Proceedings of the B.C. - Yukon Sediment Issues Workshop: April 24-26, 1990 Vancouver, B.C.

by

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Organizing Committee

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Proceedings of the B.C.-Yukon sediment issues workshop.

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Abstract

Sediment issues in B.C. and the Yukon are many and diverse in nature. In engineering, construction on alluvial fans or in areas prone to debris torrents is a significant concern. Also, in the designing of any in-stream works or in flood plain management one must have an appreciation of river morphology and sediment transport.

In water quality, contaminants (dioxins and furans) from pulp and paper mills are found to be adsorbed to sediment. In the mining sector, bed sediments are used to monitor trace metal contamination. It is apparent that sediment is increasingly becoming an important indicator for many quality concerns.

The focus in the forestry sector on sediments is on methods of identifying sediment sources and minimizing sediment loading into the fluvial environment. The role and significance of large organic debris in stream morphology is another area receiving considerable attention.

For fisheries, sediment is a deleterious substance that must be regulated. Reducing the impacts from logging and placer mining are two key areas of attention. Maintaining adequate suitable aquatic habitat for fish is the most recent thrust in this resource management.

The two day multidisciplinary workshop brought together more than 150 individuals representing consulting firms, universities, federal and provincial governments to focus on sediment-related issues. It is apparent from this workshop that there is a critical need to coordinate activities if we are to properly address these complex issues. Towards this goal, it is recommended that a technical advisory committee be established to better coordinate efforts and continue the momentum generated from this workshop.

Résumé

Les questions relatives aux sédiments en Colombie-Britannique et au Yukon revêtent une foule de formes diversifiées. En génie, la construction sur des cônes de déjection ou dans des régions souvent soumises à des torrents de débris est une source de préoccupations. De plus, il faut connaître la morphologie du cours d'eau et le transport solide pour concevoir des ouvrages dans un cours d'eau ou assurer la gestion des plaines inondables.

Dans le domaine de la qualité de l'eau, il est un fait que les contaminants (dioxines et furannes) provenant des usines de pâtes et papiers sont absorbés par les sédiments. Dans le secteur minier, on se sert des sédiments de fond pour surveiller la contamination par les métaux à l'état de traces. Il semble que les sédiments deviennent de plus en plus un indicateur important des nombreux problèmes de qualité de l'eau.

Dans le secteur forestier, l'intérêt que l'on porte aux sédiments est surtout centré sur les méthodes qui servent à déterminer la provenance des sédiments et à en réduire le plus possible la charge dans les cours d'eau. Le rôle et l'importance de gros débris organiques dans la morphologie des cours d'eau constituent une autre sphère qui suscite une attention considérable.

Pour les pêches, les sédiments constituent une substance nuisible à contrôler. La réduction des effets de la coupe du bois et de l'exploitation des placers sont les deux principales activités qui retiennent l'attention. Le maintien d'un habitat adéquat pour le poisson se veut l'orientation la plus récente prise pour la gestion de cette ressource.

L'atelier multidisciplinaire a réuni, pendant deux jours, plus de 150 personnes venues discuter des questions liées aux sédiments et représentant les experts-conseils, les universités ainsi que les gouvernements fédéral et provinciaux. Il ressort de l'atelier que la coordination des activités s'impose si l'on veut s'occuper convenablement de ces questions complexes. Afin d'atteindre ce but, il est donc recommandé de créer un comité consultatif technique qui sera en mesure de mieux coordonner les efforts qui seront déployés et de maintenir le dynamisme découlant de l'événement.

Acknowledgments

On behalf of the Water Resources Branch, we would like to thank: L. Churchland, R. Kellerhals, O. Langer and D. Wilford for their help in organizing the workshop.

We would also like to thank the chairpersons: G. Tofte, R. Kellerhals, P. Whitfield, D. Wilford and O. Langer for their session overviews and the effective job each of them did with their session.

Many thanks to all the individual presenters for their insights into the state-of-the-art knowledge regarding various topics.

M. Church provided an excellent synthesis of the workshop and certainly made us aware that a coordinated effort is needed if we are going to properly address sediment issues.

Special thanks are due to M. Church, S. McFarland and D. Walton for providing us with an appreciation of existing knowledge of the Fraser River system.

Finally, we would like to thank M. Hurcomb and L. Latino for helping with the administrative details associated with the workshop.

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1. INTRODUCTION

1.1 Background

The Water Resources Branch (WRB) of Environment Canada in cooperation with various agencies have been involved in organizing sediment issue workshops across Canada. To date workshops have been held in Guelph (1985), Charlottetown (1986), Winnipeg (1986), Regina (1987), Calgary (1988) and most recently in Vancouver (1990). These workshops focussed on identifying issues, on a regional basis, related to fluvial sediments. A multidisciplinary approach was adopted to provide the broadest perspective. These workshops have been instrumental in demonstrating the significance of sediment and have resulted in the initiation of numerous cooperative efforts to address issues.

The B.C.-Yukon workshop had the largest organizing committee, demonstrating that sediment concerns were extremely important regionally. The organizing committee included personnel from:

1. B.C. Ministry of Forests
2. Habitat Management Division (Fisheries and Oceans Canada)
3. Kellerhals Engineering Services
4. Sediment Survey Section (Environment Canada)
5. Water Quality Branch (Environment Canada)
6. Water Resources Branch (Environment Canada)

The committee was responsible for identifying key topics, selecting speakers and ensuring the workshop was properly promoted.

The main objectives of the workshop were:

1. To discuss fluvial sediment issues in B.C. and the Yukon Territory,
2. To determine how the various agencies are addressing these issues, and
3. To determine how these issues may be better addressed.

The workshop was well received as a total of 156 individuals (Appendix A) attended the two day workshop. Thirty-five individuals also took part in the one day field trip which dealt with the issues affecting the Fraser River.

1.2 Agenda

The workshop was comprised of five distinct sessions (see agenda). The first session provided an overview of existing government programs involved with addressing sediment-related issues. The presentations were structured to provide insight into the program mandate, organizational structure, current activities and future direction. The research being undertaken at universities was included to provide a more complete perspective. The session closed with a presentation on integrated management approaches. It is becoming increasingly apparent that an integrated approach to addressing environmental concerns is the way of the future. We must work on developing the most suitable management framework to meet this goal.

The other four sessions dealt specifically with sediment issues within four disciplinary fields: engineering, water quality, forestry and fisheries. The presentations were intended to be general in nature, not overly technical, so as to appeal to a diverse audience. The sessions were meant to provide an overview of the current state of knowledge within each discipline. An introductory presentation given at the beginning of each session elucidated the importance of the topics being presented and provided important linkages. Dr. Michael Church provided a synthesis at the end of each day.

1.3 Opening Remarks

Mr. Gordon Tofte (Chief, WRB) opened the workshop on behalf of Dr. Earl Anthony (Regional Director General, Conservation and Protection, Environment Canada), who was unable to attend because of Green Plan commitments. Mr. Tofte reviewed the workshop objectives and discussed the workshop format. He stressed the importance of the workshop in demonstrating the federal government's ongoing commitment to program integration, to improved communications with all concerned parties and towards cooperative ventures to address environmental concerns. He hoped that this workshop would foster cooperative efforts towards addressing fluvial sediment concerns in B.C. and the Yukon Territories. He also hoped that mechanisms would be identified which would continue to help promote sediment-related activities. He closed by thanking the workshop organizers and chairpersons for their efforts and looked forward to a productive workshop.

AGENDA

B.C. - YUKON SEDIMENT ISSUES WORKSHOP
APRIL 24 - 26, 1990

April 24, 1990

08:00	Registration	
08:30	Opening Remarks	- G. Tofte
	PROGRAM OVERVIEW SESSION	- G. Tofte, Chairperson
08:45	1) Water Resources Branch	- B. Tassone
09:15	2) Water Quality Branch	- L. Churchland
09:45	3) Fisheries	- J. Payne
10:15	Coffee	
10:35	4) Forestry	- S. Chatwin
11:05	5) Universities	- E. Hickin
11:35	6) Integrated Management Approaches	- T. Day
12:00	Lunch	

ENGINEERING SESSION

1:00	Introduction	- R. Kellerhals, Chairperson
1:20	1) Engineering Aspects for Development on Alluvial Deltas	- D. Hay
1:45	2) Flood Plain Management and Sedimentation Processes	- P. Wood
2:10	3) Debris Torrents	- P. Jordan
2:35	Coffee	
3:05	4) Use of Morphological Methods to Estimate Sediment Transport	- D. McLean
3:35	Summation	- M. Church

April 25, 1990

WATER QUALITY SESSION

08:30	Introduction	- P. Whitfield, Chairperson
08:50	1) Sediment Related Water Quality Issues in the Yukon	- G. Whitley
09:15	2) Sampling Organic Contaminants in Sediments	- T. Tuominen
09:40	3) Use of Sediment Data in Evaluation of Mining Projects	- B. Godin
10:05	4) Approaches to Sediment Quality Guidelines and Objectives	- D. Valiela, L. Swain

APRIL 25, 1990 (Continued)

10:30	Coffee	
	FORESTRY SESSION	
10:50	Introduction	- D. Wilford, Chairperson
11:10	1) Hillslope Sediments in Forested and Logged Coastal Watersheds	- S. Chatwin
11:35	2) Fluvial Sediments in Forested and Disturbed Coastal Watersheds	- D. Hogan
12:00	Lunch	
1:00	3) The Impact of Forest Harvesting on Suspended Sediment Loads in Interior Streams	- D. Toews
	FISHERY SESSION	
1:25	Introduction	- O. Langer, Chairperson
1:45	1) Suspended Sediments and Fisheries: Highlights of an Empirical Impact - Assessment Model	- C. Newcombe
2:10	2) Impact of Sediments on Fish Habitat: Status of Knowledge	- A. Smith, J. Malick
2:35	3) Fisheries (Sediment) Guidelines	- K. Rood
3:00	Coffee	
3:20	4) Linear Developments: Innovative Techniques for Sediment Control and Fisheries Habitat Re-creation	- M. Miles
3:45	Closing Remarks	- M. Church

April 26, 1990

08:30	Field Trip - Lower Fraser River	- M. Church - S. McFarland - D. Walton

2. PROGRAM OVERVIEW SESSION

2.1 An Overview of the Sediment Data Collection Program of the Water Survey of Canada in British Columbia and Yukon

Bruno Tassone
Environment Canada

This paper presents an overview of the sediment data collection program of the Water Survey of Canada in British Columbia. This is part of the larger hydrometric data collection program. Both programs are national in scope and cost-shared with their provincial and territorial partners; B.C. Water Management Branch and Department of Indian and Northern Affairs (DIAN).

One can divide the purpose of most sediment studies into 3 categories:

i) evaluation of drainage basins with respect to different environmental conditions including climate, geology, soils, topography, ground cover and land use
ii) evaluation of erosion and deposition patterns in channel systems
iii) evaluating the relationship between sediments, water quality and biota.

British Columbia and the Yukon encompass some of the most diverse environmental zones in Canada. The climate ranges from mild and wet in southwestern B.C. to extremely continental in the central Yukon. Some of the most intense storms and the greatest annual precipitation in Canada occur on coastal B.C. The region also has the greatest relief in Canada, the topography ranges from ice-covered alpine through plateaus to inland and coastal sedimentary plains. Within the region, there is a diversity of vegetation and soils and a large variety of land uses. Consequently, sediment yield varies greatly, from almost zero in well-vegetated interior plateau areas to over 1 tonne/km^2/year in glaciated areas of B.C. and the Yukon. This also implies that a network of sediment stations are required to describe the natural conditions.

Sediment problems in B.C. and the Yukon are equally diverse. In a review and assessment of sediment issues in the Pacific & Yukon Region, Kellerhals Engineering Services (1985) categorized the problems as: channel sedimentation, dredging, placer mining, reservoir sedimentation, estuary sedimentation, land use, fish habitat and water quality.

Channel sedimentation is primarily a problem in populated areas. If a settlement is on an alluvial flood plain (e.g. Pemberton Valley or Bella Coola Valley), channel sedimentation can result in increased bed levels which in turn can increase the flooding hazard and decrease dyke safety. On alluvial fans (e.g. Vedder River, Lions Bay and many other locations along the Squamish Highway), very high sediment loads composed of very coarse material may be transported over a short period of time and cause extensive property damage. There is, therefore, a need for knowledge of the rates of sediment supply prior to development along the river channels and in alluvial fans.

Dredging is performed to improve navigation, such as on the Lower Fraser River, or to obtain aggregate (sand and gravel) for use in construction.

Therefore, knowledge of the rate of sediment supply is important; in one case to design a dredging program to maintain the desired draft, in the other to manage the resource. One must also be concerned with the long term effects on channel morphology. In many areas of the Yukon and northern B.C., placer mining is an important industry. The process by its very nature disturbs the land surface and produces highly silt-laden discharges. There is a need for studies to develop standards and to collect basic sediment data.

In reservoir sedimentation studies, knowledge of the sediment load and particle size is required to estimate the useful life of the reservoir. The regulation of flow by the dam often has both downstream and upstream morphological effects which may affect channel stability.

Estuaries are often zones of human settlement. Rates of sediment transport to estuaries and the rates of deltaic growth are needed for effective development e.g. ports, training walls, etc.). The building of a structure may also affect the patterns of sediment deposition.

Changes in land use can cause changes in erosion rates, sedimentation, channel stability, fish habitat and water quality. Fish habitat is an important issue in British Columbia. Suspended sediment can affect fish mortality and the deposition of fine sediments can affect egg survival. Data are required for design and management of spawning channels and hatcheries. Suspended sediment is a basic water quality parameter. The fine fraction of the sediment load also acts as a transport medium for a variety of pollutants. Some pollutants also tend to preferentially deposit in bed sediments. Therefore, a knowledge of transport rates and depositional processes is important.

Water Survey Program

Prior to 1965, there had been only two systematic sediment data collection programs in British Columbia. From 1947-49, suspended sediment data were collected on the Kootenay River as part of the Columbia River project, and between 1950-52, a suspended load study was performed on the Fraser River for the Fraser River Board.

The Water Survey of Canada (WSC) program was started in 1965 at the request of the Department of Public Works with the establishment of 7 stations on the Lower Fraser River (Zrymiak, 1982). Sediment data were required to assist in the design of their dredging program. A program on the Columbia River at Birchbank to assess the effects of Keenlyside Dam was also started in 1965. The WSC program expanded gradually and sporadically to a peak of 45 stations in 1983. There are presently 30 stations in operation.

Much of the increase in the program was due to requests and need for data by the cost-sharing partners - B.C. Water Management Branch (WMB) and B.C. Hydro. During the recession of the mid-1980s, most of the stations operated for B.C. Hydro and the WMB were discontinued due to budget restrictions. In 1988, WRB established a miscellaneous sediment network.

There have been two types of sampling programs; a full program with the objective of determining daily loadings on a continuous or seasonal basis and a miscellaneous program in which sediment measurements are obtained only when a technician visits the station, usually 5 - 10 times/year. WSC also performs laboratory analyses on samples collected by other agencies (e.g. B.C. Hydro, Fisheries, Water Quality, DIAN or consultants working for these agencies at non WSC sites).

The major change in the program is that it has evolved from being almost exclusively project oriented (1965-84) to the present baseline network (Figure 2.1).

Much fewer data exist in the Yukon. The program was initiated in 1970 to support a Water Quality baseline investigation of proposed mining developments. There are a total of 13 sites where data are available and the program has always been baseline oriented (Figure 2.1). There are five stations being operated in the Yukon in 1990.

In 1985, a review and assessment of sediment issues in the Pacific and Yukon Region was completed by Kellerhals Engineering Services (1985). The report contained a number of recommendations. Some of the more important recommendations include: the establishment of a baseline network, undertaking of a sediment budget analysis of the Lower Fraser River, conducting studies of delta growth, participating in studies of water quality and land use effects, development of instrumentation and methodology, greater data analysis and establishment of a regional advisory committee of users.

After consultation with the Water Quality Branch and Provincial MOE, a regional network of 25 miscellaneous stations was established in 1988. The purpose was to increase and broaden the spatial coverage of stations and to provide baseline data. The intention is to operate these stations for 5 - 10 years until a sediment yield relationship is defined and then the sampling effort will be redirected to other sites. In 1990, full program stations are being operated at Mission, the base sediment station on the Lower Fraser River, Five Mile Creek near Nelson in support of a provincial study and on the Flathead River near the international border for an impact assessment of a proposed mine.

Concurrent with the redirection to a baseline data collection program we have increased the data analysis effort. Two station analysis reports have been completed; Fraser River at Hansard (Zrymiak and Tassone, 1986) and Fraser River at Marguerite (Carson, 1990) which will be printed and distributed shortly. Both have resulted in the redirection of the full programs to a miscellaneous program designed to fill data gaps. The sediment data for the Carnation Creek project, whose purpose was to determine the effects of logging on the fishery, has also been reviewed. The conclusions were that the sediment data collection program would have benefited from greater integration with other studies and researchers that bedload made up the major portion of the total load and sediment regime was characterized by infrequent movement (less than 10 days/year) but of large mass. On the Lower Fraser River, WSC has supported D. McLean's field work activities between Agassiz and Mission related to his graduate studies. Historic sounding charts of the Fraser River Delta were reviewed to determine the rate of growth (Stewart and Tassone, 1989). The main findings of this report were that the average progradation was 4.5 m/year, with a high of 8.6 m/year in the vicinity of Sandheads, which is similar to the rate documented by Mathews and Shepard (1962). Some areas showed retreat notably in the vicinity of structures such

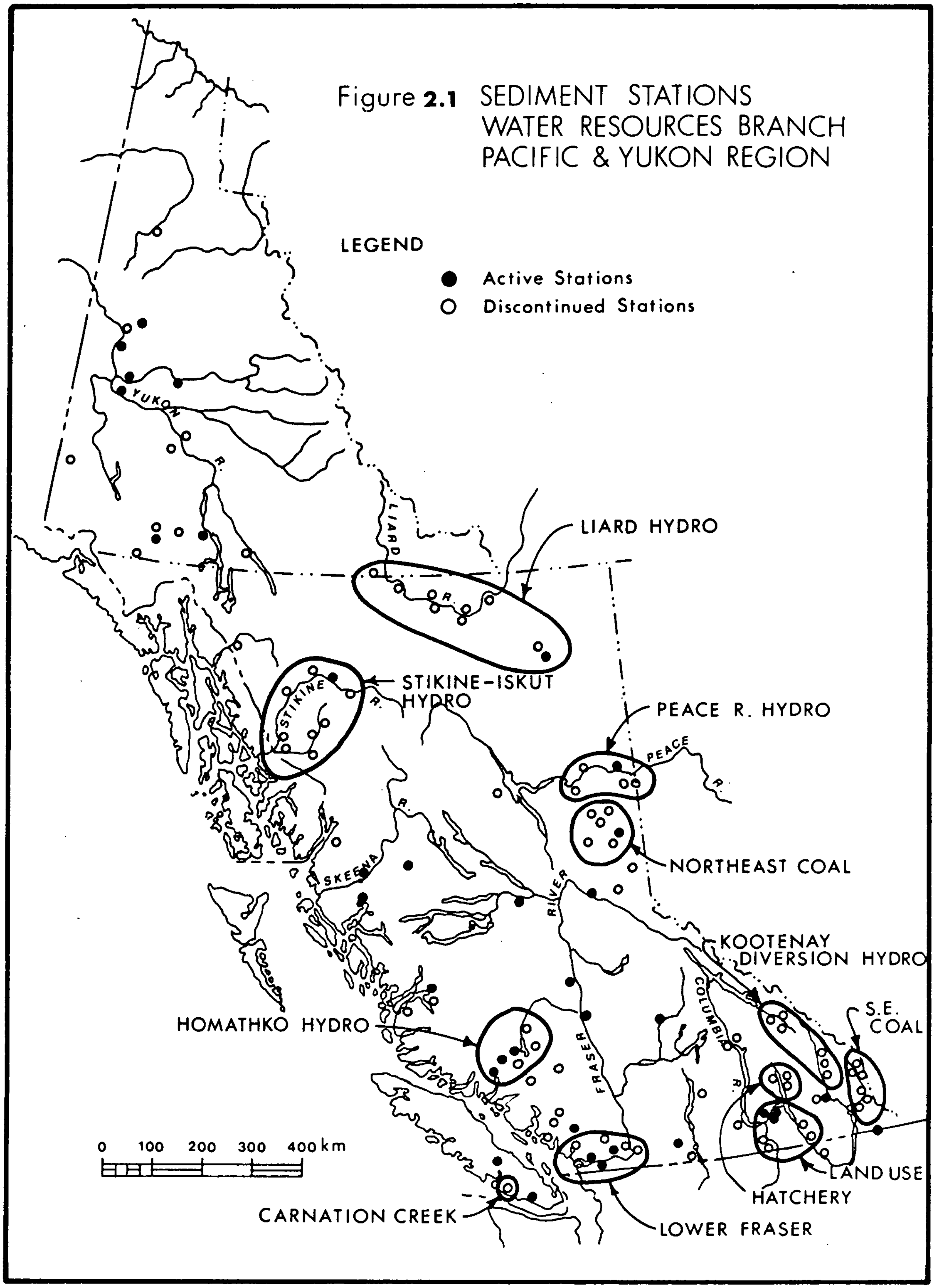

Figure 2.1 SEDIMENT STATIONS WATER RESOURCES BRANCH PACIFIC & YUKON REGION

as Roberts Bank and the Tsawwassen ferry terminal, and deserve more detailed examination. At the request of Coast Guard Canada, a sediment budget study of the Lower Fraser River was performed to assist in the design of their dredging program (McLean and Tassone, 1988). Public Works Canada dredges on average 6.0 million tonnes/year of sediments. This has resulted in an average lowering of Navigation Channel by 2.0 m since 1964. The sediment budget calculation indicates that the average outflow of bed material to the Strait of Georgia is 1.0 million tonnes/year. Other potential uses of the data analysis results on the Lower Fraser River include fisheries, water quality, and bank and flood protection.

