigilax	4	0.188	0.056	1
Cyprinidae	Rhinichthys atratulus	18	0.625	0.444	2
Cyprinidae	Rhinichthys cataractae	16	0.25	0.667	3
Cyprinidae	Semotilus atromaculatus	33	1	0.944	1
Esocidae	Esox americanus vermiculatus	1	0.062	0	2
Esocidae	Esox lucius	24	0.812	0.611	3
Esocidae	Esox masquinongy	1	0	0.056	3
Cyprinodontidae	Fundulus notatus	1	0.062	0	1
Gadidae	Lota lota	8	0.125	0.333	
Gasterosteidae	Culea inconstans	11	0.438	0.222	3
Ictaluridae	Ameiurus melas	18	0.75	0.333	1
Ictaluridae	Ameiurus natalis	9	0.5	0.056	2
Ictaluridae	Ameiurus nebulosus	1	0.062	0	1
Ictaluridae	Ictalurus punctatus	10	0.25	0.333	2
Ictaluridae	Noturus flavus	22	0.562	0.722	3
Ictaluridae	Noturus gyrinus	8	0.375	0.111	2
Ictaluridae	Pylodictis olivaris	3	0.125	0.056	2
Hiodontidae	Hiodon alosoides	1	0	0.056	2
Hiodontidae	Hiodon tergisus	3	0.125	0.1	3
Lepisosteidae	Lepisosteus osseus	3	0.188	0	2
Lepisosteidae	Lepisosteus platostomus	2	0.125	0	2
Perichthyidae	Morone chrysops	6	0.188	0.167	2
Percidae	Ammocrypta clara	2	0.062	0.056	
Percidae	Etheostoma aspirgene	1	0.062	0	
Percidae	Etheostoma caeruleum	9	0.188	0.333	3
Percidae	Etheostoma exile	3	0.188	0	1

TSS TOLERANCES OF RIVERINE FISH SPECIES*

Family	Species	Total Sites	Variable Sites	Stable Sites	Silt Tol.
Percidae	Etheostoma flabellare	17	0.438	0.556	2
Percidae	Etheostoma nigrum	30	0.938	0.833	1
Percidae	Etheostoma zonale	13	0.25	0.5	3
Percidae	Perca flavescens	14	0.625	0.222	2
Percidae	Percina caprodes	10	0.188	0.389	3
Percidae	Percina evides	2	0	0.111	3
Percidae	Percina maculata	23	0.625	0.722	2
Percidae	Percina phoxocephala	11	0.25	0.389	3
Percidae	Percina shumardi	1	0.062	0	
Percidae	Stizostedion canadense	8	0.25	0.222	2
Percidae	Stizostedion vitreum	18	0.438	0.6111	2
Petromyzontidae	Icthyomyzon cataneus	5	0.062	0.222	
Petromyzontidae	Icthyomyzon unicuspis	4	0.062	0.167	3
Petromyzontidae	Lampetra appendix	3	0.062	0.111	3
Percopsidae	Percopsis omiscomaycus	2	0	0.111	3
Salmonidae	Coregonus hoyi	1	0.062	0	
Salmonidae	Oncorhynchus mykiss	9	0.25	0.278	3
Salmonidae	Salmo trutta	13	0.375	0.389	3
Salmonidae	Salvelinus fontinalis	4	0.125	0.111	3
Sciaenidae	Aplodinotus grunniens	6	0.25	0.111	2
Umbridae	Umbra limi	12	0.438	0.278	1