In the Yukon an analysis of sediment data at all stations has been performed which has identified gaps in the data base. For 1990 and 1991, the data collection efforts have been redirected to support the Placer Mining Study. We will also provide laboratory support and the Ottawa office is providing equipment to the study. At other sites, sampling will be done to fill in the data gaps. The establishment of future sites will be done in conjunction with DIAN, our cost-sharing partner.

The program has traditionally focused on physical sedimentation problems largely associated with engineering projects by collecting standard sediment data sets. In future, the program will increasingly have to respond to changing user requirements and client needs particularly in the areas of environmental monitoring, impact assessments and environmental forecasting. This will require integration of our work with other agencies: water quality, fisheries, forestry, etc., in order to pool our skills and knowledge in data collection methods, physical processes and data analysis and interpretation. The fulfilment of these future needs on a timely and effective basis will require improved communications between the Water Resources Branch and the various users.

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2.2 Sediment as a Dimension of a Balanced Water Quality Program

Leslie M. Churchland
Environment Canada

The field of water quality includes not only the water per se, but also the biota and the suspended or deposited sediments. The importance of sediments includes their role in the transport and deposition of toxic chemicals, the transport and deposition of nutrients in estuarine and lake ecosystems, the physical nature of sediments, and their removal from or deposition in certain key areas such as spawning grounds.

The presentations today are given by Federal and Provincial scientists, and encompass the major sediment issues in British Columbia and the Yukon. They also include some of the management tools, such as water quality objectives, that have been developed to evaluate and control contaminants in the aquatic environment.

In this presentation, several illustrations are given of the importance of understanding sediments in order to understand water quality, using examples from studies which have been conducted by the Water Quality Branch (WQB). In the first example, the Stikine River in Northwestern British Columbia, proposed hydroelectric developments were anticipated to remove a substantial proportion of the sediment load generated during snowmelt, glacial melt, and Fall floods. The WQB effort concentrated on collecting information on water quality variables and sediment concentrations and relating the results to the expected effects of impoundments (Schreier and Churchland, 1987).

The overall purpose of WQB work in the Flathead River area was to evaluate the effects of altered sedimentation from coal mining or forestry activities on the quality of stream bottom habitats, with respect to fish and invertebrates (MacDonald and McDonald, 1987). In this study, sediment traps and MacNeill samplers were used in bull trout spawning areas to collect and characterize deposited sediments.

Finally, the Water Quality Branch has conducted several studies in which the focus has been to establish the level of contaminants in suspended and/or bed sediments. In the Fraser River estuary, comparisons were made between types of continuous flow centrifuges, to determine ease of use and efficiency in collecting the fine particle size fraction. (Churchland et al., 1987). A continuous flow centrifuge, in combination with a Goulden large sample extractor, is presently being used to determine concentrations or organic contaminants in the suspended sediment and water at the border reach of the Columbia River. The results of WQB studies in establishing levels of dioxins and furans in sediments upstream and downstream of freshwater pulp mills (Mah et al., 1989) will be presented during the program of the workshop.

Characterizing sediments and water quality conditions is a complex task, with a substantial effort in quality assurance and quality control required to understand the limitation of the sampling and analytical techniques used. In addition to studies which compare sampling techniques for sediments and water quality samples, the WQB has examined the analytical methods used to estimate suspended sediment concentration. The attached table 2.2 shows that the non-filterable residue (NFR) method (Inland Waters, 1979) provides an estimate of 46-89% of the total suspended sediment concentration value as determined by the filtration method (Guy, 1969). This difference is removed if the subsampling step in the NFR method is eliminated. Continuing efforts in quality control/quality assurance are required to ensure that the limitations of sampling and analytical methods for water quality variables, including sediments, are well understood.

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Table 2.2 Effect of Analytical Technique on Determination of Suspended Sediment

Location	Date Sampled	Suspended Sediment Concentration (mg/L): Non Filterable Residue[1] A	B	C	Total[2] Concentration by the Filtration Method
Liard River	16/05/84	107 ± 8	165 ± 14	172 ± 21	187 ± 10
Swift Current Creek	28/07/84	488 ± 10	561 ± 9	540 ± 15	549 ± 9
Squamish River	07/06/83	83 ± 3	137 ± 7	142 ± 9	137 ± 10
Fraser River at Mission	22/06/83	100 ± 12	157 ± 15	148 ± 17	156 ± 33
Greely Creek	29/07/84	180 ± 18	437 ± 90	455 ± 57	390 ± 92
Sumas River	16/11/83	25 ± 4	29 ± 4	35 ± 6	32 ± 1

[1]Note: Numbers are arithmetic means and 95% confidence limits; sample size is ten.
A is the non filterable residue analysis of a 100 ml subsample from a 250 ml bottle; (IWD, 1979).
B of the total contents of a 250 ml bottle.
C of the total contents of a 100 ml bottle.

[2]Guy, 1969.

2.3 DFO Program Activities Related to Sediment

John Payne
Department of Fisheries and Oceans

Mandate

Under the Constitution Act the Federal Government has jurisdiction over marine, coastal and inland fisheries. In British Columbia and Yukon responsibility for the management of resident sportfish has been delegated to the Provincial and Territorial Governments, with DFO retaining responsibility for marine and anadromous species.

Sections 35 and 36 of the Fisheries Act provide DFO with the authority to protect fish habitat from harmful alteration and the deposit of deleterious substances respectively. Sediment issues are dealt with by DFO under both these sections, e.g. the alteration of habitat by dredging for navigation or borrow, and the alteration of habitat or impact on fish from the addition of sediment from logging, construction or placer mining.

Effects of Sedimentation on the Fisheries Resource

Spawning gravel: sediment can influence two critical properties: permeability and porosity. Permeability affects delivery and removal rates of oxygen, carbon dioxide and other metabolites to and from incubating eggs and alevins; low porosity can restrict intragravel movement of alevins and create a barrier to emergence.

Rearing: sediment can interfere with the feeding success of sight feeding fish; can reduce food sources by blocking sunlight penetration, thus reducing primary production, and by changing the substrate so that it becomes unusable by preferred benthic organisms; and can destroy overwintering habitat by filling the interstices in cobble/large gravel substrate.

Fish health: suspended sediment can affect fish by inducing high stress levels and causing physical damage to gills.

For further details and additional references, see Department of Fisheries and Oceans and Environment Canada (1983).

DFO Program

DFO's recent activities in this area have been directed at research programs and studies to quantify the effects of sediment on fish and habitat, and the use of that information in support of the development of guidelines for the conduct of industrial operations such as logging, placer mining and urban development. All of these research programs and studies have been carried out in cooperation with other government agencies and industry.

Research

1. Carnation Creek

This long term study of the effects of logging on a small west coast watershed was begun in 1970 with a pre-logging data gathering phase. Between 1976, when logging began, and 1986 there was a 4.6% increase in the small gravel fraction (2.38-9.55 mm) in spawning areas of the creek and a 5.7% increase in the sand fraction (0.074-2.38 mm). Over the same time period survival to emergence of incubating coho salmon fell from 29.1% to 16.4%, and 22.2% to 11.5% for chum salmon. Changes in the spawning gravel composition explained 28% of the drop in coho egg-to-fry survival and 50% of the chum. Entombment was probably the major cause of mortality because pore spaces in the substrate were filled mainly with coarse fines.

Much of the sediment that affected the quality of the spawning gravels come from scoured stream banks or from channel sediment that has been previously stored behind large organic debris which suffered realignment or was lost (Scrivener and Brownlee, 1989).

As of the beginning of the 1990-91 fiscal year, DFO will cease to play a major role in the study until such time as the regenerated forest has achieved canopy closure. At that time it is our intention to reinstitute studies in order to determine whether the system is approaching its pre-logging state.

2. Fish/Forest Interaction Program, QCI

This is a 12 year study, begun in 1981, to document problems and potential solutions involved with logging on steep slopes. Results to date show that logging has accelerated the frequency of mass wasting by a factor of 34 from 0.12 failures/km^2/year in unlogged terrain to 4.1 failures/km^2/year in logged; 29% of landslides entered stream channels at a rate 23 times higher in logged terrain than in unlogged; total estimated debris yield from mass wasting originating on unlogged slopes was 1.6 m^3/ha/year, and logging increased this by a factor of 35 to 58.2 m^3/ha/year; and 39% of the displaced material entered stream channels in unlogged areas as opposed to 47% in logged. Resulting degradation of fish spawning and rearing habitat was also noted (Poulin, 1986).

Studies are continuing with regard to methods of mitigating these problems in such areas as alternative harvesting systems, silvicultural systems and practices, hillslope rehabilitation and stream rehabilitation.

3. Yukon Placer Mining

As part of an agreement between government agencies and Yukon placer miners regarding interim sediment discharge levels, a three year study is being carried out on biological, physical and economic aspects of the problem. An environmental and economic review and appraisal of available information has been carried out and reported (Norecol, 1989), and a two year field investigation is now underway.

The physical component of this investigation will determine: sediment releases from specific placer activities and increases in sediment in mined streams; sediment budgets and regimes in natural, mined and receiving streams; the downstream limit of detection of placer sediments; the infiltration of sediments into substrate; and channel morphology in natural and mined streams. The biological component will determine: how fish are distributed among stream habitats with regard to depth, velocity, substrate type and sediment; how fish utilize the various habitats at different seasons; fish spawning and rearing habitats in relation to the potential effects of mining; and how incubating eggs are affected by mining.

The results of the study are to be used to evaluate the effectiveness of the 1988 Yukon Fisheries Protection Authorization (Government of Canada, 1988) and support changes if required.

4. Lower Fraser River Gravel Budget Study

The Fraser River has formed a gravel-bedded channel in the reach between Hope and Sumas. This reach is heavily utilised by spawning salmon (up to 5 million pinks and 230 000 chum) and has also provided a source for the extraction of large quantities of gravel (up to 235 000 m^3 annually). Studies have been undertaken to determine how the available morphologic and sediment transport data can be utilized to assess the impacts on fish habitat from gravel mining and to identify locations where gravel removal can occur with minimal impact.

Kellerhals et al. (1987) determined that the averge annual bedload in that reach of the Fraser River is 100 000 m^3/year (85% gravel, 15% sand). Although gravel mining has been severely curtailed since 1983, the three remaining operations removed 106 000 m^3 in 1987. Northwest Hydraulic Consultants Ltd. (1989) carried out a pilot study on one section of the reach and demonstrated the applicability of a method for assessing potential gravel mining sites. They are currently (1990) extending the methodology to the entire reach and are preparing a set of classification maps which will provide resource managers with a tool for assessing where gravel removal operations can be carried out with minimal impacts on the overall channel morphology and fish habitat.

Guidelines

The results of studies, plus the experience gained in DFO's day-to-day activities, are used in the development of guidelines for the conduct of various activities. Such guidelines are usually developed in concert with other government agencies and the industrial sector involved, and generally contain recommendations for the control of sediment. Examples are the coastal fish/forestry guidelines (B.C. Ministry of Forests et al., 1988) and the land development guidelines (Department of Fisheries and Oceans, 1978), currently undergoing a major review.

A DFO guideline has also been developed for use by deparmental staff in assessing the gravel supply in B.C. streams and potential effects on fish habitat of its removal (Sutek et al., 1989).

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2.4 Overview of the B.C. Ministry of Forests Program in Sediment Research and Management

S. Chatwin
B.C. Ministry of Forests

Ministry Organization

The British Columbia Ministry of Forests research program is highly decentralized. There are six Forest Regions in the province; these are centered in Vancouver, Williams Lake, Prince George, Nelson, Smithers and Kamloops. Each region has its own team of research scientists specializing in pedology, hydrology and geomorphology as well as other forest sciences. Technical co-ordination of the research program is by the Research Branch in Victoria, while operational consulting, training and involvement in specific watershed planning processes are administered from the respective regional offices.

In total, the Ministry has 5 hydrologists, 3 geomorphologists and 7 pedologists active in sediment related operational research. This effort is bolstered by hydrologists and pedologists working for the larger forest companies (eg. MacMillan Bloedel Ltd. and Fletcher Challenge Ltd.). Close ties are also maintained with Forestry Canada, which has 1 hydrologist and 2 pedologists active in similar research areas. In addition, a large number of contract research is co-ordinated and administered by Ministry staff. This includes many contracts to B.C. universities for projects ranging from undergraduate to post-doctoral studies as well as for faculty research programs. Approximately 1 million dollars were contracted out on soil and sediment related issues in 1990. A large amount of the work is through inter-ministry, co-operative projects. For example, the Fish-Forestry Interaction Program (based on the Queen Charlotte Islands) and the Carnation Creek Experimental Watershed (on Vancouver Island) are long term multi-agency programs.

The main emphasis of the Ministry's research program over the past decade has been on development of watershed impact assessment techniques, analytical tools to help forest planners, and on basic research into hillslope and stream channel processes. The focus has been largely on forest harvesting related issues; the Ministry is responsible for the harvest on over 250,000 ha. of land each year, this accounts for 75,000,000 cubic metres of wood. However, because a large percentage of the watersheds harvested have important anadromous fish streams, integrated resource management issues are usually encountered. Many research topics have arisen as a result of concerns common to the Ministry of Forests, the federal Department of Fisheries and Oceans and the provincial Ministry of Environment. Certainly the federal Fisheries Act has been a prime motivator to resolve integrated resource issues. In recent years there has been an increased effort in silvicultural and old-growth related hydrological research. The following sections outline the Ministry's efforts over the last 5 years.

MINISTRY SEDIMENT RESEARCH

Sediment Sources

Increasingly sophisticated methods of terrain assessment have been developed for the identification of future, or potential, sediment sources. Terrain mapping classification systems, using 5 slope stability classes, have been developed and used to predict landslide susceptible forest lands. The system has been applied to nearly 1 million acres of steep forest land, primarily in coastal British Columbia. In conjunction with the mapping, extensive areas have been inventoried, particularly on the Queen Charlotte Islands, to identify the extent, severity and site characteristics of landslides. Methods of quantifying the stability classes, and creating statistics on the probability of failure for each terrain association have been developed (Rollerson and Sondheim, 1985). Others have used landslide surveys to assess site characteristics common to landslides and this has been useful for site evaluations (Chatwin and Rollerson, 1983; Rood, 1990). An ongoing project is using Digital Terrain Mapping to describe hillslope geometry algorithms to predict hillslope failure susceptibility (Niemann and Howes, in press). In an ongoing thesis at UBC, the various stability mapping systems are being critically tested to compare the actual landslide occurrence against what was predicted ten years ago (Young, in progress).

A major handbook to aid identification of unstable terrain, prevention and stabilization of soils, and rehabilitation of disturbed sites has been completed recently (Chatwin et al., 1990). The handbook is intended for use by road engineers and foresters primarily. Related operational assistance include handbooks dealing with hydroseeding techniques for prevention of cutslope erosion (Carr, 1980), as well as research results on trials with re-establishing grass, shrubs and conifers on landslides (Beese, 1990). A comprehensive system for watershed inventory of sediment sources and priorization and scheduling of rehabilitation efforts has been developed and is now being applied in national parks (Carr and Wright, 1990).

Related work in the interior of British Columbia is focused on minimizing soil disturbance through sensitive site identification. A number of sensitivity keys have been produced. These address soil compaction, surface runoff, forest floor displacement and mass wasting hazard for interior sites (Lewis, 1990).

Sediment Delivery

While the largest efforts have been made in the field of potential sediment source identification, increased efforts are aimed at determining sediment delivery and routing characteristics. That is, the downslope and downstream fate of sediment is becoming an increasingly important component of our research. Data from 250 landslides are being analyzed in a co-operative project with the University of British Columbia. This study considers landslide run-out distances, amounts of sediment deposited in streams and on the slopes, and an attempt is being made to develop an empirical method of predicting landslide sediment delivery (Rollerson and Fannin, in progress). A conceptual model for linking hillslope delivery to stream channel sediment delivery has been developed and applied to the northwest B.C. watersheds (Hogan and Wilford, 1989) and a similar approach has been used in eastern B.C. (Chatwin and Toews, in press). A long term study on the Queen Charlotte Islands is examining the linkage between landslide sediment and woody debris delivery and channel changes; the highly episodic nature of landslide events and storm intensity on the Queen Charlotte Islands showed that landslides have occurred even during relatively low magnitude storms with 2 year return periods and that the antecedent soil moisture levels were important (Hogan and Schwab, 1990).

Sediment Budgets

Sediment budget research is considered to be the highest priority for the Ministry over the next 5 years. Research is currently underway in several B.C. locations. Carnation Creek, with a drainage basin area of 10 km^2, has a 17 year continuous record of bedload and suspended sediment monitoring that spans time periods before and after logging (Hartman and Scrivener, 1990). These data are currently being reviewed in a sediment budget context. Work in the Tsitika River watershed (drainage basin of 400 km^2) has begun recently (Hogan and Chatwin, 1990). This is in response to perceived sedimentation impacts on fresh water fisheries and on the near-shore habitats of resident killer whales as a result of timber harvesting. It is critical that the relative importance of sediment derived from natural sources and logging activities be determined. A third sediment budget study is planned for the Stuart River watershed located in north central British Columbia.

Previous sediment budget research is limited. An intensive study of landslides in logged and forested watersheds on the Queen Charlotte Islands showed that steep slope areas logged in the 1970s were contributing, on average, 34 times more sediment to stream channels than similar forested watersheds. The longevity of this impact remains unknown (Rood, 1984). A synoptic survey showed that surface erosion from landslide surfaces on the Queen Charlotte Islands lasted decades, with forest regeneration being delayed for 40 years (Smith et al., 1986). One watershed sediment budget study on the Queen Charlotte Islands identified landslides and streambank erosion as the main contributors to bedload supply in moderately high gradient streams (Roberts, 1987), while a second study found that a short section of logging road was responsible for 70% of the entire suspended sediment load during an intense rainstorm (Bruce and Chatwin, 1988). In a detailed synoptic sediment sampling program on the Queen Charlotte Islands it was found that storage of fine sediments in stream systems is very limited. Even following landslides the majority of the fines are washed to the estuary within a year (Hogan and Beven, in press). Fine sediment storage was primarily restricted to back-channel and over-bank environments.

In the interior of British Columbia, sediment work was begun in the 1970s at Slim Creek by the Ministry of Environment. This study identified road construction in sensitive soil areas as the highest point source of sediment (Brownlee et al., 1989). Recent reviews of the watershed indicate that the roads continue to contribute significant quantities of sediment even 15 years after logging. In the Kootenays, an intensive study of the water quality impacts of a major forest fire found that sediment levels returned to pre-burn levels within 2 years of the fire (Gluns and Toews,1989).

Stream Channel Morphology

Channel morphology changes following landslides was the subject of a major synoptic study on the Queen Charlotte Islands (Hogan, 1986). The important role of large woody debris (LWD) in determining channel morphology, bedload storage and surface sediment textures, and in creating fish habitat was documented for a range of logged, forested and mass-wasted streams. This study has at present been underway for three years and is focussing on the rate-of-recovery of mass-wasted streams (Hogan, 1989). An important conclusion is the role of log jams in controlling channel, sediment storage and transfer characteristics of steep coastal watersheds. An ancillary UBC thesis is examining the downstream changes in bed material texture in logged and unlogged streams. This study critically evaluates the relative importance of the role of log jams and hillslope, valley-flat and stream channel inter- relations (Rice, 1990).

Stream channel morphology studies are also being conducted in Carnation Creek. Conventional air photographs and detailed channel surveys conducted annually for the last 18 years, supplemented with very low level air photographs obtained from helium filled balloons, are presently being analyzed to document sediment characteristics and related morphology. In conjunction with UBC, a study of bedload sediment movement patterns in a logged stream channel is continuing. Results from these coastal studies will be tested in interior streams in a regionalized synoptic study of the role of large woody debris in different biogeoclimatic zones (Hogan and Chatwin, in progress).

The Ministry currently has only one on-going study of a large river. Historical channel changes on the lower Skeena River have been mapped using air photographs covering the last 40 years (Hogan and Schwab, 1990). The maps were used to make recommendations on expected plantation life of alluvial sites and to recommend silvicultural strategies. Single season rates of island erosion and bar deposition have been further documented over the last 4 years by repeat river surveys. The results will be used in attempt to construct bedload sediment budgets for the lower Skeena River, following the approach presented by McLean on the Fraser River. The interest from a forestry perspective lies in determining whether logging within the upper Skeena River watershed and its tributaries has in any way affected sedimentology of the lower river.

We have a single study of small stream morphology in the interior, where Fubar Creek morphology and its microclimate in logged and unlogged reaches are being compared. (Hogan et al., in progress).

Regionalization

A co-operative project with UBC is attempting to regionalize British Columbia into homogenous zones based on hydromorphological criteria, and to link these regions to the biogeoclimatic system (Church and Thomas, in progress). At a finer scale, a contracted UBC thesis is examining ways of using digital terrain model data to objectively assess similarity between watersheds by critically evaluating a variety of morphometric properties (Cheong, in progress).

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2.5 Fluvial-sediment Studies at B.C. Universities

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Introduction

University research into questions directly related to fluvial sediment in British Columbian river systems is limited largely to work at the University of British Columbia and at Simon Fraser University. Specifically, most work has been conducted or directed by Professors Mike Church and Olav Slaymaker (Geography, U.B.C.) and Ted Hickin and Mike Roberts (Geography, S.F.U.) and has been undertaken from the perspective of the fluvial geomorphologist interested in explaining river processes and fluvial geomorphology at a variety of time scales. There is a much larger body of university research, however, which, although relevant to the present concerns, is rather less directly related to fluvial sediment problems so just a sampling of this work will be outlined here.

This selective inventory includes only very recently completed or ongoing work and is organized by type of research as follows: (A) physics of sediment entrainment and transport studies; (B) measurement techniques and instrumentation; (C) geomorphology and sediment transport; (D) contemporary sediment budget studies; (E) Holocene sediment budget studies; (F) regional analyses of suspended-sediment yields; and (G) other related research; (some studies are multifaceted research contributions and warrant cross-listing among the research types).

The Research Inventory

(A) Physics of sediment entrainment and transport measurement

The physics of sediment/flow interaction remains poorly understood and this group of studies addresses some of the unresolved problems in relation to the science of sediment entrainment and suspension.

(a) A flume study of gravel entrainment (Mike Church/John Wolcott; U.B.C.)

The classical approach to sediment entrainment assumes that individual grains are isolated and constrained only by their inertia. This laboratory study demonstrates that this assumption is untenable because it ignores the structural arrangement of stones which is shown to be fundamental in understanding bed stability, entrainment, and bedload transport rates (Wolcott, 1990).

(b) Intermittent suspension processes (Mike Church/Michel Lapointe, U.B.C.)

Fine sediments (sands and finer) are entrained directly into suspension and the key to understanding this process is the role of turbulence. This study examines fluctuations in velocity and sediment concentration (using an optical back-scatter probe) above an active dune bed of the lower Fraser River, near Mission (Lapointe, 1990).

(c) Magnetic and radiotracer study of sediment dispersion (Mike Church & Marwan Hassan, U.B.C.)

With the aid of magnetic and radiotracer tagging, this study aims to describe the statistical properties of grain movements of some 1000 stones in Carnation and Harris Creeks. These data will allow specification of travel distance, an important component of survey-based estimates of transport rates. In addition, this study is concerned with the effect of bed morphology and sediment structures on transport rates.

(d) Bedload transport measurements, Harris Creek (Mike Church, K. Fetcher, Marwan Hassan, and John Wolcott, U.B.C.)

At Harris Creek near Lumby, bedload transport is being measured directly during the seasonal snowmelt flood by accumulations in a series of pit traps in the channel bed. The principal focus of this study is to better understand the processes which control placer mineral deposition.

(B) Measurement techniques and instrumentation

Improvement of sediment transport information requires improved measurement techniques and this group of studies looks at a various indirect measurements as alternatives to the conventional (and not too reliable) methods.

(a) Optical back-scattering measurement of suspended-sediment concentration (Mike Church/Michel Lapointe, U.B.C.)

In this study an optical back-scatter probe has been tested successfully in the Fraser River to obtain continuous, high-resolution records of suspended-sediment concentration. The sensor is deployed on a submerged instrument platform designed for stable operation on a live sand bed (Lapointe, 1990)

(b) Flow structure as a basis for estimating suspended-sediment load in the Squamish River estuary (Ken Rood & Ted Hickin, S.F.U.)

Measurements of sediment concentration and calibre have been obtained in relation to flow structures (boils and ambient fluid) in Squamish River estuary. It is clear that most suspended sediment in the water column is transported in large eddies and it is hoped that these measurements, together with other data on frequency and size of these flow structures, will provide the basis for a new method for estimating the suspended-sediment transport rate (Rood and Hickin, 1989)

(c) Sand wave propagation, Fraser River (Mike Church & Ray Kostaschuk, U.B.C.)

In order to provide an independent measure of the bed load component of the sediment budget in the outer main arm of Fraser River, sand-wave propagation has been monitored (for the past three years) using serial echo sounder profiles. Initial results are consistent with other types of load measurement (Kostaschuk, Church and Luternauer, 1989)

(d) Continuous bedload measurement (K. Fletcher, U.B.C.)

K.Fletcher (Geological Sciences, U.B.C.) has under development a continuous weighing device for submerged use in field pit traps, which prospectively will be useful for measuring bedload transport and for studying intrusion of fine materials into gravels

(e) Aerial remote sensing of sediment plume characteristics (A. Roberts, S.F.U.)

Art Roberts conducts research into airborne sensing (aerial photography and multispectral video) of suspended-sediment concentration in river sediment-plumes, including that of the Fraser River. The research program has achieved considerable success in estimating suspended-sediment concentration (10-400 mg/l) from surface reflectance characteristics and present research is aimed at improving measurement performance further through in-flight sensor tuning based on simultaneous on-board image analysis (Liedtke,1988; Roberts and Liedtke, 1986; Liedtke, Roberts and Evans, 1986)

(f) Suspended-sediment rating curve analysis (Mike Church/M.P. Thompson, U.B.C.)

In this study the potential of improved suspended-sediment rating curve methods has been examined, resulting in the development of a general statistical model suitable for use on seasonally modulated rivers (such as the Fraser). Extension of these principles to bed load-sediment transport currently is being investigated (Thompson, 1988)

(C) Geomorphology and sediment transport

The net result of sediment transport is the modification of alluvial river morphology. If average transport distance and volume of sediment eroded/deposited per unit length of channel are known, then sediment transport can be calculated for the period between successive surveys. This provides a means to estimate sediment transport on time scales appropriate to the stability of the river and suitable for management requirements. Furthermore, it obviates the need for expensive, protracted (and, for bed load, notoriously difficult) sampling programs.

(a) Lower Fraser River sediment transport by bar survey (Mike Church/David McLean, U.B.C.)

David McLean has shown that this morphological method works extremely well in a retrospective analysis of the major Water

Survey of Canada measurement program on Fraser River between Hope and Mission (McLean and Mannerstrom, 1985; McLean, 1985;1990). The method is now being applied to Carnation Creek (in collaboration with Dan Hogan, British Columbia Ministry of Forests, and Leslie Powell, Federal Fisheries), a channel with a very different natural time scale, where direct measurements of transport distances are available.

(b) Squamish River sediment transport by bar survey (Ted Hickin/Henry Sichingabula, S.F.U.)

This study by Henry Sichingabula documents channel changes and mass transfers in the Squamish River over several decades based on sequential aerial photography of the channel boundary and bars. In addition to Provincial Government photography an important part of this record is low-level 35mm stereoscopic coverage obtained by the Remote Sensing Unit at S.F.U. (Sichingabula, 1986)

(c) Squamish River Estuary sediment transport by bathymetric-survey differencing (Ted Hickin, S.F.U.)

This study uses bathymetric differencing on the Squamish River delta to obtain a decades averaged estimate of total sediment transport for Squamish River at Squamish. Results are consistent with limited suspended-sediment measurements in the estuary and with similar long-term specific yields from other basins in the same region (Hickin, 1989).

(D) Contemporary sediment-budget studies

The culmination of sediment transport studies in rivers is the comprehensive sediment budget which accounts for sediment inputs, storage and outputs by river reach. Such budgets are being developed for the lower Fraser River at contemporary time scales (monthly to decade scale).

(a) Fraser River Estuary (Mike Church/Ray Kostaschuck, U.B.C.)

This study has concentrated to date on measuring suspended load and bed load flux over the tidal cycle, and mainly during the freshet, in the outer main arm of the Fraser River. The ultimate goal is to specify the sediment budget for this estuarine reach of channel.

(b) Lower Fraser River sediment transport by bar survey (Mike Church/David McLean, U.B.C.)

This study by David McLean, noted under C(a) above, constitutes a reach by reach sediment budget for the lower Fraser River based on a major field survey of channel changes over several years.

(E) Holocene sediment budget studies

Sediment budgets for far longer time scales than those noted above are relevant to the present concerns about management because they provide a long-term context in which to evaluate short-term fluctuations in the contemporary rates of sediment transport in our rivers. These studies have been conducted by geomorphologists interested in rates of erosion and sedimentation in basins during the last 10 000 years (since deglaciation).

(a) Fraser River delta (Mike Roberts/Harry Williams/Harry Jol, S.F.U.)

This study has documented the internal architecture of the Fraser River delta from extensive shallow seismic and drilling surveys over several years. These data together with radiocarbon and tephra based dating control provide the basis for a model of delta growth (and rate of sedimentation/transport) during the last 6000 years (Jol, 1988; Williams, 1988; Williams and Roberts, 1989).

(b) Squamish River (Ted Hickin/Greg Brooks, S.F.U.)

Greg Brooks has completed a detailed field survey of fluvial sediment sources in the upper Squamish River basin and is using extensive radiocarbon dating control to construct a history of sediment delivery to the Squamish River during the Holocene. Initial results indicate very important discrete non-glacial sediment supply events dominate the character of the present river (Brooks, 1990).

(c) Lillooet River (Olav Slaymaker/ Mike Bovis/Peter Jordan, U.B.C.)

Peter Jordan and Olav Slaymaker have used field surveys and process-based estimates to construct an order-of-magnitude Holocene sediment budget for Lillooet basin. Their results point to the occurrence of large unidentified sediment inputs, possibly catastrophic and massive slope failures (Jordan and Slaymaker, 1990).

(d) Sediment yield, Kwoiek Basin (Olav Slaymaker/Catherine Souch, U.B.C.)

This study makes use of a Holocene lacustrine sediment column to estimate local sediment yield/transport rates in a basin in the Coast Mountains (Souch, 1990).

(F) Regional analyses of suspended-sediment yields

Regionalization of sediment-yield data for British Columbia has been undertaken in order to elicit geographic patterns and point to possible environmental controls. Such regionalization also is useful as a guide to yields in unmeasured basins (that is, most of them!).

(a) Regional sediment-yield studies (Mike Church & Olav Slaymaker, U.B.C.)

The general pattern of sediment yield for the Province has been determined using Water Survey of Canada archives. Surprisingly, specific sediment yield increases downstream in most rivers, indicating that most sediment in our rivers comes from the river banks and not from the land surface. This likely is a consequence of Pleistocene glaciation which has left valley glacial sediments as the main source of sediment (Slaymaker, 1987; Church and Slaymaker, 1989; Church, Kellerhals and Day, 1989)

(b) Regional sediment-yield studies (Ted Hickin/Henry Sichingabula, S.F.U.)

This three-year study by Henry Sichingabula has just begun and is designed to further elucidate the geography of fluvial sediment yield in the Province as well as address questions about the temporal scales of sediment yield variation in particular basins.

(G) Other related research

To the extent that alluvial river morphology is an expression of erosion and deposition of sediment, a great deal of University research could be assigned to this category. It might be more useful (and certainly more manageable), however, simply to note a few examples in conclusion.

Mike Church (U.B.C.) and his collaborators (including Rolf Kellerhals, Mike Miles and Ken Rood) have several rivers under long term observation. These rivers were selected because changes underway as a result of engineering works can be interpreted as field experiments on the effects of regime change. These include Peace River below Bennett Dam (since 1967); Kemano and Nechako Rivers (retrospectively since 1952 using air photography) and Bella Coola River.

A number of studies on within-channel and overbank sedimentation of suspended fines has been undertaken by Ted Hickin in collaboration with Gary Brierley (S.F.U.) on Squamish, Fort Nelson and Muskwa Rivers. Detailed facies-based inventories of floodplain sediments are an important record of sediment storage and potential sediment sources as rivers rework their older floodplain sediments. Similar inventories have been established by U.B.C. geomorphologists for Bella Coola River (Desloges and Church, 1987) and by S.F.U. geomporphologists for the lower Fraser floodplain (Morningstar, 1988).

Allen Gottesfeld (U.B.C.) is studying trends of alluvial sedimentation during the last 250 years on a transect across the Coast Mountains into the Interior Plateau in the Skeena, Nass and Stikine drainage basins. From his dendrochronological analysis of floodplain and terrrace forests he has been able to recognize a more active fluvial phase in the late 18th and early 19th centuries when active braiding and aggradation occurred in many reaches in response to increased runoff during the 'Little Ice Age' climatic excursion of the 17th to 19th centuries.

The lateral migration (and thus eroded sediment production) characteristics of a large group of British Columbian and Albertan Rivers has been studied by Ted Hickin and Gerald Nanson (S.F.U.). Suspended-sediment load and sediment residence time are closely related to the level of channel migration activity.

Another project directed by Mike Church (U.B.C.) aims to improve our understanding of the hydrologic behaviour of river basins by examining the links between runoff, source areas, and stream chemistry and sediment in four basins with contrasting landuse. In cooperation with the Water Quality Branch of the Inland Waters Directorate, and with the initiative of John Zeman, the work in one of these basins (Similkameen River) is being developed to emphasize the critical importance of hydrological factors in the setting of water quality guidelines and in pursuing realistic water quality objectives. Fe, Cu, Zn and cyanide concentrations regularly exceed CCREM guidelines in Similkameen River, especially at high flows in association with high suspended-sediment concentrations.

Deltaic sediments represent a major sink for river sediment and the flood-related silt/sand rythmites in the Fraser, Squamish and Indian River deltas are the subject of a comparative sedimentological study currently in progress (Ted Hickin, S.F.U.). The work on the Squamish River is being done in conjunction with a drilling program designed to specify the rate of delta progradation (and therefore, sediment transport/deposition rate) during the last few thousand years. Early returns suggest that the contemporary rate is representative of the average rate for the last 650 years.

Fluvial sedimentation rates on a number of B.C. coastal river deltas (including Fraser, Squamish and Nanaimo) have been monitored for several years by wetland ecologists Ian Hutchinson and Susan Smythe (S.F.U.) and turbidity and suspended sediment measurements in local deltaic waters have been measured by biologist Larry Albright (S.F.U.) as part of his study of photosynthesis efficiency in wetland environments.

Under the direction of Mike Church, U.B.C. students have conducted a range of applied studies of channel morphology, gravel quality, major sedimentation episodes, debris jams and their role in mediating sediment transport in small coastal streams, in support of aquatic habitat studies. The work has mainly been done in the federal/provincial Fish/Forestry Interaction Program in the Queen Charlotte Islands. A current project is to develop practical survey methods to describe a 'disaggregated hydraulic geometry' which preserves measures of stream variability in depth and velocity. These measures are of interest in habitat evaluations.

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3. ENGINEERING SESSION

3.1 Civil Engineering Aspects: An Overview

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A wide range of sediment problems affect many different civil engineering works in B.C. A comprehensive review of Water Survey of Canada's sediment data collection program in B.C. is available in Church et al. (1985), which addresses the various engineering aspects in considerable detail. In this present overview, the main sediment issues related to civil engineering are discussed in roughly the historical order by which they became active concerns in B.C. Comments emphasize those issues not covered by later speakers in this session and aspects of sedimentation that appear to be particular to B.C. and to the Yukon or aspects for which improved approaches can be suggested.

1) Navigation: The effects of sediment deposition on navigation in estuarine river mouths, and particularly in the lower Fraser River has been one of the two issues behind the first sediment collection efforts in B.C. The initial objective of predicting the annual dredging needs early enough for budget planning has proven unobtainable, but the data are now quite invaluable for general management and planning along the lower Fraser (design of training works, borrow dredging, gravel mining, etc.). The latest of a long series of planning studies is Fraser et al. (1986).

2) Flow regulation for fisheries management: Qualicum River flows were regulated with a dam and elaborate outlet works on Horne Lake for the primary purpose of improving fishery values downstream. Sedimentation problems such as the degradation of the spawning gravels due to deposition of fines and lack of gravel cleaning by major floods, also vegetation encroachment onto the gravel bars, reduce the effectiveness of the project. With the benefit of hindsight it is obvious now that a better understanding of fluvial processes would have led to a different, less intrusive project design (Fraser et al., 1983).

3) Reservoir sedimentation: Concern over the life expectancy of reservoirs planned for the Fraser River and Columbia River is the second issue behind the start of systematic suspended sediment collection in B.C. in 1965. With the benefit of 23 years of data it is now clear that the reservoir life concerns were generally not justified and some of the data collection may have been an overkill. Significant reservoir sedimentation problems can, however, occur and have been identified in two hydro-electric project studies: the Kootenay River diversion would probably turn Columbia Lake into a large, deltaic marsh over a period of less than 200 years (Galay et al., 1983) and an impoundment of the Peace River with a dam at the Alberta border might be filled in remarkably quickly by the suspended load of the Beatton River (BC Hydro and Power Authority, 1976). Upstream aggradation due to delta growth into reservoirs is another, related problem of

significance at several sites in B.C. An up-to-date analysis of sediment yield in B.C. is given in Church et al. (1989).

4) River channel modifications: Dikes, highways, railways and pipelines often interfere with river channels and the associated flood plains through encroachments, temporary or permanent diversions, and channelisation. Steep gradient and large gravel bed loads make B.C. and Yukon rivers more unstable laterally than what one commonly sees elsewhere in North America. Channel modifications should not be designed just for the river as it appears at the time the project is being developed, but for all reasonable likely river alignments of morphological process rates which are normally obtainable from a review of the historic air photo sequence. From forty to eighty years of coverage is available anywhere in Canada.

5) Water intakes: The design of effective water intakes on streams with significant gravel bed loads requires a good understanding of the local bed load transport process and of the probable morphological evolution of the river in the vicinity of the intake site.

6) Hydrological hazards: The extent and diversity of the hydrological hazards affecting many developments in B.C. and in the Yukon are only beginning to be recognized. Sediment plays a role in several important hazard categories such as debris flows, flooding on alluvial fans, avulsions on fans and deltas and flooding upstream of alluvial fans blocking major valleys. Kellerhals and Church (1990) provides a recent discussion of fan management problems in B.C.

7) Environmental assessments: The environmental assessment of various engineering works is rapidly becoming a major part of most river engineer's daily work. Unfortunately, it is often not time well spent, because most B.C. projects are still designed with little or no attention to environmental aspects. Once the design is completed, the project is assessed by an environmental consultant and, depending on his/her findings, some mitigation or compensation is designed and tacked onto the project. Often enough the matter could have been resolved at the project development stage for a fraction of the overall cost. Another major environmental problem in B.C. is the overemphasis on fish at the expense of all other environmental matters, because only fisheries has a reasonably effective regulatory framework.

Due to the undeveloped, laterally unstable nature of many rivers in B.C. and in the Yukon, environmental assessments should look not only at the impact of a project on the present river, but also on the presently active fluvial processes. It is ongoing fluvial processes such as bank erosion, meander cutoffs, delta progradation, etc., that assure the long-term persistence of certain fluvial habitats (Kellerhals et al., 1987). The monitoring of environmental mitigation works is often sadly lacking, at least from an engineering point of view. Boulders are placed in rivers and much effort is expended to see whether fish use the newly created habitat, but whether the boulders are likely to remain in place for more than a few years does not appear to generate much interest.

Hydro-electric projects affect downstream flow and sediment regimes. Complicated interactions of erosion, deposition and tributary inputs often make it difficult to predict even the relatively straight-forward effects on downstream sediment loads. The more important impacts on the fluvial morphology are far more difficult to estimate. Kellerhals (1987) and Kellerhals and Church (1989) summarize the present state of the art.

8) Design of fish habitat compensation: The implementation of a no-net-loss policy by the federal fisheries authorities (Dept. of Fisheries and Oceans, 1986) has created a new, entertaining endeavour for river engineers - the design of compensation fish habitat. It often involves trying to build what generations of engineers have strived to eliminate, e.g. log jams, unstable channels, marshes, flood plains, scour holes, etc. Sedimentation and erosion are major considerations in most of these designs. Excavated side and back channels, embayments, and tidal marshes should not fill in quickly and riparian structures need to withstand floods. Re-establishing spawning beds reliably remains a challenge for which there is no solution in sight. Flexible, long-term monitoring studies are essential for the development of more effective designs (Kellerhals et al., 1987).

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3.2 Engineering Aspects for Development on Alluvial Deltas

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Alluvial deltas are sediment masses deposited by rivers in lakes and oceans. The variety of physical conditions and engineering properties which can be encountered on deltas reflect the numerous factors playing a part in the delta building process. The formation, shape and structure of a delta are affected by many factors including those associated with the river such as river discharge, sediment discharge, and grain-size distribution; and factors associated with receiving water such as bathymetry, water level fluctuations, wave climate and currents. Deltas may also be pre or post-glacial formations with substantially different soil strengths being developed in each case.

Sediment properties may vary widely both laterally and vertically on a development site, requiring careful geotechnical sub-surface investigations to delineate the stratigraphy and sediment properties.

River deltas attract development - either for agricultural use because of the availability of fertile soils, or for industrial and residential developments because of the relative ease of construction and serviceability. Proximity to water for potable or industrial uses, access to deep sea transportation, ease of excavation, and flat slopes are but a few of the attractive features. The scale of development may range from a few homes located on a small delta formed on the shore of a steep walled inlet to an industrial complex located adjacent to a metropolitan area. Engineering concerns are generally common to both the large and small developments, although the level of acceptable risk may be greater for small developments.

The engineering aspects for development on alluvial deltas are basically concerned with stability of structures and safety of occupants. Both the static and dynamic stability of structures require investigation and design.

Static stability resulting from shear failure along a classic slip circle is generally a concern for heavy structures, such as breakwaters, constructed on steep forest slopes. Locating the structure more shoreward or loading the toe of the slope with fill are common solutions to preclude shear failures.

Of significant concern in static design are problems which may arise from total or differential settlement resulting from the consolidation of underlying soils. Mature deltas which have had the opportunity to prograde and develop flat slopes are characteristically comprised of deep layers of compressible silts, clays and/or peat which require careful foundation design to manage settlement. Typical design solutions include preloading the surface to consolidate the soil; excavation and reloading; pile foundations, and raft foundations.

Dynamic stability is likely the single most important aspect of engineering on deltaic sediments. In a broad sense the dynamic aspect of stability is associated with time-dependent loading, either due to seismic events, waves, or currents. Seismic events and/or waves may induce the phenomena of liquefaction in which the soil mass loses strength and acts as a liquid. Loose, fully saturated silts and sands, which are typical of many delta sediments, are particularly prone to liquefaction. The load applied by seismic or water wave is short compared to the time required to dissipate the pore pressure within the sediment, resulting in excessive pore pressures and sudden loss of soil strength.

The results of liquefaction may include submarine slides, floating of buried pipelines, and loss of foundation bearing strength with subsequent foundation failures. Densification of underlying soils, removal of silt layers, and/or the placement of select backfill are some of the methods used to preclude liquefaction-related failures.

Perhaps more familiar to river and coastal engineers are the aspects of dynamic stability related to erosive processes. An understanding of the local geomorphology forms a background to developing potential solutions to natural causes of erosion. Interrupting the supply of sediments or modifying current or wave patterns are two common factors which lead to erosion. Erosion control methods vary widely from artificially supplying deficient sediment to armouring banks or modifying currents.

Sedimentation and aggradation are also important aspects to consider in engineering design. Sedimentation is potentially problematic at water intakes or drainage outlets, or in harbours and navigation channels. Aggradation may result in channel avulsions or increased river bed levels with the attendant exposure to increased flood levels.

Finally, any developments on deltas must be cognizant of ground water and flood levels. Ground water levels are critical with respect to drainage and foundation designs and flood levels are critical with respect to damage costs and safety. Many deltas are exposed to the dual threat of floods from high river levels and high lake or ocean levels. Tsunamis and rising sea levels are also factors to be considered.

During the presentation examples of these various engineering aspects are drawn from the Fraser River and Bear River deltas - representing mature and immature deltas, respectively.

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3.3 Floodplain Management and Sedimentation Processes

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The concept of floodplain management has been well established in British Columbia since the early 1970s. The general objective could be expressed as reaching a rational basis for man's use of floodplain lands, in harmony with natural processes and without undue risk to man-made structures. This goal is affected through regulation of subdivision of lands within the 1:200 year floodplain by the Water Management Branch and also by implementation of local building bylaws.

In many stable alluvial systems appropriate floodwater surface profiles can be computed, and expectations of river erosion and migration can be established from erosional history, to form the basis of floodplain regulations. An example is presented of the Nicola River in the central interior of British Columbia where examination of historical mapping and aerial photography established erosional trends over the past 100 years or so within a meander "corridor" of the river's floodplain (McMullen, 1983). By contrast, areas of sediment accumulation pose special problems because of adverse effects on lateral channel stability as well as flood levels. The Chilliwack/Vedder River alluvial fan, located about 80 km east of Vancouver presents a graphic case history illustrating this point.

The Chilliwack River drains a basin of about 1250 km^2 before debouching onto its fan, flowing through the Vedder River to join the Fraser River. Stream flows range from minimums of less than 20 m^3/s in the early fall to flashy peaks of up to 856 m^3/s instantaneous (Dec. 26, 1980) due to intense winter rainfall. Lesser secondary annual peaks occur due to spring snowmelt (WSC Sta. 08MH001 1911-1931, 1951-date). The river has a long history of flooding and floodplain management problems such as on Dec. 3, 1975, when flooding necessitated payment of about $700,000 for flood damage relief. The cause of problems is directly related to high stream flows and sediment deposition; the answer was the construction in the late 1970s of a comprehensive system of setback dykes under a federal/provincial cost-sharing program.

Because of the flooding problem, coupled with a valuable fishery resource and proximity to historically developed areas, the Chilliwack River has been well studied at various times. This has ranged from morphological studies (IPSF Commission, 1977; McLean, 1980), hydraulic and flooding studies (WIB Report, 1978; WCHL Ltd., 1977), sediment sampling and stream gauging (Environment Canada 1972; 1976), to an ongoing program of bed monitoring surveys.

The geomorphic fan limit occupies some 3500 ha containing numerous remnants of previous channels now expressed as local drainages and ground depressions. The fan was subject to at least one major channel avulsion within historical times when the former Chilliwack River channel overflowed its banks in 1876 and occupied the previous bed of Vedder Creek (draining into what was then Sumas Lake). An estimated 3 000 000 m^3 of scour occurred to form the new channel. Historical records abound with references to works and efforts to ensure that the river stayed in the new channel. The situation was complicated in 1923 when Sumas Lake was drained and dykes built to contain river flows through the Vedder Canal to the Fraser River.

Evidence of granular bedload build-up in the present river channel included a rise in the WSC gauge of about one metre over the period 1954 to 1975. Suspended sediment sampling and bedload sampling (using 1/2 VUV and Basket samplers) by Water Survey of Canada in the early 1970s indicated a suspended sediment load of about 535 000 tonnes in 1975 with 10 400 tonnes of bedload during an annual discharge of about 2.57×10^6 dam^3. Most of this occurred during the then record period instantaneous discharge of 787 m^3/s in December, 1975, resulting in an estimated 200 000 m^3 deposition on the fan.

Studies related to the design of flood control works (WCHL Ltd., 1977) calculated a mean annual accumulation on the fan of about 50 000 m^3, causing an average annual bed increase of 0.05 m. Infrequent, large floods deposit up to 200 000 m^3 in single events relating to an average bed increase of about 0.2 m through the bridge reach.

In the late 1970s, comprehensive flood protection was implemented in several stages including excavation of over 500 000 m^3 of gravel and construction of 7 500 m of setback dykes at a total cost of about $400,000. In addition, land was required to establish a management area between the dykes. The Vedder River Management Area comprises a 325 ha corridor of active river channel and floodplain. A management committee with representation form Water Management Branch, local authorities, parks and recreation, and fisheries meets to coordinate usage of the area (VRM Committee, 1983).

Within the management area, side-channels provide habitat for steelhead, coho, pinks, chum and cutthroat trout; islands provide habitat for wildlife including blue herons; recreationists include fishermen and campers; and some land is leased for agricultural purposes. Flood control maintenance includes monitoring of sediment accumulation by successive surveys. The Vedder River Management Area is perhaps a model demonstrating cooperation between sometimes conflicting interests of environmental preservation, recreational opportunity and development of flood threatened lands. In many respects the problem of flooding and sedimentation has necessitated a cooperative venture of mutual benefit to all concerned parties.

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3.4 Debris Flows and Their Influence on the Sediment Regime of Rivers in the Coast Mountains

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A debris flow is the rapid downslope movement of a saturated slurry of soil, stones, and other material such as organic fragments. Debris flows are amongst the most common mass movement and sediment transporting processes operating in mountainous terrain. In northwestern North America, the term "debris torrent" has been applied to debris flows consisting of non-cohesive, predominantly coarse debris, often containing a high proportion of organic material, which is confined in a steep channel (Swanston and Swanson, 1976). Debris flows of this nature are frequent in small, steep watersheds in the Coast Mountains of British Columbia; however, their importance as natural hazards, and as agents of erosion and sediment delivery, has only been appreciated in the last 15 years.

The nature and properties of debris flows have been reviewed by Costa (1984) and by Van Dine (1985). Debris flows are most frequently initiated during high-intensity rainstorms. In order for a debris flow to occur in a channel, sufficient debris which can be readily mobilized must be present in or adjacent to the channel. This debris commonly originates as shallow debris slides in overburden, or as rockfall. Debris torrent channels are steep, about 10-30°; consequently, debris torrents are usually limited to small watersheds, typically about 0.4 to 7 km^2. Debris flows can also be initiated by other means, such as outburst floods of ice, moraine, or landslide dammed lakes, liquefaction of landslide debris, and volcanic eruptions. Some such debris flows are larger, and occur on gentler slopes, than those of the more common "debris torrent" variety. In the Coast Mountains, recorded rainstorm-triggered debris flows have ranged in magnitude (volume of sediment delivered) from several thousand to about 60 000 m^3; however, debris flows of up to several million m^3 have originated from landslides in Quaternary volcanic rocks.

Most of the research on debris flows in British Columbia has concentrated on a few areas where they present a hazard to settlements or engineering works, most notably the Howe Sound and Fraser Valley-Coquihalla areas (for example, Hungr et al., 1984, and Church and Miles, 1987). Some recent work has been done on the role of debris flows as sediment sources for rivers, and on their effect on behavior of rivers during floods (Jordan, 1987). An inventory of the Squamish and Lillooet watersheds (combined area of 6900 km^2) found over 200 recently active debris flow channels. In these watersheds, debris flows act as an important link in routing sediment from active colluvial sources at high elevations to the valley bottom. Debris flows account for a large proportion of the watersheds. Most of the sediment, typically 75-90%, is bedload-calibre material.

The role of debris flows in delivering sediment to rivers depends on three main factors: the geometry of the valley bottom relative to the debris flow; the magnitude of debris flow events relative to the size, and sediment transporting capability, of the river; and the frequency of debris flows. Many debris flows deliver their sediment to the upper parts of alluvial fans, where it is stored for long periods, and is slowly reworked by fluvial activity. At relatively few locations, debris flows deliver sediment directly to river channels. In some cases, episodic sediment inputs from debris flows dominate the morphology of the river for some distance downstream.

Large debris flows which enter a river channel at a confined location can cause the river to aggrade and widen its channel downstream, as a result of the introduction of an unusual quantity of sediment. In extreme cases, a debris flow can totally block the flow of a river, leading to the risk of an outburst flood. Recognition of the potential hazard of such sediment delivery events is necessary in understanding the behavior of rivers during floods, and in designing engineering works such as bridges and dykes.

Several examples are presented in this paper in which debris flow events have had substantial impacts on the morphology and flood behavior of rivers. These include the 1984 debris flows on Turbid Creek in the Squamish River watershed, the 1984 flood and debris flow on the Ryan River near Pemberton, and several events along Meager Creek in the upper Lillooet River watershed.

Although a number of examples of debris flows and their effects on rivers have been described, quantitative information is scarce. Our understanding of the role of debris flows as sediment sources is limited both by the lack of sediment data for mountain rivers, and by a lack of information on the magnitude and frequency of debris flows, in all but a few locations.

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3.5 Morphologic Methods of Estimating Bed Load Transport

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The application of morphologic methods for estimating long term bed load transport rates on gravel bed rivers in British Columbia is discussed (McLean, 1990). The discussion is restricted to a particular class of engineering problems that are associated with the effect of sedimentation on flooding and channel instability or to general problems of river management related to assessing impacts of gravel mining or dredging on river regime.

In general terms, morphologic methods rely on using the observed patterns of channel change to provide quantitative information about bed load transport and sedimentation.

Two alternative variations are described. In the simplest case, a sediment budget can be used to assess long term transport rates. This approach requires volumetric information (successive channel cross sections along the river) and a known boundary condition (for example, the incoming load to the reach) in order to provide actual long term sediment loads.

Bed load transport rates may also be estimated from historical channel changes determined from air photos or planimetric maps. This approach is more generally applicable than the former method since there is a substantial amount of historical data available in air photo and map libraries. However, the method requires some information on the characteristic "Step Lengths" for sediment movement between erosion and deposition sites along a channel.

Examples of these two methods are presented using data from Lower Fraser River between Hope and Mission. This study reach is unusual because there is a substantial amount of historical survey data available. Also, Water Survey of Canada has carried out a conventional bed load sampling program at Agassiz since 1967 using Basket samplers.

As a result, it is possible to compare the estimates from the various methods and assess their overall reliability and suitability.

It was concluded that the morphological methods were more reliable than conventional short term trap sampler measurements. Furthermore, it appears the morphologic methods will be the most practical methods that are available in most instances during engineering investigations. This is because the results are estimated over relatively long time scales (years or decades) which is comparable to the relevant time scales in most engineering problems.

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4. WATER QUALITY SESSION

4.1 Sediment and Water Quality

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This section of the workshop focuses on sediment as a water quality variable. Three aspects of importance of sediment as a water quality variable are discussed in this introduction: sediment as a moderator of water quality; sediment - flow relationships; and sediment scale effects. These three aspects serve only to highlight the role of sediment in determining water quality; other aspects are also important.

Sediment acts as a moderator of water quality through physical and chemical effects. These effects serve to modify the patterns of water quality that would exist in the absence of sediment. Physical effects such as transport, deposition, and remobilization act to move materials through a system. Chemical effects include simple and complex reactions centred on the preferential affinities of material such as organics and metals for sediments. The impact of sediment on water quality patterns results from inequalities of these processes (Vaughan, 1988).

Until recently, there has been no systematic classification of the relationships of sediment with flow. The typical responses of sediment to a flow event is a function of physiographic and hydrologic features. These events are observed at a variety of time scales: years, days, hours, minutes and even seconds (if we can measure at that scale). Williams (1989) proposes five classes of models:

Class 1 - Single valued-line concentration-discharge relationship
- 1A - linear
- 1B - Curve slope increasing with discharge
- 1C - Curve slope decreasing with discharge

Class 2 - Clockwise Loop concentration-discharge relationship

Class 3 - Counterclockwise loop concentration-discharge relationship

Class 4 - Single value plus loop relationship

Class 5 - Figure 8 concentration-discharge relationship

This classification system provides a basis for a more comprehensive understanding of sediment in relation to flow, enhancing our ability to understand the effects of sediment on water quality.

Temporal and spatial scale effects exist (Ongley, 1987). On a spatial basis, is the sediment delivery ratio (i.e. the amount exported compared to the amount generated in a basin) applicable to quality as well as sediment? What are the spatial scale effects of transport, deposition, and remobilization? How does the sediment delivery ratio apply to seasonal and storm phenomena? How continuous is downstream transport?

On a temporal basis, there is a need to determine the effects of lags caused by time of transport. Transit time effects may include physical, chemical and interactive effects. Artifacts may exist as a result of contemporary measurements.

Sediment is an important water quality variable. Studies of sediment in relation to water quality continue to need simplifying models to allow improvements in our ability to extrapolate to new situations. In considering the effects of sediment and water quality, caution continues to be the most powerful tool.

The papers in this session expand on these concepts as they relate to phenomena in the Paciic and Yukon region.

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4.2 Sediment-Related Water Quality Issues in the Yukon

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Introduction

The Yukon occupies 483 450 square kilometres of northwest Canada. The southern half of the territory (between 60 and 65 degrees north) is similar to adjacent northern British Columbia, consisting of an interior plateau between a massive range of coastal mountains (Saint Elias Mountains). Snow melt and glacier melt drive the annual discharge cycle and the transport of sediment in the rivers and larger streams.

The southern Yukon contains most of the population of 30 000, the infrastructure and industry. Mining and tourism are major industries, but the more traditional activities of hunting, trapping, fishing, logging, transportation and placer mining are important. Placer mining is the major human activity introducing sediments into streams and rivers.

Water Quality Data

Most of the water quality data on Yukon rivers have been collected by D.I.A.N.D. Water Resources and Water Survey of Canada D.O.E. Suspended sediment (total nonfilterable residue dried at 103-105 degrees C) is estimated in rivers and streams with one or more samples taken from the top one metre at one or more locations on the cross section at intervals through a study period. The data thus forms a time series which can be examined graphically. Two stations, the Yukon River at Carmacks and the Yukon River at Lewes River Dam have about ten years of data available.

Suspended Sediment and Discharge

Whitfield and Whitley (1986) examined the relationship of some water quality variables with discharge in the Yukon River basin. Suspended sediment was found to lead discharge through the annual discharge cycle. Graphs of suspended sediment plotted against discharge exhibited positive slope and clockwise hysteresis. Other variables showing similar behaviour were turbidity, colour, total iron, copper, zinc, manganese, and lead, extractable arsenic and total phosphorus. This behaviour of suspended sediments and related variables has been observed on other river systems (Whitfield and Schreier, 1981).

Suspended solids in rivers draining glaciers can exhibit complex behaviour during glacial melt (Bryan 1972). Glacial systems in the Yukon have not been well studied. A major impediment is the difficulty of measuring discharge in glacial rivers.

The relationships between suspended solids and discharge was studied in small forested watersheds in Australia by Rieger and Olive (1985). Twenty storm events were sampled on five watersheds and 39 individual storm hydrographs were examined. Single rise storm events with a sediment lead made up 23% of the hydrographs. Other patterns made up the remaining hydrographs. No identifiable pattern was the largest single group. Data for a similar analysis in the Yukon have not been collected. The behaviour of Yukon streams small enough to respond to single storm events could be quite different from the rivers that have been examined.

Placer Mining

Placer mining is an important industry in the Yukon and northern British Columbia. Surficial materials are washed through a sluicebox into a settling pond. Water from the settling pond flows back into the stream. Discharge and suspended solids data for placer mined streams are difficult to obtain. The major impediment is the lack of discharge data. A study in Alaska compared water quality in mined and unmined streams. The background stream exhibited a significant positive correlation between iron and discharge while the mined streams did not. The variation in turbidity and total residue was very large for the mined streams and no significant correlations were found between these two constituents and other physical or water quality characteristics. On one mined stream, total residues increased from an average of 111 mg/l before mining began to 1126 mg/L. Settlable solids increased from undetectable to a high of 3.5 mL/L. (Bjerklie and LaPerriere, 1985). These results suggest that the relationships observed on the Yukon Basin rivers do not apply to actively placer mined streams.

Placer mining disturbs materials which have been buried for considerable periods of time and may result in the release of heavy metals into streams. LaPerriere et al. (1985) found that total arsenic, lead, zinc and copper and dissolved arsenic and zinc were significantly higher in some Alaskan streams below active placer mining sites than in those that were not being mined or those that had never been mined.

Environcon Limited (1986) studied sedimentation from Yukon placer mining operations and found that most of the sediment in the main receiving streams originated from active placer mines in the watershed. Suspended solids concentrations and suspended sediment loadings were observed to vary in response to mining operations. The magnitudes of these parameters typically increased immediately below industrial inputs and then decreased downstream. The rate of decrease was dependent upon dilution, stream velocity and the length of stream over which the suspended material could settle.

Conclusion

Time series of suspended sediment and discharge data are becoming available for rivers in the Yukon. Visual examination of plotted data can provide information about the processes at work. Glacially fed, active placer and small streams may not exhibit the same relationships between suspended solids and discharge as larger interior streams and rivers. Suitable data are needed for representative streams.

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4.3 Sampling Organic Contaminants in Sediments From the Vicinity of Inland Pulp Mills

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Bed sediments, along with fish, were used to identify areas contaminated by organic compounds, specifically dioxins and furans, in the vicinity of inland pulp mills in B.C.

Because of concerns about dioxin and furan contamination from bleached pulp and paper mills, Environment Canada and the Department of Fisheries and Oceans began a program in January 1988 to sample for dioxins and furans in the vicinity of pulp and paper mills in B.C. The main purpose of this program was to measure levels of dioxins and furans in sediments and biota from the vicinity of the mills and to identify areas of contamination. Environment Canada had the responsibility of sampling the inland mills. The study on the inland mills is documented in the report by Mah et al. (1989) and this is the work that will be discussed in this paper.

Sediment was selected as one of the sampling substrates because:

- hydrophobic compounds such as dioxins and furans are not very soluble in water and are therefore likely to be sorbed onto sediments and be present at higher concentrations in the sediments than in the water;

- sediments can integrate contaminants in the aquatic environment over a period of time.

Bed sediments were sampled in the spring of 1988 from the vicinity of the ten inland pulp mills shown in Figure 4.3. Sampling was conducted in the pre-freshet period to minimize the expected loss of deposited fine sediments with their associated organic contaminants during high flow.

Three sediment samples were collected upstream and downstream of the pulp mills. Sites selected were those where the deposition of fine sediments was expected. As fish and sediments were collected from approximately the same location, upstream sampling was conducted as far upstream as was judged reasonable to decrease the likelihood of fish swimming to areas affected by the pulp mill discharges. Downstream sites were located as close as possible to the discharge. Each sample consisted of at least three grabs; only the top few centimetres were used for the sample. The sediments were analysed for the following: particle size, moisture content, total organic carbon, dioxins and furans.

The analytical results showed that sediments at most upstream sites had undetectable levels of dioxins and furans. The exceptions were two sites upstream of the pulp mills at Quesnel on the Fraser. These sites were, however, approximately 130 km upstream of the pulp mills at Prince George. The majority of sediments collected downstream of the mills showed detectable concentrations of furans only, specifically, 2, 3, 7, 8 tetrachlorodibenzofuran (T4CDF) and total T4CDF (with concentrations ranging from less than detection limit (10 pg/g) to 4521 pg/g). The two

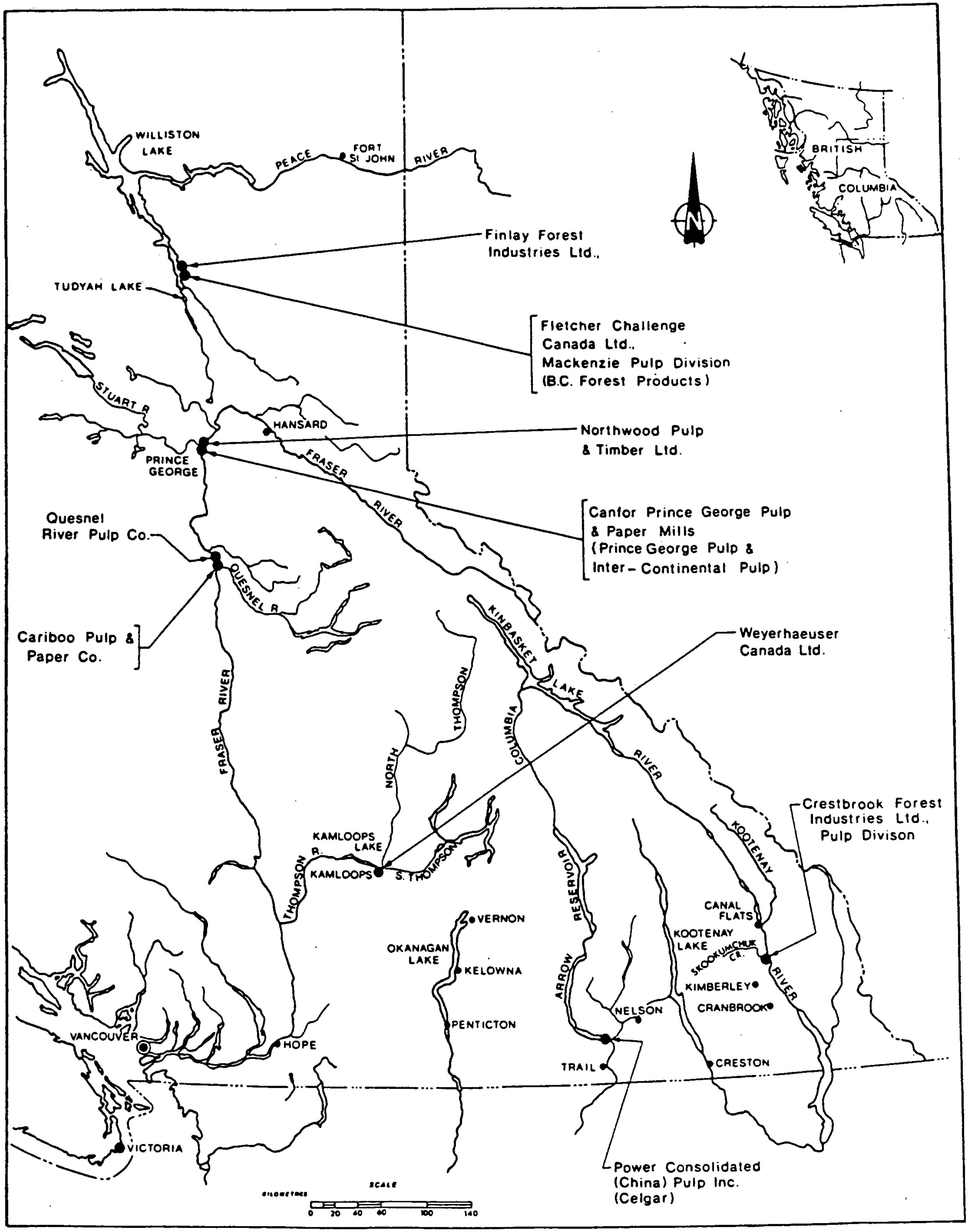

Figure 4.3 Locations of Ten Pulp Mill Areas Studied

sites on Williston Lake, also showed levels of other congener groups of dioxins and furans. The concentration of T4CDF in the downstream sediments did not show a statistically significant relationship to either percent fines (silt plus clay) or organic carbon content.

In conclusion, bed sediments collected downstream of inland pulp mills served as indicators of furan, and in some cases, dioxin contamination in the aquatic environment.

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4.4 The Use of Sediment in Impact Evaluation of the Mining Industry

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Sediments have long been recognized for their ability to adsorb toxic chemicals. The integration of toxic chemicals in the sediment allows one to determine impact even if the survey is not performed during pollution events. The sediment study approach gives more flexibility to infrequent surveys without compromising on the information value of such a study. The impact assessment is based on three components: the extent of contamination, the toxicity, and the benthic community alterations. This approach has been proposed by Chapman (1986) with the sediment quality Triad. The "Procedure for the Assessment of Contaminated Sediment Problems in the Great Lakes" proposed by the IJC (1988) also used this tiered approach.

Determination of the Degree of Contamination

The first consideration in evaluating the impact, using sediment chemical analysis, is to determine the level of contamination of sediments downstream of the mining project. The first step is to determine the pre-operation level in the sediments. This can be determined by the analysis of metal levels in the sediment prior to the development of the industry. In several cases this is not possible and therefore other techniques have to be implemented. Since lake sediments are deposited layer by layer over the year, providing that the sampling station is located in a depositional area, the deep section of the cores are older and reflect the baseline conditions. The depth at which sediment concentrations can be considered as baseline depends on the sedimentation rate and diagenesis factors. The sedimentation rate can be determined by traps or radionuclear markers. In rivers the baseline levels can be determined by sediment concentrations in the upstream control station, or by analysis of the chemical make-up of the larger fraction size sediment such as the coarse sand fraction (2-4 mm).

The degree of contamination is obtained by evaluating the chemical composition of recently deposited sediments. The ratio between the recently deposited sediment and the baseline express how extensive the contamination has been. Recent sediments are obtained in the lake either by sediment traps, or by scooping using an Eckman dredge. Core samples can also demonstrate the progression of the contamination over the years. Recent sediments in river systems should be collected during low flows from depositional areas. Sediment traps can also be used.

Determination of Bioavailability

The establishment of a level of contamination alone in sediments is not sufficient to evaluate impact, since it does not address the interaction between metals and organisms. Further information can be derived either by sediment bioassay or by metal partitioning.

The sediment bioassays procedures use either a sediment extract or expose the whole sediment to invertebrates for colonisation. Extractions used for bioassays are not standard at this point and vary from using sediment pore water to using organic solvents. These bioassays use bacteria, algae, zooplankton, insect larvae or fish as test organisms. The most common bioassay response is the LC50, but chronic, behavioural and enzymatic inhibition also has been used.

The speciation of the trace metals in the sediments affects their bioavailability. The sediment are subject to weak extraction for removing the adsorbed metals to strong extractions expressing the residual fraction or silicate matrix. These extractions when performed in sequence constitute a gradient of metal-sediment interaction.

Determination of Benthic Community Alterations

Benthic invertebrates are used in assessing the degree of alteration in the benthic community. It is important to evaluate how the in-situ community responds to increased metal concentration and metal bioavailability. Benthic communities are analysed in the traditional way by grab samples or replicate samples collected from artificial substrates. Each sample is screened to a specified mesh size and preserved for taxonomical identification and enumeration. Data interpretation include techniques such as density, species composition, tolerance groups, and diversity indices.

Determination of Impact

Based on the information generated, the quality of the sediment can be determined as to whether an alteration in community structure is due to physical deterioration or whether contamination induced a degradation of the environment.

Traditionally, impact evaluation focused on the degree of contamination in the sediments. The Triad approach described by Chapman (1986) has the benefit of considering separate effects in a complementary fashion in order to evaluate the degree of environmental degradation.

Initial Impact Assessment of Goosly Lake Based on the Triad Approach

Equity Silver Mine Data

The mine started in 1980 extracting silver and gold from their operation. In 1982, Acid mine drainage (AMD) was discovered as releases from the waste rock reached the receiving waters. AMD spills usually occurred in spring and were observed in 1982, 84, 85, 86, and 89. The mine has generated 74 millions tonnes of waste rock and based on the 1987 pumping rate, produced 550 000 m3 of raw AMD. Raw AMD has a pH of 2.6 with 200 mg/L D.C_u, and 100 mg/L D.Zn. The mine is closing in 1992. The closing plan included the operation of a lime treatment plant to control metal releases in perpetuity.

Contamination Data

Except for chromium, most metals show a certain degree of surface contamination as demonstrated in the core profile. The most important metal contaminants in Goosly Lake are cadmium, lead and arsenic, based on the sediment core data. Mercury is also a metal of special interest due to its high toxicity. Copper released by the mine has been carefully controlled since high concentrations can be found in their acid rock leachate. The sediment data shows that copper has been successfully controlled.

Bioassay Data

The bioassay showed that the sediment did not release acutely toxic chemicals however, strong evidence of reproduction impairment (Ceriodaphnia test) were shown as well as genotoxic effects (Mutatox).

Sediment Extraction Data

Sediment extraction techniques showed that cadium was easily released from the 1987 and 1988 sediments. A major portion of other trace metals were included in the organic-sulphide fraction. Further refinement of the analytical procedures should allow separation of the organic fraction from the sulphide, since they have different biological implications even though they react the same to oxidants.

Benthic Invertebrates

Benthic invertebrates sampling failed to collect any sensitive species (no mayflies, caddisflies or stoneflies). Benthic invertebrates indices showed low diversity, and low richness. Invertebrate density at station 10 was especially low.

Future Perspectives

It seems that the sediment Triad approach has great potential as a screening tool for pollution studies. Relevant hypothesis can be derived from the results. It is important to perform a more detailed assessment in order to better determine the spatial and temporal extent of the contamination. Metal diagenesis and sedimentation rates should be evaluated. It is important to know if the metal will be embedded or remobilised as they reach the anoxic zone. Fish populations in Goosly Lake should be evaluated as for metal contamination, and for growth and reproduction status.

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4.5 Approaches to Sediment Quality Guidelines and Objectives

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Federal Perspective

Environment Canada has obligations under the Canadian Environmental Protection Act (CEPA) to define and publish environmental quality guidelines and standards, including those for sediments. In addition, CEPA includes the former Ocean Dumping Control Act, which specifies sediment quality criteria to evaluate ocean dumping activities. Through the Canadian Council of Ministers of the Environment (CCME), Environment Canada participates in development of environmental guidelines and related activities jointly with the Provinces and Territorial Government. One of these activities is clean-up of contaminated sites; nationally, the Water Quality Branch has been asked to take the lead in ranking, and developing assessment criteria and clean-up criteria for contaminated sites. The CCME has published a protocol for sediment quality guideline development.

Objectives and guidelines for sediment quality have not been extensively developed or used except for (1) managing ocean dumping and dredge disposal in a variety of areas, (2) managing contaminated sediment sites in the Puget Sound area (Puget Sound Water Quality Authority, 1987). However, sediment guidelines and objectives can be valuable to measure the quality of sediments, assess their potential effects on organisms, and to aid management decisions on activities affecting sediment quality in aquatic systems. Along with water quality objectives, ecosystem objectives and sediment objectives will be increasingly used to manage aquatic systems. The B.C. Ministry of Environment is developing sediment quality objectives and the CCME is planning development of Canadian Marine Sediment Quality Guidelines in the near future.

A number of major approaches have been used to develop sediment guidelines. Detailed technical reviews of these efforts have been published by Chapman (1989) and Persaud et al. (1989). In general terms, these include the background approach, the water quality guidelines approach, the water-sediment partitioning approach, the sediment toxicology approach, and the biological effects approach. In many cases, combinations of these approaches have been used.

The background approach samples concentrations of contaminants in sediments and selects concentrations considered acceptable; it does not allow prediction of the amount of protection afforded nor of the effects of exceedances over those guidelines.

The water quality guidelines approach uses existing guidelines on the interstitial water of sediment; it does not account for intake of sediments or contaminated food organisms by the biota living in the sediments.

The water-sediment partitioning approach calculates the concentrations to expect in sediments in equilibrium with water meeting water quality guidelines and uses those sediment concentrations as guidelines; again, this approach assumes the only exposure of the organisms in the sediment is via the interstitial or overlying water.

The sediment toxicology approach determines the effects of spiked or contaminated sediments on benthic organisms and determines a no-effect or acceptable effect level; this is a very useful approach but is expensive and time-consuming.

The biological effects approach examines the sediment's biota for biological abnormalities, changes in community structure or abundance, or other biological correlates of known levels of contamination in sediments. This is useful in dealing directly with biological effects, but must be interpreted carefully in case sediment characteristics other than the contaminant concentrations are the cause of the observed biological effects.

Combinations of several of the above approaches appear to be most useful in triangulating on guideline levels that will be protective of aquatic life but not overly restrictive. The Water Quality Objectives Division is considering defining sediment guidelines and objectives on the basis of toxicological information and biological effects information primarily, but also using background and contaminant partitioning information where it is available and applicable.

The definition of sediment quality guidelines using any of these approaches requires careful consideration of sediment characteristics over and above the degree of contamination with specific toxicants. The chemical composition of sediments, including the amount of organic matter, will greatly affect the partitioning of chemicals between sediments and water; the particle size and surface characteristics of sediments will also greatly influence the uptake of pollutants by adsorption. The particle size relative to the transport capacity in a water body will determine whether pollutants in sediments are in the suspended or deposited phases, which have different biological effects. The particle size and organic content of sediments are major determinants of the kinds of invertebrate animals found in bed sediments; thus biological differences from one sample to another cannot be ascribed to different concentrations of a toxicant without comparing or matching the two samples for sediment type.

Provincial Perspective

The B.C. Ministry of Environment (MOE) is establishing water quality objectives for high priority water basins throughout British Columbia (MOE, 1986). By definition, water quality consists of water, sediment, or biota, while objectives consist of numerical concentrations to protect the highest and best use of the water at a particular site (MOE, 1986). Objectives have been established for fresh and marine waters; however, objectives for the latter will not be included in this brief discussion due to the focus of this workshop.

Sediment quality objectives have been established for a number of freshwater systems in British Columbia. The first were for chlorophenols and PCBs in the Fraser River Estuary in 1985 (Swain and Homs, 1985), while objectives for metals in sediments in the Brunette River system were proposed in 1989 (Swain, 1989).

Direct toxicological data on the effect of these characteristics on biota, including bioconcentration and uptake are generally not available for sediments from freshwater systems in British Columbia. Therefore, the same general philosophy was used in these water bodies to establish the objectives. In both, the approximate concentration was determined for sites not under the direct influence of sources of these contaminants. This is not an easy assignment since contaminant concentrations in sediments are dependent on the particle gradation and organic content. This procedure has one built-in assumption based on toxicity; that the sediment concentrations at these unaffected sites are themselves not toxic to organisms which they may come into contact.

The sediment gradation for sediments collected in the Brunette River system was similar to those for samples from Kanaka Creek and the Pitt River above the Alouette River confluence. Both the Pitt River and Kanaka Creek samples would be considered as being relatively uncontaminated. Taking the higher value for these two sites and increasing these by about 20% to account for laboratory precision problems, the following values were established as objectives for the Brunette River system: maximum (dry-weight) values of 30 µg/g copper, 5.0 µg/g for lead, 0.07 µg/g for mercury, and 70 µg/g for zinc (Swain, 1989).

The establishment of objectives for chlorophenols and PCBs in the Fraser River Estuary was more difficult, since this large river is tidally influenced, and few data existed on other estuaries for these organics, especially when these objectives were first proposed, well over a half-decade ago. Therefore, with no ideal site nearby to use as a reference, existing levels in sediments from within the lower Fraser River were used to develop objectives. The values chosen were maxima (dry-weight) of 0.03 µg/g for PCBs and 0.01 for the sum of tri-, tetra-, and pentachlorophenol (Swain and Holms, 1985).

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5. FORESTRY SESSION

5.1 Introduction to the Forestry Session

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Of all the Sediment Issues Workshops held across Canada, this is the only one that has a forestry session. Questions and comments raised at the workshop illustrate WHY. Sediment production by forestry activities is a very real concern within public and resource management circles. The presentations in this session provide an insight into the sediment related research and management activities underway in British Columbia.

It is perhaps easy to come to quick or simplistic conclusions regarding forestry activities and sediment. However, it is good to bear in mind the comments made by Dr. Church in his summary of yesterday's presentations, "erosion and sedimentation are very complex physical processes". Add to this the political, economic and biological factors surrounding forestry and sedimentation, and things become very complex. Complex or not, the issue is central to integrated resource management, and has had the benefit of good research and management support. This will become clear in the three forestry presentations.

Focusing research and management effort on forestry sediment issues has been an integrated effort. An example is the Fish-Forestry Interaction Research Program (FFIP) that is addressing mass wasting in the Queen Charlotte Islands (Poulin, 1984). The program involves a broad spectrum of agencies at the technical and management level: B.C. Forest Service (BCFS); B.C. Ministry of the Environment (MOE); Council of Forest Industries (COFI); Department of Fisheries and Oceans (DFO); Forestry Canada (FC); Forest Engineering Institute of Canada (FERIC); and the University of British Columbia (UBC). The program also drew on private consultants and benefitted from public input. Extension of research results through publications, newsletters, fieldtrips and workshops has been an important aspect of FFIP. The program has led to changes in management procedures and land use practices.

Another example of integration is the Coastal Fisheries Forestry Guidelines (B.C. Ministry of Forests and Lands et al., 1987). The Guidelines identify practices to reduce erosion and sediment production, and were the product of a concerted effort by most of the organizations involved in FFIP. The Guidelines translate research results and operational experience into field level site specific guidelines.

The Watershed Workbook (Wilford, 1987) is a tool to address watershed level or cumulative effects issues surrounding stream channel integrity. Again, the Workbook evolved under the direction of a technical and steering committee composed of most of the organizations involved in FFIP.

An integrated/interdisciplinary approach to sediment issues was perhaps engendered by the Carnation Creek Experimental Watershed that was initiated in 1970 (Narver, 1982). Many of the active "players" in the forestry sediment issue either did field work in the watershed or have been involved in the numerous Carnation Creek Workshops (Hartman, 1982; Chamberlin, 1987). The ten year review workshop of the Carnation Creek Program provided the focal point for the initiation of the Coastal Forestry Fisheries Guidelines.

Experience with forestry sediment issues in British Columbia highlights that integration of agencies is the only path to successful resolution. Integrating agencies develops an interdisciplinary approach. Since no individual has the "total picture" it only makes sense when addressing "complex problems" to share different points of view and expertise. A good illustration is the three speakers in this session: an engineering geologist/geomorphologist who has worked for both the forest industry and the BCFS; a fluvial geomorphologist who has been one of the pioneers in small coastal stream geomorphology; and a forest hydrologist who has worked for DFO and the BCFS, and has a background in biology, teaching and logging. It is important to highlight the logging background - since any plans will fail if the "implementors" are not involved in the process, the interdisciplinary approach used in B.C. includes management and logging staff.

Two players that we have tried not to include are lawyers and judges. Experience has taught us that if a problem isn't solved at the field level, it sure won't be solved in court. Focusing on the letter of the law instead of the intent doesn't help integrated resource management. Most players in the forestry sediment issue have recognized that winning "court battles" doesn't mean you win the "war". In a nut shell, we'd rather have rich aquatic ecosystems rather than rich lawyers.

Foresters are also interested in rich forest ecosystems. Since the sediment that winds up in streams is the basic component of the upland growing site, considerable attention has focused on keeping the "dirt" where the tree roots can use it. Some examples are: identifying unstable sites (Wilford and Schwab, 1982); modifying forest harvesting (Sauder and Wellburn, 1987); reducing logging disturbance (Lewis et al., 1989); looking at alternative silvicultural systems (Sanders and Wilford, 1986); revegetating disturbed sites (Carr, 1980 and 1985); and determining the effect of mass wasting on site productivity (Smith et al., 1986).

In summary, forestry-sediment issues are a very real concern in British Columbia. Agencies have joined together in a positive atmosphere of cooperation and have taken an interdisciplinary approach to research, planning and management. The next three speakers will provide insights into our progress and areas that still need further work.

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5.2. Hillslope Sediments in Forested and Logged Coastal Watersheds

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The forest industry in much of coastal British Columbia is operating in one of the more naturally unstable areas in North America. As the accessible valley bottom areas are harvested, an increasing percentage of the harvest takes place on steep, marginally stable, mountain slopes. As a consequence, landslides are common and an increasing management constraint to forest operations. The main concern with landslides is not forest land loss, but rather it is the impact on river sedimentation and channel morphology and the consequent damage to fish habitat, domestic water supplies, recreation and other resource users. The Queen Charlotte Islands are presented as a case study to outline how forest land use practices alter hillslope sediment delivery to stream channels. The paper concludes with the implications this has on forestry policy management practices and future sediment monitoring requirements.

Landslide Characteristics in Forested Watersheds

Perhaps no other area in North America has such a high natural incidence of landslides as the Queen Charlotte Islands. Gimbarvesky (1988) has counted over 8,300 landslides identifiable on 1:50,000 air photographs and Rood (1984) estimates that the actual number could be as much as 70% greater. The average failure frequency is 4.8 landslides per square kilometre of forested terrain. The volume of the landslides ranges from a few hundred cubic metres to over 10,000 m^3 but average 1,600 m^3.

Both natural and logging induced landslides on the Charlottes are usually either debris slides (60%) or debris flows (40%). The composition, by volume, of the material in natural landslides is typically 25% trees, 40% gravel to boulder-sized material and 35% silt (Chatwin and Rollerson, 1983). In an inventory of 264 natural landslides, occurring over an area of 167 km^2, Rood (1984) calculated average failure rate frequencies in forested steeplands of 0.12 landslides per square kilometre per year, producing a sediment yield from forested terrain of 1.6 m^3/ha/year. This yield is significantly larger than yields measured from most other Pacific Northwest areas. These figures imply a continuous yearly input into stream channels, however Schwab (personal communication) has evidence that the vast majority of these landslides are highly episodic and can be ascribed to four large storms that occurred over the last century.

Approximately 39% of the mass-wasted material, or 0.62 m^3/ha/year directly enters streams, primarily impacting the higher gradient reaches in the upper watershed. The remainder of the material is stored on the slopes, in fans, or within the gullies. The probability of a landslide entering a stream is size dependent: only 22% of landslides less than 500 m^3 directly enter streams, while 70% of landslides greater than 5,000 m^3 will enter a stream (Rood, 1984).

When landslides enter the streams, they will either stop, scour a distance of a few hundred metres or else scour the entire length of the channel. When the volume of the debris flow is greater than 2000 m^3 then the length of channel scour can be extensive, and may include the entire stream length. Much more commonly however, the channel is scoured for 100 to 200 m and then the debris flow stops, forming a large debris jam within the channel. Flow dynamics within the debris flow tend to propel the lighter woody debris to the front of the flow creating a log jam with a train of gravel and silt built up behind the jam. Commonly the debris flow is eventually stopped by a pre-existing debris jam, and the net effect is a coalescing into a much larger jam.

Logged Watersheds

The incident of mass-wasting increases markedly on logged slopes compared with forested slopes. Landslide inventories on logged areas throughout western North America have recorded landslide-affected areas of between 2.5-times to 6-times the area measured in similar forested terrain (Swanson and Dyrness, 1975). Studies by Megahan et al. (1978) revealed that slope failures were most frequent 4 to 10 years after logging, and returned to pre-logging levels about 20 years post logging.

Again, landslide rates on the Queen Charlotte Islands are amongst the highest recorded. A survey following a major storm in 1978 (return period of 5 years) showed that the numbers of landslides were 14 times greater and landslide erosion rates were 41 times greater for clearcuts than for natural forest terrain (Schwab, 1983).

An intensive survey by Rood (1984) revealed that on average there were 29.7 landslides per square kilometre of logged terrain, indicating a landslide frequency of 4.1 events per square kilometre per year. The overall effect of the logging was to accelerate the frequency of landslides by 34 times.

Total sediment yield increased dramatically in logged and roaded areas. In clearcuts, debris flows are more common than debris slides. Debris slides contribute 16.8 m^3/ha/yr and debris flows contribute an additional 33.9 m^3/ha/yr for a total clearcut sediment yield of 50.7 m^3/ha/yr. Logging road failures, 20% of the total, contribute an additional 11.1 m^3/ha/yr. In the logged areas, a significantly high percentage of landslides directly entered streams, 47% versus 36% in the forested areas, resulting in an estimated sediment production to streams of 27.6 m^3/ha/yr or 34 times the natural rate.

Comparison of Logged and Forested Landslide Characteristics

Hillslope logging on the Queen Charlotte Islands has affected the source areas, the quantity, the timing and the composition of sediment delivered to streams. While debris slides originating in logged areas are smaller than from forested areas, debris flows are larger. In logged terrain, the annual sediment yield entering streams is derived primarily from debris flows (67%) in contrast to that source in forested terrain (37%). In both clearcut and forested areas, the more uncommon large landslides are by far the most significant in sediment yield: landslides over 5000 m^3 in size supply over 70% of the sediment yield to streams.

A larger percentage of mass-wasted material enters streams in logged terrain than in forested terrain. More than three quarters of the extra sediment and woody debris yield to streams occurs in the higher gradient (3° to 10°) reaches in the upper part of the watershed. By contrast the forested terrain has a much higher proportion of its yield occurring in the lower gradient reaches.

The character of the debris entering the stream is also different: 20-25% of the forested landslide is made up of trees often 10's of m long while in clearcut areas, the majority of the organic material is smaller logging slash, typically less than 2 m in length. This has major implications on channel morphology; this will be discussed in the following paper.

The frequency of sediment input to streams also changes. In forested areas, landslides appear to be highly episodic, associated with 10-25 year rainstorm events. In logged areas, the triggering rainfall event is much less, with the 2 year rainfall event sufficient to trigger mass-wasting (Hogan and Schwab, 1990).

Management Strategies

The impact that logging has on sediment yield, and the consequent alterations in channel morphology and fish habitat is well recognized by the B.C. Forest Service. Accordingly, a number of policy and management practises were introduced in the early 1980's to try and mitigate the impacts. The majority of these changes have been directed at trying to reduce the incidence of hillslope mass-wasting. The introduced changes include:

1. Reductions in the Timber Supply Areas (TSA's).
   As a result of land classified as Environmentally Sensitive, for slope stability reasons. These reductions can be substantial; for example the Queen Charlotte Island TSA's were reduced by 16% (approximately 40,000,000 m^3 of wood).

2. Slope Stability Mapping.
   Increasingly sophisticated methods have been developed for classifying land for slope hazard identification. To date virtually all of the timber land on the Islands (500,000 ha) has been mapped at a scale of 1:20,000 and rated for slope stability using a 5 class system.

3. Harvest Planning, Logging Guidelines, and the Referral System.
   Slope stability maps are extensively used to plan road locations and cutblock patterns so as to avoid sensitive area. An inter-agency supported set of logging guidelines, the "Coastal Fishery-Forestry Guidelines" (1988), gives detailed logging prescriptions in order to avoid slope stability and sedimentation impacts. It is now routine for any marginally susceptible terrain to be field checked by a geotechnical expert. All planned cutting permits must be referred to Federal and Provincial Fisheries agencies for approval, which usually involves a field investigation, prior to any logging.

4. Alternate Harvesting Systems.
Alternatives to conventional harvesting methods are being evaluated. Ground disturbance levels with skyline logging systems can, under favourable terrain, result in significantly less ground disturbance and less road construction by providing significantly more lift of the logs. Helicopters offer the potential to eliminate mid slope roads, and to carry out partial cutting of the forest to provide enough root strength and to maintain slope stability.

5. Improved Road-Building Practises.
The backhoe's greater versatility in handling and utilizing excavated material and constructing drainage ditches, compared to crawler tractors, has resulted in dramatic decreases in road-induced landslides.

6. Future Sediment Data Needs
Reduction of sediment yields to levels normally characteristic of forested streams requires reduction of sediment supply at the source. Single sediment monitoring stations at stream mouths are useful for measuring changes in suspended sediment levels before and after logging and for constraining sediment budget models. However, in order to prioritize sediment control money and effort, there is a need to develop sediment budget models and measure sediment yield from individual source areas. A distributed network of stations in a single research watershed is more useful for forest management than is a network of single watersheds.

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5.3 Fluvial Sediments in Forested and Disturbed Coastal Watersheds

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The first presentation in this Forestry Session discussed the pathways that sediment follow from the hillslope to the stream channel. It was shown that sediment is produced by various processes, at different rates, and that the delivery of sediment to the water course can be influenced by certain timber harvesting activities. My presentation deals with in-stream sediment issues that frequently become a focus for forest management in coastal British Columbia. After considering the types of in-stream sediment issues important from a forestry perspective, our future information needs are apparent.

Once sediment and organic debris have been delivered to the stream channel, further downstream transfer depends on many factors. These include characteristics of the sediment introduced (particle size and quantity), location of the material input along the channel network, hydrology (nature of floods) and channel structure. In-stream movement of sediments by either suspended or bed load transport mechanisms depends to a large extent on these characteristics. Suspended sediment consists primarily of fine sand, silt and clay-sized particles that may be moved downstream relatively rapidly and deposited locally in overbank or back-channel environments, or possibly along the mainstem channel. Sediment transported as bed load consists primarily of coarse sand and larger particles. This "coarse" material is moved less frequently and is usually stored within the channel zone for much longer durations than are the "fine" sediments. Both fine and coarse sediment characteristics have important implications to many resources, particularly fisheries, but in coastal British Columbia coarse sediment has been studied in more detail than fine sediment. Accordingly, in this presentation more emphasis will be placed on coarse sediment characteristics and associated channel structure as they relate to fish-forestry interactions.

The impact of forestry activities on fine sediment transport and sedimentation of salmonid spawning gravels have ranged from undetectable to severe in areas outside of British Columbia (Everest et al., 1987). However, suspended sediment data are rare for the small coastal B.C. watersheds and the impact of sedimentation is poorly documented. Fine sediment deposition is commonly considered to be of relatively little importance because of terrain and hydrological factors. The streamflow hydrographs for these watersheds have peak flows between October and February as a result of rain and rain on snow events. Frequent, high intensity rain storms generate flood flows that are usually sufficiently large to transport all available fine sediment in suspension. This sediment is often flushed completely through the stream system and is not deposited in significant quantities until it enters tidal waters. In Carnation Creek, the only intensively studied watershed on the west coast of Vancouver Island, there has been no increase in suspended sediment yields after road construction or logging (Scrivener and Brownlee, 1989). Carnation Creek is a small watershed (drainage area ~ $10 km^2$) with mean annual precipitation ranging between 2500 and 4800 mm and has steep slopes with surficial materials derived from volcanic rocks. There has been a 6% increase in the sand content of the bed material surface layer, but this was due to bed load transport (Scrivener and Brownlee, 1989). This relatively small change in sediment texture contributed directly to reduced survival of coho and chum salmon during the period of egg incubation. A study of a single rainstorm on the Queen Charlotte Islands showed that 70% of the entire sediment yield from a 15 km^2 watershed was produced from a short section of logging road (Bruce and Chatwin, 1988). The background concentrations were less than 5 ppm and the concentrations were 9-times higher along the problematic section of road. This indicates that sediment supply is more important than the transport capacity of the channel. Another study of suspended sediment regimes in the Queen Charlotte Islands failed to show increased concentrations in logged or mass wasted watersheds compared to forested watersheds (Hogan and Beaven, in prep.). This study also showed that although fine sediment is relatively rare in salmonid spawning gravels, there is abundant fine material stored in other sedimentary environments, such as along channel margins, in side and back channels and in overbank zones.

The main points regarding fine sediments in coastal watersheds are that: 1) there are few suspended sediment data; 2) the transport rates are generally low with short duration, high magnitude concentrations restricted to flood events when sediment is available (sediment supply limitations); 3) the fine sediment is usually flushed entirely through the stream system; and, 4) the fine sediment has generally less importance to fish habitat degradation in coastal watersheds than in other environments, such as interior regions where fine textured sediment sources are more abundant.

Although there has been considerably more research into coarse sediment characteristics in coastal watersheds, there are very few studies of bed load. Bed load samples are expensive, difficult to collect and have not been used extensively to resolve forestry-related issues. For example, the 17 years of bed load data collected at Carnation Creek (Tassone, 1987) have received minimal use to-date in terms of resolving fish-forestry interaction problems. Perhaps one reason for this is that bed load measurements represent the amount of material passing a point, rather than movement and storage along the stream system. This is unfortunate because bed load sediments are often considered to be an important component of habitat degradation. Very few other studies will have the level of funding provided to Carnation Creek so it appears unlikely that too much more bed load data will be available for small, coastal B.C. watersheds.

Bed load and suspended sediment data quantify material output from an area; of more interest to forest managers is how sediment is stored along the stream channel. Sediment storage characteristics have direct implications to fish habitats and many other stream users, such as recreation and domestic water supplies. In-channel sediment storage characteristics can also be strongly influenced by natural and logging related hillslope processes (e.g. debris torrents). Therefore, the importance of sediment to channel structure is of central concern in forest management issues. Two studies concerning fish-forestry interactions on the Queen Charlotte Islands are presented to illustrate this point.

The first study deals with how stream channels adjust over time to sediment inputs derived from landslides, due either to natural or logging related causes (Hogan, 1989). A paired watershed study is being used to compare stream channels with various ages of mass wasting disturbance with similar channel types in undisturbed basins. This presentation will discuss preliminary results from an on-going study.

A fundamental consequence of debris torrent inputs to stream channels is the establishment of sediment wedges associated with debris jams. Specific sedimentological, morphological and hydraulic changes occur upstream and downstream of the jams. The location, size and function of each jam controls stream morphology and their distribution along the water course influences the spatial adjustment of the channel. The integrity and longevity of the debris jams control the temporal response of the channel. Initial results indicate that severe morphological alterations persist during the first decade following debris torrenting, but the channel begins to develop more normal characteristics during the second and third decades. The morphological nature of stream channels 30 years after disturbance begins to resemble undisturbed channels. A series of generalized models showing the temporal evolution of these streams are presented.

Sediment characteristics also depend to a large extent on the temporal and spatial nature of log jams. Bed material texture does not vary in any simple systematic manner along the channel. For instance, there is no straight forward relationship between distance downstream and bed material texture. Rather, texture is highly variable and this is attributed to mass wasting inputs and debris jams. While the jam is new and fully intact it acts as an efficient sediment trap; the channel aggrades upstream and surface texture become progressively finer. Sediment texture coarsens downstream of the jam structure due to degradation. The extent of this armouring is dependent on the nature of the log jam upstream. With the gradual breakdown of the debris jam over time, stored sediment is re-supplied to the downstream reach and fining occurs.

Debris jams occur frequently along these coastal streams, but between the jams, individual pieces of large organic debris (LOD) exert an important influence on channel morphology and bed material sediment. In-stream LOD characteristics were evaluated in unlogged and logged coastal watersheds of the Queen Charlotte Islands in a second study (Hogan, 1987). The study examines the input, storage and output components of LOD budgets, how these are altered in logged and/or torrented channels and how these changes influence the recovery of disturbed channels. Results showed that the actual arrangement of LOD along the channel was altered in logged and torrented channels. Consequently, the scouring and trapping of debris pieces were altered. A less complex morphology results, including diminished pool area and more uniform depth, width and sediment texture variability.

Another important implication of the altered LOD architecture is the influence on sediment storage and channel stability. There are between 3 and 4 times as many storage sites in the forested streams compared to torrented or heavily impacted logged channels. However, the torrented channel has 6 times more sediment volume per unit area. Consequently, there is much more sediment stored in fewer locations in the logged and torrented channels compared to unlogged watersheds. This indicates that the stability of the unlogged channels is greater because sediment is stored more evenly along the channel. This buffers the effects of large flood flows and the movement of individual compartments of sediment. Floods in heavily impacted logged channels may displace infrequent debris obstructions, resulting in major redistribution of sediment.

The implications of these studies to resource management are important. If landslides, either natural or logging related, deliver large volumes of sediment to the stream, specific channel changes will occur at the site. The sediment may then be pulsed downstream and may progressively impair habitat for various durations. The length of time, and relative severity, that habitat is degraded is only now just being determined quantitatively. Also, it is very difficult to attempt habitat rehabilitation when little is known about how channel sediments change over time. Channel stabilization and rehabilitation structures should be designed to perform well over the long term, but designs are usually based on the channel condition at one point in time. A better understanding of the spatial and temporal nature of a stream channel's response to altered sediment supply characteristics, both from upland and up-stream areas, is required for this application.

In summary, from a forestry-fishery management perspective, we are interested in several features of fluvial sediments besides those traditionally addressed by the Water Survey of Canada. We are interested in determining such things as:

1. where does the sediment come from (sediment source identification)?;
2. how is sediment stored along the channel (channel stability)?;
3. how long is the sediment stored within the channel zone (residence times)?;
4. how do sediment characteristics change along a stream channel and over time?; and,
5. given the complexity of these channel types, how many samples are required to properly describe their sediment characteristics?

Therefore, additional suspended and bed load sediment monitoring data would be useful to our work if it could assist in providing answers to these questions. It also seems reasonable that further work should be done in hydrologically and geomorphically homogeneous regions so that findings can be extrapolated to other watersheds. Therefore, future sediment monitoring programs should be aimed at:

1. a regionalization of river types based on geomorphic and hydrologic criteria;
2. increased effort to determine the important sediment sources in each region; and,
3. more morphological information to accompany all water quantity and quality monitoring data (nature of stored sediment and debris stored within the reach).

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5.4. The Impacts of Timber Harvesting on Sediment Loads in the Interior of British Columbia

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There is little documentation of the impacts of forest harvesting on sediment loads in the interior of British Columbia. This is surprising because many members of the public believe that streams are permanently degraded as a result of upland forest harvesting. They likely derive this belief from the erosion scars that are evident on many logged areas throughout B.C. An important "sediment issue" is to determine which circumstances of upland erosion result in downstream sediment yield changes. In areas such as the interior of B.C. the geology, surficial materials, and topography vary widely and one would expect the impacts of land use to reflect this diversity. The summary of sediment data for B.C. by Church et al. (1989) illustrates the diversity in sediment yield by watershed size and outlines some generalizations one can make about the Water Survey of Canada data set. The documentation relating land use to erosional and sediment impacts is derived largely from research done in the United States (Rice et al., 1972).

Considerable effort is devoted to protecting streams from sediment input during the planning and monitoring of road building and forest harvesting operations. Fisheries, domestic and irrigation water supply are the principle resource interests that have a concern with sediment yields. The Ministry of Forests takes into consideration the water quality interests of resource users in planning for roadbuilding and forest harvesting operations. Once again documentation of the success of these programs and procedures is lacking.

Four studies have been identified that attempt to document the impacts of logging activities on sediment yield and sediment concentrations. The most intensive of these studies was the Slim-Tumuch study which was conducted in the Prince George Region between 1972 and 1975 (Slaney et al., 1977; Brownlee et al., 1988). This study attempted to document the impacts of a typical logging operation on fish habitat quality in a tributary of the Fraser River east of Prince George. Several studies more limited in scope by Hetherington (1976), Eremko (1989), and Gluns and Toews (1989) also included some analysis of forest harvesting activities on suspended sediment concentrations.

Considerable suspended sediment data have been collected in the Nelson Forest Region to document the impacts of proposed forest harvesting activities on suspended sediment levels (Salway, 1986). These data mostly illustrate sediment levels in the preharvesting phase. Some of the study stations have been operated by Water Survey of Canada. A graphical examination of data from the Anderson Creek and Five Mile Creek drainages near Nelson demonstrates some important characteristics of sediment loads in many interior streams. For the most part the suspended sediment levels in these streams are very low. The maximum loads are carried during the early spring snowmelt peaks. Often the first substantial increase in flow during the spring snowmelt season will have relatively high sediment concentrations. This is likely the result of the stream channel being flushed of material that has been transported during the previous low flow season. Once the channel is "clean", suspended sediment levels are no longer as high as predicted by the flow/discharge relationship. These data would suggest that suspended sediment transport is supply limited rather than energy limited.

The sediment budgeting and routing concept is a useful method of evaluating forest harvesting impacts from both a quantitative research and qualitative impact analysis viewpoint. In a research context it provides a framework within which to structure and evaluate sediment studies that have been undertaken. From an impact evaluation viewpoint, it provides a framework for prioritizing activities that might be undertaken to rehabilitate a watershed, a context for evaluating activities that may have impacts on sediment levels. The utility of this concept in research is illustrated in the work of Kelsey, Reid, and Megahan as presented at the 1980 Sediment Budgeting and Routing Symposium (Swanson et al., 1982). If one examines the British Columbia studies mentioned here, one finds that only a limited portion of the work of the sediment movement picture is documented. In the Hetherington, Eremko, and Gluns and Toews studies, the concentrations rather than sediment load are measured. The Eremko and Hetherington studies only measure sediment in the headwater areas. A sediment budget approach would measure sediment transfer between various segments of the system.

This workshop is to focus on "sediment issues". I believe the most significant technical issues facing us relate to the linkage between upland watershed management strategies and downstream sediment yield. There is a demand to derive a forest harvesting strategy on a watershed specific basis that mitigates the effects of harvesting over the long term. In my consulting work I am repeatedly asked to suggest harvesting strategies to minimize sediment impacts over the long term. Several strategies to make this linkage have been derived. The U.S. Forest Service has been particularly active in attempting to formulate sediment yield increase models and methodologies. Two that I am aware of are the WRENSS methodology (Water Resources Evaluation of Nonpoint Silvicultural Sources) (EPA, 1980) and the Region 1 Water Yield Increase Model of the U.S.F.S. (U.S.F.S.n.d.). In the Nelson Forest Region we have tried to apply parts of these and similar methodologies, but documentation is lacking with respect to changes, the linkage of flow changes due to forest cover removal to increased sediment yields, and to absolute changes in sediment yield. Inherent in the second model is the assumption that as water yield increases due to forest cover removal, the frequency and magnitudes of flows capable of moving sediment will increase, and consequently the sediment loads will increase. From a hydrology viewpoint the assumptions may fail in many watersheds because the magnitude of peak flow increases is dependent on the distribution of the cutting within the watershed rather than on the total water yield increase. A second problem with the model is that in many of our watersheds the sediment yield is likely sediment supply limited rather than energy limited as the model assumptions would indicate. In southeastern B.C., our principle strategy is to reduce sediment sources by identifying risk areas in the upland landscape and planning harvesting operations accordingly. The general strategy is thus to minimize the addition of new source areas from either a mass wasting or a surface erosion viewpoint. Peak flow increase is also a concern and a general set of guidelines that limit the magnitude of harvesting in the upland landscape are being derived. These are based on known principles of snow accumulation and melt on a watershed basis (Toews and Gluns, 1986).

In closing, I believe the present collection of sediment data by the Water Survey of Canada, although limited, is important. To maximize the utility of the sediment yield information that is being collected I believe it is necessary to carry out further studies to document the linkage between land use and sediment yield changes. The sediment budget concept will be useful in formulating such studies.

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6. FISHERIES SESSION

6.1 An Overview of Sediment and Fish Interrelationships in British Columbia and Yukon Streams

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This session will very generally outline the effects of sediment on the aquatic life present in British Columbia and Yukon streams. Since the group of fishes mainly affected by sediment includes the grayling, char, whitefish, trout, and salmon, the following considerations will apply to most streams in these areas. The reader should not consider this presentation to be a complete review of the topic. For such the reader should refer to the excellent classic review by Cordone and Kelly (1961) and many other excellent reviews published in the past two decades.

For the purposes of the review, sediment is considered as inorganic matter ranging in size from the fine colloidal clays (particles less than 0.004 mm in diameter) to larger particles commonly referred to as fine pebbles (particles 2-4 mm in diameter). This class of particles is commonly referred to as fines by salmonid biologists concerned with stream gravel quality. It is this size range of particles that are of greatest concern and it is the impacts of these sediments that will be considered in this review. It should be noted that silt is a particle size from 0.004 - 0.062 mm in diameter and is within the size range considered as sediment in this review.

Sediments have always been present in British Columbia and Yukon streams and since the last ice age have played an important role in the development of streams, habitat, and stream life. Large amounts of sediments are presently carried by natural processes into most of our streams. This process is of course very active in watersheds that are geologically young, whereas the more stabilized watersheds have streams that are relatively sediment free during all or at least a portion of each year. Sediments create the habitat that fish production ultimately depends upon. For instance, the gravel deposits in a stream are sediments that are essential builders of salmonid habitat. Unfortunately, the introduction of harmful quantities of fine sediments to streams by man or natural processes can devastate fish production.

In streams characterized by stable lower sediment regimes, one will find forms of plant and animal life which have been selected by natural processes and are tolerant of those levels. Each species may be able to compensate for variations in sediment levels from stream to stream, or from one day to the next, but it cannot physiologically and morphologically compensate to survive very different sediment regimes from one stream to another, or from one generation to the next. Therefore any change in the watershed that will cause a significant increase over natural sediment levels will generally have some detrimental effect on aquatic life. Usually the greater the increase or the longer the duration of higher sediment levels in a salmonid stream, the greater will be the adverse effects on the animal and plant life present in that stream.

Fine sediments are subtle, ubiquitous water pollutants that have shaped stream life in the past and are a constant and significant threat to present stream communities because of man's activities. Poor land use practices, construction and mining activities have been responsible for an accelerated movement of sediment into most salmonid streams in this province. The role sediments play in reducing production in salmonid streams has been difficult to document and for this reason its severity has often been overlooked or not emphasized adequately in the management of water quality in B.C. and the Yukon.

Available data indicates that sediment can affect all forms of stream life. This session attempts to review these known effects as they relate to the primary producers, the invertebrates and the production of salmonid fishes in our streams. Sediment in a salmonid stream can be considered as a very broad-spectrum pollutant affecting all life forms from primary producers to adult fish. However, the effects of sediment on all the different life forms in a particular stream will not necessarily occur simultaneously. The overall impact on the aquatic community is as complex as the interrelationship between the various organisms in the stream.

Fine sediments will affect the primary producers, the primary consumers (the invertebrate populations) and the secondary consumers (the fish populations). The major impacts of sediment on the primary producers are through turbidity induced impacts on light availability, scour of the substrate and smothering of substrates upon which algae attach.

The impacts of sediment on the next trophic level is more complex. A reduction in primary production will of course impact on the invertebrate population dependent upon that energy source. The sediments will also interfere with feeding and breathing mechanisms, and also scour and smother the substrate where the invertebrates live. Certain species of invertebrates thrive in fine sediments; however, it must be noted that these deposits are usually very stable, not mobile, and not established in a haphazard manner.

Sediment is probably responsible for the greatest mortality of salmonid fish species. These impacts are greatest on the egg and alevin stages due to the clogging of spawning gravels. The living space required by juvenile fish (e.g. interstitial spaces in boulders) can also be adversely affected by significant sediment releases. The sediment will have a direct impact on juvenile and adult fish by harming gill structures and in extreme cases even clogging their gills. Indirect impacts on fish are of course exerted through the impacts on the food chain and the consequent reduction in food supply. Turbidity can also reduce the feeding efficiency of the salmonids since they are sight feeders.

The impact of a sediment release on stream production will depend on the organisms present, streambed composition, the season, stream flow, stream velocity, background sediment levels, the volume of the release, the duration of the release and the composition of the sediment. The above parameters dictate the degree to which sediment will decrease production or harm stream life. However, a sediment release into a productive salmonid stream will most often have some harmful effect regardless of the status of the above parameters. It must, of course, be realized that these same sediments may create productive deposits in low gradient areas of the stream or form valuable deltas in the estuary once the sediments are flushed out of the stream where they may have exerted a deleterious impact.

The obvious effects of sediment on fish production will have greater impact on certain stages of the life cycles. This will, of course, vary from species to species. Sediment causes the greatest reduction of salmonid production by causing mortality in the egg and alevin stages of development. An increase of sediments in the stream during the spring freshet may have a reduced impact, providing the sediment carrying capacity of the stream is not surpassed. Once certain salmon species (i.e. pink and chum salmon) have reached the fry stage, they migrate directly to the ocean, thereby avoiding further exposure to the effects of sedimentation. Chinook, coho and trout species must spend part or all of their lives in the stream. Such fish are thus more prone to be affected by abnormal stream sedimentation, especially after the spring freshet. During the summer when stream flows are low, temperatures high, and the stream is filled to capacity with rearing fish, a sediment release can greatly reduce salmonid populations by reducing their food supply.

However, it must be emphasized that one cannot look only at the obvious direct effects on fish to gauge the damage sediment can have on a stream. Although sediment affects all stream life, these effects are not exerted equally on primary producers, invertebrates and fish. These life forms are linked together by food chains so any deleterious effect on algae will affect aquatic invertebrates and fish that depend on energy produced in the stream. It is for this reason that one cannot examine the effects of sediment on fish alone. For instance, it is most often of academic value to be concerned at what level stream sediments will clog the gills of fish or reduce their hiding areas. In most cases the entire food chain complex upon which these fish must depend, would have been damaged well before the fish was directly harmed. If stream life is to be adequately protected from abnormal sediment levels, we must measure and be concerned about the more subtle effects of sediments. Cordone and Kelly (1961) most aptly describe this concern: "...short-term discharges of sediment may do little visible damage to fishes, bottom fauna, or fishes' eggs, but may interrupt the entire biological complex through effects on algae".

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6.2 Suspended Sediments and Fisheries: Highlights of an Empirical Impact-Assessment Model

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Historical Background

Although fisheries managers have always known that suspended sediments can harm aquatic ecosystems, they have been unable to estimate the amount of damage caused by a pollution event. This partial knowledge resulted in efforts to limit the permissible concentration of suspended sediments to a low level without placing a limit on the duration of the exposure.

The accepted maximum concentration (*) in streams with salmon and trout, usually 10 or 25 mg/L, was chosen in the belief that a fishery could exist indefinitely without serious harm at these levels. This subjective assumption, put into practice more than 15 years ago, has proven to be durable: it is still in use today (Newcombe, 1986; Pommen, 1989). It has been a useful device because it sets a threshold below which fisheries values are fairly well protected; but it is a compromise that fails to correlate the severity of a pollution episode with the severity of harmful effects. Thus its uses are limited, and it can now be considered to be an "old" or traditional model.

Severity of Effect as a Function of Exposure

Now that there is more information in the primary literature, it is possible to expand the traditional model. The new model is based on empirical observations and considers three types of information,
1) concentration of suspended sediments,
2) the duration of the exposure, and
3) the resulting effects (harmful and beneficial).

There are numerous other variables such as the size and angularity of the particles, the water chemistry (particularly temperature and oxygen concentration), and the size of the organism, its age, and its taxonomy, that have not yet been included in the new model for want of sufficient information.

Nevertheless, the three main elements of the model are consistent with the kinds of information used in traditional bioassays--experiments in which organisms are exposed to pollutants at known concentrations, for known durations, for the purpose of producing ill effects. Such knowledge is used to develop environmental quality guidelines or for impact assessments.

The data on which the new model is based come from primary literature and technical reports. The methods used to collate these data were designed to

(*) British Columbia Ministry of Environment (10 mg/L above background when the concentration of suspended sediments is less than 100 mg/L).

be thorough and reproducible. Reports that provided one or more of these three elements of bioassay were potential sources of relevant information for the new model. Missing information could often be obtained from the author by personal communication, or by combining the published results of two or more related studies.

The database that grew out of the literature review contained a wide range of exposures, where "exposure" is defined as the product of concentration (mg/L) and duration (hr). Exposure is a useful concept because it provides a single value that links the major variables--concentration and duration--with known impacts.

The concept of exposure can be refined to create a dimensionless number that serves as an indicator of the level of stress caused by sediments in aquatic ecosystems. Since the values for "exposure" (expressed as mg.hr/L) range from small to very large, it is convenient to reduce the range by taking the natural logarithm of all such values. The resulting value, which ranges from -1 to 18, is termed the "Stress Index," where Stress Index= ln (exposure).

Since the Stress Index is a natural logarithm (base approximately 2.7), each unit increment in Stress Index represents an increase in exposure of approximately 2.7. Thus, for example, a Stress Index of 10 represents an exposure that is about 2.7 times greater than a Stress Index of 9.

Analysis of the available data indicates that the two variables, concentration and duration, account for more than 70 percent of the variability in the data on harmful effects. By contrast, the single variable, concentration, accounts for a mere 40 per cent (Newcombe and MacDonald, In press).

Although suspended sediments cause dozens of different harmful effects (Newcombe, 1986), each of which can be ranked in order of severity so as to create a continuum ranging from mild to severe, it is possible to make useful generalisations. These are proposed as guidelines, for use by resource managers who need to assess the severity of impact caused by pollution from suspended sediments.

Three simplified categories of harmful effect, arranged in order from most severe to least are,

1) Major Impact (Stress Index >12)
2) Moderate Impact (6> Stress Index <12)
3) Minor Impact (Stress Index <6)

These three categories provide guidelines that can be applied whenever the concentration of suspended sediments and duration of exposure are known or may be estimated. Fortunately, the resolution of the new model will improve as the database grows. Ultimately, the model will make it possible for us to know in great detail, the nature and extent of the environmental damage caused by suspended sediments in aquatic ecosystems.

Although the model should improve over time, it offers substantial predictive capacity now. Thus, there are immediate applications in litigation and in the setting of better guidelines and regulations across Canada. Applications range from the protection of pristine salmon streams, to the pollution problems caused by ocean dumping.

Practical Applications

In the few years since the model was developed, it has been implemented in the following settings;

1. British Columbia

   Assessment of impacts from re-suspended sediments during the cleaning of a spawning channel (see details in following section);

2. California

   Assessment of impacts caused by the removal of deposited sediments from behind a dam;

3. International Boundary (British Columbia/Montana)

   Assessment of risk posed by a proposed mine. (In this instance, the model was implemented for the International Joint Commission's Flathead River Study Board, by the Biological Resources Committee 1987).

Implementation of the Suspended Sediments Impact Model

The removal of deposited sediments from the gravels of the Little Qualicum (River) Spawning Channel (item 1, above) is a task that creates considerable quantities of suspended sediments. The timing of life-history phases of various species of fish (in the artificial channel, and in the river) places limits on the timing of gravel cleaning operations. At all times of the year impacts are likely to occur, but late June is the time when these impacts are thought to be at a minimum. Ideally, cleaning should be done during times of freshet when high stream flows would carry the load of suspended sediments downstream, but here, this is not possible. Thus, the question of when and how to clean the gravels provides a unique opportunity. It is an example of a pollution problem that is completely within the control of fisheries experts. It is therefore an activity that can be guided by predictions of the Stress Index Model; yet it also provides annual opportunities to study the model, and to develop confidence in its predictive properties.

The water quality data collected during the gravel cleaning operation of 1989, Table 6.2.1 (Bill McLean, Quinsam River Hatchery, Fisheries and Oceans

Table 6.2.1

Cumulative STRESS INDEX in the Little Qualicum River resulting from cleaning of gravel at the Little Qualicum Spawning Channel in 1989. (*)

Consecutive Episodes of Pollution by Suspended Sediments	Concentration of Suspended Sediments (mg/L)	Duration of Pollution Episodes (hr)	Exposure (mg.hr/L)	STRESS INDEX	Cumulative Stress Index
20-Jun	70	7.38	513	6.24	6.24
21-Jun	171	9.75	1670	7.42	7.69
22-Jun	512	7.70	4694	8.45	8.84
23-Jun	10	4.00	42	3.73	8.84
23-Jun	5	7.00	33	3.48	8.95
26-Jun	17	3.50	58	4.07	8.85
26-Jun	67	8.00	537	6.29	8.93
27-Jun	152	3.75	568	6.34	9.00
28-Jun	218	4.20	908	6.81	9.11
28-Jun	75	1.83	138	4.92	9.12
28-Jun	73	3.67	269	5.60	9.15
			9430	9.15	

(*) Bill McLean, Quinsam River Hatchery, Fisheries and Oceans Canada. Personal Communication

Canada. Personal Communication), indicate that substantial amounts of sediments are discharged from the artificial channels into the Little Qualicum River.

The period of sediment discharge lasted 11 days. Pulses ranged from 2 hours to 8 hours at a time; and the concentrations ranged from a high of 512 mg/L to a low of 5. This wide range of variability is typical of the data on which the Stress Index is based.

In the first day of gravel cleansing, the Stress Index increased to ~6; thus, potential impacts were minor (bordering on moderate impacts). During the second day of gravel cleansing, the Stress Index increased to >6, and by the 11th day, it was >9. A Stress Index of 9 is associated with physiological illness in fishes, thus it represents a level at which there is significant potential for impacts.

<u>Accumulation of Impacts</u>

When the model was being developed, pulses of sediment pollution were assumed to have cumulative effects if the time between them was too short for organisms to restore damage that might have occurred. On a biological time-scale (depending on the type of organism and the life-history phase), restoration occurs over weeks or months, not hours or days. Since the refractory period in the Little Qualicum River was on the order of hours, Stress Index is assumed to have accumulated over the duration of the gravel cleaning operation.

Although potential impacts in the River would have been moderately severe at the point where the suspended sediments were discharged, there are other factors that should be considered. The first is that the discharge was timed to avoid life-history phases of valued salmon and trout. Thus, the probability of impact at the time of the discharge might have been low.

A second factor is the likelihood of further damage,

1) when stream flows increase causing the sediments to be re-suspended at a time when this would not naturally occur; or
2) if the suspended sediments re-deposit on natural spawning beds.

Since the Little Qualicum River is known for its natural runs of salmon and trout, the probability of future impacts might have been relatively high. Certainly, annual discharges of this kind could cause gradual reductions of population size in some fish species in the natural population. Dramatic impacts would not begin to occur until the Stress Index exceeded 12 units. At this level of pollution, large areas of blanketing would be observed, and fish would be notably absent from the areas of heaviest impact. These fish, displaced from the best areas of the stream, would have to compete for reduced resources, and would fail to thrive. Reduced fecundity and reduced spawning success would create a much diminished fishery.

Fortunately, the example of the Little Qualicum River and its problem of suspended sediments from the cleansing of artificial spawning gravels is not this severe. However, the seriousness of the potential impact can be inferred from the year-by-year reductions in egg-to-fry survival in the spawning channel. It is this reduction that makes gravel cleaning necessary. These reductions constitute a form of data which, if combined with data on suspended sediments concentrations during the year, could provide further substance to the Stress Index Model in an area where additional data are required.

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6.3 Impacts of Sediments on Fish Habitat: Status of Knowledge

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This paper reviews effects of sediments on fish habitat and identifies information gaps. The information originally was reviewed to determine future study requirements for the Yukon Placer Implementation Committee, but it applies to the status of our knowledge on effects of sediments in general.

Concerns related to the effects of sediments on fish habitat include

- sedimentation of water courses and
- increased levels of suspended solids and turbidity

Sedimentation refers to deposition of fine particles onto and their incorporation into the stream bed. Three major concerns are associated with sedimentation: 1) reduction in egg to fry survival, 2) reduction in stream carrying capacity for juvenile rearing and overwintering, and 3) reductions in benthic invertebrate food sources.

The effects of sedimentation on survival of salmonid fry is associated with reduced flow of oxygenated water, abrasion, and inability of alevins to emerge from the redds. Sedimentation which occurs during the incubation period is most critical. There is a quantitative dose/relationship to changes in gravel quality. For every 4% increase in granitic fines (<6.3 mm) in the substrate over 20%, chinook survival to emergence is reduced by approximately 10%. Also, at 30% fines in the redds, the percentage of emergent fry is reduced by 30 to 80%.

Little is known of the effects of sedimentation on broadcast spawning species, although it apparently reduces survival of these fish as well. The one available study (Fudge and Bodaly, 1984) demonstrated significant reduction in survival of lake whitefish eggs in an artificial lake subjected to sedimentation with silty clay. Further studies of grayling and other broadcast spanners are required.

Sediment accumulations apparently affect salmonid rearing habitats, but in the field it is difficult to separate sediment effects from other factors affecting juvenile abundance. If volumes of settled sediments are large enough to reduce pool volumes, or if riffle areas become inundated with fines, juvenile salmonid populations are reduced. Similarly, populations are reduced when spaces between rocks become filled with sediment, which reduces overall habitat diversity and availability of refuges.

Interstitial spaces among the rocks are particularly important for overwintering salmonids. Carrying capacity is reduced as these spaces are filled with sediments. One study of a heavily sedimented stream in Idaho (Hillman et al., 1987) demonstrated that when cobble substrate was added, chinook salmon overwintering densities increased eight-fold, as a result of increased cover among the rock crevices.

Many fish species rely on benthic invertebrates for food, and these species should be affected by changes in their food supply. A number of studies have demonstrated that the abundance (density) of benthic organisms decreases and the community structure changes downstream of sediment sources such as active placer mining. The pattern of community structure typically is a shift from filter feeding and predatory species (mayflies, blackflies, stoneflies, caddisflies) to detrius feeders (chironomids).

However, it is not clear how these changes affect fish. For example, Dipteran larvae (including chironomids) are a preferred food source of chinook salmon and Arctic grayling. Thus, shifts in community structure caused by sediment deposition which favour chironomids may not affect fish, although changes in overall abundance would.

Suspended sediments affect fish directly by causing diverse biological responses, such as stress, impaired feeding, reduced growth, and reduced tolerance to natural environmental stresses. Critical concentrations of suspended solids for the free-swimming stages of salmonid fishes are in the range of 100 to 300 mg/L. In addition, suspended sediments and turbidity alter fish movements and distribution and affect feeding ability.

Arctic grayling are virtually absent from water courses disturbed by placer mining, where there are extremely high concentrations of suspended sediments (often several thousand mg/L). Fish utilization of water courses also decreases at high turbidities, even when suspended solids levels are low. This is particularly true for visual feeders, such as grayling.

The common feature limiting fish presence is prolonged elevations in suspended sediments or turbidity, which occur throughout the spring and summer. However, grayling and salmonids migrate through many natural systems, including glacerized rivers, which have seasonally high levels of suspended sediments.

While concentrations of suspended sediments that affect fish survival or health have been documented, few studies have addressed the effects of specific sediment characteristics such as particle size and shape, organic content, and metal content. One study (Servizi and Martens, 1987) showed that fish tolerance to suspended sediment decreased as particle size and angularity increased. Little further information is available on the modifying influence of sediment characteristics on their biological effects on fish. Future studies of sediment effects should address these issues.

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6.4 Fisheries (Sediment) Guidelines

Ken Rood
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The Placer Mining Industry

Placer mining in the Yukon Territories started in 1874, but the major growth in the industry started with the discovery of gold on Bonanza Creek in 1896. The level of activity and value of gold produced has fluctuated drastically over the last 100 years. Recent production has been the greatest since 1917: total value of gold production in 1988 was $65,000,000 (Gilbert, 1988). Placer mining occurs over much of the southern Yukon, though, most gold is recovered from unglaciated portions of the Klondike, Sixtymile, lower Stewart and Indian River drainages (Debicki and Gilbert, 1986).

Placer Mining and Sediment Releases to the Environment

Most placer mines are in small to moderate-sized basins and most properties have been previously mined. The most productive operations are in an area of discontinuous permafrost. Often several to one hundred or more feet of "black muck" (frozen silts and organics) overlie gravel deposits (Debicki and Gilbert, 1986). Barren gravels may overlie pay gravels at the base of the section.

Gold is recovered from the pay gravels by "sluicing" , hydraulically separating the gold from the gangue with running water. Pay gravels are commonly moved to the sluice with earthmoving equipment though hydraulic monitors are used in some operations.

Sediment enters streams during the following mining operations:

Site Preparation: Mechanical removal of overburden is generally by large "cats" which rip frozen ground. Material is stored on the property. Hydraulic removal is either by "monitoring" or by "ground sluicing". In monitoring a jet of water is directed at the overburden to wash it away. Ground sluicing occurs during spring freshet. Waters are diverted over the ground surface to thaw the permafrost and carry away the silt and organic material.

Stream Diversion: It is often necessary to divert the existing stream in order to access pay gravels. Stream diversions may result in increased slope along streams and erosion of the bank and bed.

Sluicing: Effluent from the sluice box, which carries fine sediment in the gangue generally is directed to a settling pond before returning to the stream. The quantity of gravels sluiced in 1988 was estimated to be eight to ten million cubic yards. Envirocon (1986) states that the majority of pay gravel samples contained less than 15% silt. As much as 1.5 million cubic yards of fine sediment are discharged by sluicing operations.

Settling Ponds: Nearly all operations employ settling ponds, commonly constructed as earthen berms with an over-berm outlet structure. The effectiveness of the ponds is highly variable. Flushing of settling ponds, during the spring freshet, creates additional sediment load as does erosion of abandoned settling ponds by streams.

The Regulatory Framework for Placer Mining

Mining activities are regulated by the Northern Inland Waters Act, the Fisheries Act (Sections 31 and 33), and the Yukon Placer Mining Act. Sediment discharges are now regulated by the Yukon Fisheries Protection Authorization under Section 31(2) of the Fisheries Act (Canada, 1988). An accompanying Policy Directive for the Protection of Fish and Fish Habitat in the Yukon from Placer Mining Activity, signed by the Ministers of Fisheries and Oceans, Environment and Indian Affairs and Northern Development provide more details and discusses conservation and restoration of fish habitat. Inspection and monitoring are discussed in a memorandum of understanding between the three ministers. An advisory committee, the Yukon Placer Implementation Review Committee (IRC), has been set up to review implementation of the sediment discharge standards, review the suitability of the standards and review placer mining water licences issued by the Yukon Territory Water Board that differ from the Policy Directive.

Sediment discharges are related to "stream type", where the stream type reflects biological use. Type I streams are salmonid spawning streams and Type II are salmonid rearing streams. Type III streams are those with anadromous salmon migration, freshwater species other than grayling or arctic grayling. Type IV streams are those with no fish, or no fish of any value to sport, commercial or domestic fisheries and typically are historic placer mined streams. Type V are uncategorized streams which require classification prior to sediment discharge.

Sediment discharge standards are expressed in settlable solids (mL/L) or suspended solids (mg/L) in excess of natural background levels upstream of the mine or other upstream mines. Settlable solids are measured with an Imhoff cone. The approach is inexpensive and measurements may be easily collected by placer miners.

Issues not Adressed by the Sediment Discharge Standards

Most suspended sediment discharge standards for protecting fish and fish habitat are expressed in suspended solids (Department of Fisheries and Oceans and Environment Canada, 1983). A literature review by Norecol (1989) was unable to locate laboratory or other studies of sediment effects on fish that measured sediment loadings in settlable solids.

Relationships between settlable solids and suspended solids exist, but the two measures of sediment concentration are typically poorly related. Both the Environmental Protection Service (1985) and ESL Environmental Sciences Ltd (1989) indicate that over a number of streams only very weak relationships may be expected, though there is some expectation that within one drainage a better relationship may be established.

The practical lower limit for measurement is about 1 mL/L (APHA 1981, p. 96). At low concentrations, readings are subjective because of the difficulty of determining the "top" of the settled solids. Readings less than 0.1 mL/L are generally reported as zero, though this may represent a moderate sediment load.

Compliance points are not specified in the authorization, but they are typically placed in the effluent path downstream of the settling pond, but above the receiving stream. Sediment concentrations in the creek depend on natural loads and other upstream placer activity.

A type IV stream (and its operators) may be in compliance. If this stream discharges directly to a Type I stream, sediment discharges will be elevated above natural levels by placer activity even though there is no placer mining on the Type I stream. This is a common situation along the Klondike River which is, in part, a Type I spawning stream.

Review of the Protection Authorization by the IRC

As part of their mandate the IRC is reviewing the sediment standards schedule. An initial study (Norecol, 1989) reviewed the existing literature and identified required field studies. A second phase, The Yukon Placer Mining Study -- Phase II, contracted to ESL Environmental Sciences Ltd is underway. This field program is aimed at collecting the hydrological, sedimentological and biological data required to assess the suitability of the existing standards and collecting the economic data necessary to evaluate the sediment discharge schedule.

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6.5 Linear Developments: Innovative Techniques for Sediment Control and Fisheries Habitat Re-creation

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Introduction

Fisheries regulations can place severe restrictions on the timing of in-stream construction and on the amount of sediment which can be generated by such activities. The "No Net Loss Policy" (Fisheries and Oceans, 1986) can also require that compensation be provided for any loss of potential fisheries habitat. This paper describes some of the measures which have been developed to minimize sediment production and re-create fisheries habitat on a variety of recently completed linear developments in British Columbia. Key references describing relevant mitigation techniques and assessing their performance is included, as well as a listing of some perceived research and management priorities related to sediment issues and fisheries habitat re-creation.

The Importance of Project Management

Much of the information presented in this talk arises from experience on a variety of B.C. Ministry of Transport and Highway's projects and on the B.C. Telephone Company's Lightguide Transmission Project. The highway projects are noteworthy due to the number and variety of measures which have been undertaken to provide fisheries habitat. The work on the Coquihalla Highway Project stands out as being particularly innovative and this was acknowledged through the presentation of the B.C. Association of Professional Engineers Environmental Design Award in 1982 (Readshaw and Kent, 1982). The B.C. Telephone Company Lightguide Project similarly set new standards for sediment control of river crossings during the installation of a buried fibre-optic cable. This project was awarded the B.C. Association of Professional Engineers Environmental Design Award in 1989 (Harder and Associates Ltd., 1988).

In both of the above cases, senior management, (with the "assistance" of the regulatory agencies) ensured that environmental concerns were addressed in all phases of the project. Specific strategies which contributed to the success of these two projects included:

i) Identifying, and where possible avoiding, problematic sites at an early stage in the design process;

ii) Designing the project in a manner which minimized the requirements for in-stream construction or other activities which might create adverse environmental effects;

iii) Designing structures located within the flood plain in a manner which reduced the likelihood for on-going or unexpected maintenance requirements.

iv) Including environmental constraints in the contract documents and ensuring the successful contractor was aware of the environmental requirements;

v) Hiring environmental monitors to ensure the environmental objectives were met and to represent the concerns of the Federal and Provincial fisheries agencies;

vi) Developing a co-operative atmosphere in which (in most circumstances) the design team, the regulatory agencies, the contractor, the construction supervisors and the environmental monitors worked together to overcome operational problems as they arose; and

vii) Implementing a comprehensive re-vegetation program on all exposed slopes and undertaking a post-construction monitoring program to identify sites requiring remedial action.

These factors boil down to a commitment on the part of the project owner to "do it right", and the subsequent hiring of qualified personnel to ensure this objective was achieved. From an environmental perspective three items stand out:

i) For maximum effectiveness, environmental objectives must be incorporated at the design stage and this requires a close working relationship between the design engineers and the environmental consultants;

ii) Fisheries habitat re-creation can generally be accommodated at relatively little cost if the desired works are specified in the contract documents. In contrast, if these structures are added as an extra work order, significant inefficiency arises, costs escalate and the likelihood of adequate restoration or compensation diminishes; and

iii) Construction contractors can provide valuable ideas for achieving environmental objectives; efforts to explain regulations and ensure they are "on-side" can result in a less stressful and more successful project.

Sediment Control

A summary of selected techniques for minimizing sediment production arising from "construction in-and-about a stream", is presented in Table 6.5.1 along with a number of descriptive references. The most innovative techniques are those for placing buried pipelines under stream channels without open trenching of the river bed. On small streams it is possible to flume or pump water across an excavated trench, however on larger streams this becomes impractical. The traditional construction technique of open trenching can result in substantial sediment production, particularly if more than one crossing occurs on a given stream. On small diameter pipeline projects these impacts can be avoided through techniques for auguring, pushing or drilling under the stream bed. Auguring and pipe-pushing (using a large hoe fitted with a thumb instead of a bucket to ram

TABLE 6.5.1: SELECTED TECHNIQUES FOR MINIMIZING SEDIMENT PRODUCTION

CONSTRUCTION PROBLEM	MITIGATION TECHNIQUES	REFERENCES
stabilizing cutslopes in erosion-prone sediments	- slope stabilization using geotextiles, revegetation, and bio-engineering	10, 11, 22, 24, 25, 43, 48, 50
constructing diversion channels in erosion-prone sediments	- selective armouring of river bed and banks,	21, 24, 34, 50, 34, 47
	- construction sequencing to avoid working in the wet	
stabilizing river banks subject to fluvial erosion	- minimizing the need for instream encroachments and streambank stabilization through the use of reinforced earth walls	10, 24, 25
	- delaying streambank clearing and grubbing until construction equipment is on site	47
	- keying-in over-sized rip-rap to prevent erosion and reduce the need for emergency repairs.	21, 27, 34
	- use of spurs to reduce the need for stream bank armouring and increase channel habitat diversity	21, 34
	- bio-engineering	42, 48
installing buried pipelines under the bed of a stream	- fluming and/or pumping runoff around the construction site	47
	- construction of settling ponds	47, 51
	- staged coffer dam construction	
	- horizontal auguring	
	- horizontal pipe-pusing	
	- directional drilling	9

the pipe across) have the disadvantage of relatively poor directional control. In contrast, horizontal directional drilling can achieve remarkable accuracy over distances of hundreds to thousands of metres. Drawbacks however include high mobilization costs and difficulty in drilling through materials which contain large boulders within a finer textured matrix. Where trenching across a river is unavoidable, the sequential placement of coffer dams on either side of the river can successfully isolate the working site from the river flow and reduce sediment production to minimal levels. These techniques have proved sufficiently successful that timing restrictions for such instream construction activities may no longer be necessary.

Fisheries Habitat Re-creation

A summary of selected techniques for re-creating fisheries habitat is presented in Table 6.5.2 along with references providing descriptive information or assessments of how the installed structures affected fisheries productivity. The listed mitigation techniques do not require routine maintenance, flow control measures or additional river-training structures. In addition, they can all be built using the kind of excavation equipment and materials which are readily available on most construction sites. The longevity and long-term stability of most of these structures is however unknown and long-term post-project monitoring at selected locations is therefore required. The size of rock used in rip-rap and boulder groups is of critical importance and experience indicates that the design specifications must be strictly enforced to prevent undersized rock being delivered to the construction site. Where possible such structures should be keyed-in and possibly tied together to prevent unravelling due to local scour. Sedimentation rates in excavated channels and embayments are also important design considerations. Air photograph interpretation and field inspections to determine historic amounts of sediment deposition at analogous sites appear to be the best way to predict potential sedimentation rates. Bottom depth can be over-excavated to prolong the life expectancy of these features, however it is likely that periodic re-excavation may be necessary to ensure habitat productivity is maintained.

Some Perceived Research and Management Priorities

i) The development of flexible regulations on sediment releases in which the size and amount of sediment which may be released is determined by the background or natural sediment levels and the capacity of the receiving stream to dilute and transport any introduced material.

ii) Investigation into the optimum timing for sediment releases as a function of the seasonal variation in flow. Timing constraints are now based on when eggs are in the gravel and this may result in sediment releases during low-flow periods when the river is least able to cope with increased loads.

iii) Documenting the long-term changes in channel morphometry and sediment transport which have occurred as a result of various types of land use, river regulation or training activities. The study should include an analysis of historical air photos, as described in Church

TABLE 6.5.2: SELECTED TECHNIQUES FOR RE-CREATING FISHERIES HABITAT

DESIRED CHARACTERISTICS	MITIGATION TECHNIQUE	REFERENCES
low velocity areas adjacent to river encroachments	- installation of groynes or very coarse rip-rap	36
juvenile salmonid and trout rearing habitats	- installation of oversize rip-rap, single boulders and boulder groups	1, 3, 14, 15, 16, 21, 23, 27, 29, 30, 31, 35, 41, 44, 46, 50, 53, 54,
	- placement of large organic debris	6, 7, 41, 46, 52
	- installation of gabions or log steps	20, 28, 30
	- placement of organic debris as a detrital food source	37
juvenile coho rearing habitat	- re-activation of cut-off wetland areas	21, 35, 49
	- excavation of channels and ponds, preferably in areas with a ground water or tributary water supply	12, 35, 40, 49
holding habitat for adult steelhead	- restoration of gravel pits	5, 33
	- installation of rip-rap spurs to promote scour hole formation	2, 20, 27, 30, 32, 35, 44
juvenile chinook habitat and creation of intertidal marsh	- excavation of embayments	39, 49
	- placement of groynes to promote sediment deposition	26, 27, 50
	- construction of islands within a tidal estuary	4
creation of spawning habitat	- placement of gravel spawning platforms in excavated channels which carry little or no sediment load	17, 18, 19, 23

et al. (1987). Where possible the biological implications of the observed changes should be documented and any opportunities for enhancement of fisheries habitat should be identified. The types of projects which could be usefully investigated include:

a) Long linear encroachments associated with roads, railways and dyking projects (e.g. the lower Fraser or Skeena Rivers);

b) Rites of historic river-training to facilitate log driving (e.g. the KitsumKalum and Nass Rivers);

c) Sites where dramatic changes in stream morphometry have occurred due to unknown causes (such as the Kitimat and Zymoetz Rivers);

Documentation of the effects of river regulation (both augmented and diminished flows) and logging on stream morphology have or are being undertaken. A systematic investigation of the effects on various-sized streams in a variety of biogeoclimatic settings would however be desirable.

Two of the objectives of the above projects would be to:

a) provide a better basis for impact prediction on new projects; and

b) identify fisheries impacts arising from completed projects which could be either rectified or compensated for.

iv) Determination of the cumulative effects of progressive riverbank armouring in terms of biological productivity and the physical effects on stream morphology, river hydraulics and sediment transport.

v) Investigation of the effects of removing large organic debris by the Fraser River Debris Trap on channel stability and biological productivity in the lower Fraser River.

vi) Documentation of the long-term physical stability and biological productivity of structures used to re-create fisheries habitat.

vii) Compilation of information on design criteria, physical stability and biological performance for completed habitat mitigation or compensation developments. This information should form the basis for an up-to-date handbook of recommended procedures for developing replacement fisheries habitat in B.C. streams.

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7. SUMMARY

7.1 Closing Remarks

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In 1984, the Water Resources Branch of Environment Canada commissioned a review of fluvial sediment related issues in the British Columbia and Yukon Region (Kellerhals Engineering Services, 1985). The ostensible purpose of the review was to help the Branch plan its continuing programme of sediment measurements, which is conducted by the Water Survey of Canada staff. A major theme of the review was the complex nature of many of the problems associated with fluvial sedimentation, leading to the conclusion that measurements and problem analyses would increasingly require techniques different than those conventionally applied in the past, and should involve increasing cooperation amongst a number of concerned agencies.

The meeting was called to follow up that review; to determine which issues defined there -- or others -- really are of concern, and where progress may be made toward managing or resolving them, particularly by cooperative work. Accordingly, the workshop has been organized into a group of generalized themes for application of information about sedimentation.

What is the outcome? The workshop has concentrated exclusively on "near-term" issues of fluvial sedimentation associated with current land development and resource use. This is not surprising. Both the thematic organization of the workshop and the preoccupations of nearly all of the presenters prefigured this outcome. It remains important to record that fluvial sedimentation is also the primary agency of change in river morphology in the long term. In a world increasingly concerned with the possible consequences of pervasive environmental change, the longer term perspective should be kept clearly in view. The problem of defining effective means to document and respond to the effects of persistent secular change in riverine systems is difficult.

It is significant, but equally unsurprising, that the presentations all have emphasized protection of environment and resources from untoward consequences of fluvial sedimentation, over more traditional concerns with managing sediment passage or sedimentation around engineering works.

To obtain a more acute view of what this workshop has achieved, I think it is necessary to detour into what might be called the 'institutional sociology' of sediment management. The only really effective regulations concerning sediment in streams stem from the federal Fisheries Act, as described by John Payne. The fisheries services have major authority to control sediment in streams, lakes and coastal waterways. We have learned what is the impact on fish of sediment, hence why sediment must be controlled by regulation. I have gained the sense that the desiderata -- the objectives for fluvial sediment management from the fisheries perspective -- are considered for practical purposes to be known. I did not hear any suggestion that these desiderata should be held under continuing, cooperative scrutiny in what is, after all, a continuously changing environment. But we must keep in view the difficult regulatory assignment that the fisheries services have: it is not wise to present the appearance of doubt about the bases for regulatory authority.

Authority for regulating water quality has been less clear, more because of the remarkable complexity of the subject than because of lack of regulations. However, there is rapidly escalating public concern that effective regulation be established. The workshop has recognized that measurement programmes for water quality have affinities with clastic sediment monitoring and that there is room for cooperative effort. Consequently, I was surprised not to hear any specific proposals for cooperative or coordinated programmes.

What we have heard at this workshop is what we are doing. "We" is each agency in turn -- particularly each federal government agency -- which appears to have its own programme designed to resolve the problem of fluvial sedimentation within its own, fairly narrowly construed mandate.

Contrast these appearances with that of the forest land use group. This group has a very broad mandate to prevent sedimentation problems of any kind related to its land management activities from developing. It knows that it is on the receiving end of the regulatory efforts. For clastic sediment movement and yield, the regional group led by the British Columbia Ministry of Forests presents the appearance of having in place a diverse programme of applied research studies. It is attempting to translate results into operations manuals, and it is looking for cooperation with other interested agencies in public, education and private sectors. The only concrete proposals presented to this workshop about needs for new kinds of information came from this group. They particularly emphasized the need to be readily able to identify sources of sediment, and to be able to follow -- ultimately to predict -- the movement of sediments through drainage systems. Here is a good example of a significant problem that will require innovative methods and considerable cooperation to resolve. Essentially, it concerns the mobility of sediments in the entire landscape -- through entire environmental systems. This topic impinges upon the regulatory concerns of all water management agencies.

This brings us to a new subject which ought to have been discussed in this workshop. What is the best way to examine environmental, or biogeophysical, systems (I mean ecosystems, but with the physical substrate prominently included) in order to manage them effectively? We are in fact attempting to determine that, each from our own perspective, by isolating that part of the system that is of particular concern to us, and attempting to obtain an optimum management strategy for that part. In some cases, the perspective is dictated by regulatory or managerial responsibilities. Is this reasonable?

A presentation by Charles Newcombe provides an interesting insight into this question. He introduced a summary 'stress index' for aquatic ecosystems. His stress index is, in essence, a measure for cumulative impact on the functioning ecosystem. This approach presents a marked contrast with observation of the effects of specific circumstances on specific parts of the system. The latter stems from a reductionist way of looking at ecology: it corresponds with the classical way of doing science. But is it the appropriate philosophy for the applied science of managing large, complex systems?

I will answer by asking some more questions. Is it our ultimate purpose to protect fish (for example), or to protect the population of fish? The answer to this question seems to me not to be simple; in fact, to depend upon the level of current resource exploitation of the fishery in question. But sometimes the sustenance of the population is clearly more important than the size of the current stock. How do populations respond to transient stresses (such as high sediment concentrations) which could be natural and might be prolonged? Losses become higher as the stress becomes cumulatively greater. However, there may be significant thresholds at which losses increase very rapidly, and there may also be population levels that generate significant genetic 'bottlenecks'. These matters underlie a question of real interest; can we maximize yield from more than one resource simultaneously? If the exploitation of one resource induces unacceptable stress in another, the answer is 'no'. In fact, we cannot maximize yield from even one resource if it induces unacceptable stresses in another population. I think that the questions ought to be 'can we protect the long term management possibilities for all the resources?', and 'can we find some joint optimum, or near optimum, level of exploitation of these resources?' The answer to both of these questions is 'yes', provided that the biogeophysical system and the security of diverse populations of organisms are the foci of management.

What does all this have to do with sediment, and with the institutional sociology of resource management? Sediment in rivers is the way in which some resource managing activities (forestry, agriculture, urban land development, mining, industries discharging process water) bring stress to bear on others (fisheries, water itself, environmental aesthetics). So long as the management and regulatory authority for these various resources is vested in agencies with single resource foci, jointly optimum development is unlikely to occur unless the agencies cooperatively pool their management responsibilities and prerogatives. Of course this happens in a number of practical ways at the field management level, but on the evidence of this workshop it does not appear to be happening much at the level of research and development to better understand the nature of the management problem and the biogeophysical system (here, the riverine environment) that is to be managed.

This meeting should continue, but in a format which allows more chance for dialogue and less for presentations of the way it is (with apologies to some excellent presenters). One recommendation of the 1985 sediment issues review was that a technical advisory committee (to the Water Resources Branch) be established. I am sure, in view of the major issues involved, that it is not just the Water Resources Branch that needs such a committee. I expect that we all do, collectively. But someone must start a dialogue. I will conclude this summary by introducing one theme for possible consideration.

In several presentations, major projects have been reviewed. Some data were quoted, and they were sharply questioned as to context or representativeness. We must continue to review major field studies to understand what they really teach us about sediment problems, and what they really imply for management. I return to the forest land use presentation for some examples.

Carnation Creek and the Fish-Forestry Interaction Programme are the most significant studies of fluvial sedimentation related to land use conducted in British Columbia. Fluvial sedimentation represents a good example of the difficulty inherent in environmental science: it is characterized by complex systems, and dominated by geographically variable boundary conditions and temporally variable forcing which limit the generality of results (i.e., geography and weather matter). The FFIP synoptic study typified the kind of inventory based investigation that it usually is feasible for agencies to conduct. What we learn from such a programme is some of the mechanisms of erosion and sediment transfer, and how human activities may influence them. We learn that <u>quantitatively</u> for some forty drainage basins on the Queen Charlotte Islands. The results are <u>qualitatively</u> valuable for what they teach us about how the sediment transfer system generally works. The experience of conducting the programme is valuable for indicating what may be most significant issues to consider elsewhere and how to anticipate them. But the quantitative results pertain to the Queen Charlotte Islands. It is a subject of current study to determine how to extend the findings just to the uninvestigated parts of the islands. So we must be careful about how we apply the results of specific studies.

Carnation Creek teaches another sort of lesson. It was designed as an experimental study of forest land use. In landscape studies, experimentation is a fraught procedure. Was the landscape unit typical? Did the pattern of weather during the project skew the results? Do external pressures (e.g., the fishery) affect the results? These are difficult questions, but they are not reasons to dismiss the project. They must inform the results that we take away from the study, and we must be prepared for new quantitative results or different phenomena -- but for the same difficulties -- in new contexts. The greatest value of studies such as that at Carnation Creek is its long term view. This study approaches the time scale of significant secular changes in river systems, and it is capable of revealing the ultimate causes of change (which routine monitoring of the river does not). For this reason, we need more Carnation Creeks.

John Payne pointed out that the studies of resource development impacts that management agencies regularly conduct often can be viewed as field experiments. Yet they are almost never followed up in the long term. He is correct, although only a small number of studies probably would be worthwhile to follow up because both conditions are sufficiently clearly defined to permit satisfactory definition of the "experiment", and because the experiment appears as if it will yield worthwhile experience. What we certainly know from Carnation Creek is that extensive, active cooperation from the entire "sediment community" will be necessary to make such studies successful.

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8. RECOMMENDATIONS

Michael Church's independent review of the workshop is thought provoking. It is apparent that, indeed, environmental issues relating to sediment are being approached, in many cases, from too narrow of a perspective - a bias inherent in our existing organizational structures.

It is unlikely that the structure of the various government organizations will change dramatically in the near future, so we must work on changing attitudes within these structures. To compensate for organizational barriers we must learn to work more cooperatively, no matter how difficult this may be.

Michael Church does recommend a mechanism in which we can pursue this avenue. He advocates the formation of a technical advisory committee comprised of representatives from the various agencies. This committee would be responsible for providing a more holistic perspective and fostering cooperative efforts towards addressing sediment-related environmental concerns.

Therefore, the main recommendation from workshop is that:

> *The Water Resources Branch take the lead and establish a technical advisory committee to focus on addressing sediment issues in British Columbia and Yukon.*

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