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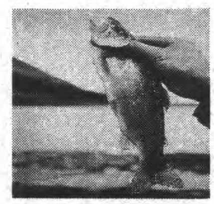
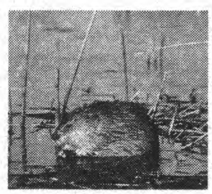
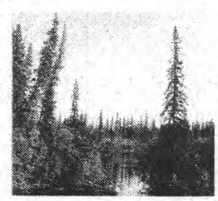
Northern River Basins Study





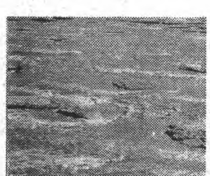





NORTHERN RIVER BASINS STUDY PROJECT REPORT NO. 133

SEDIMENT DYNAMICS AND IMPLICATIONS FOR SEDIMENT-ASSOCIATED CONTAMINANTS IN THE PEACE, ATHABASCA AND SLAVE RIVER BASINS



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Prepared for the
Northern River Basins Study
under Project 5315-E1

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PREFACE:

The Northern River Basins Study was initiated through the "Canada-Alberta-Northwest Territories Agreement Respecting the Peace-Athabasca-Slave River Basin Study, Phase II - Technical Studies" which was signed September 27, 1991. The purpose of the Study is to understand and characterize the cumulative effects of development on the water and aquatic environment of the Study Area by coordinating with existing programs and undertaking appropriate new technical studies.

This publication reports the method and findings of particular work conducted as part of the Northern River Basins Study. As such, the work was governed by a specific terms of reference and is expected to contribute information about the Study Area within the context of the overall study as described by the Study Final Report. This report has been reviewed by the Study Science Advisory Committee in regards to scientific content and has been approved by the Study Board of Directors for public release.

It is explicit in the objectives of the Study to report the results of technical work regularly to the public. This objective is served by distributing project reports to an extensive network of libraries, agencies, organizations and interested individuals and by granting universal permission to reproduce the material.

This report contains referenced data obtained from sources external to the Northern River Basins Study. Individuals interested in using external data must obtain permission to do so from the donor agency.

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Whereas the above publication is the result of a project conducted under the Northern River Basins Study and the terms of reference for that project are deemed to be fulfilled,
IT IS THEREFORE REQUESTED BY THE STUDY OFFICE THAT;
this publication be subjected to proper and responsible review and be considered for release to the public.

F. J. Wrona — 14 May 96

(Dr. Fred J. Wrona, Science Director) (Date)

Whereas it is an explicit term of reference of the Science Advisory Committee "to review, for scientific content, material for publication by the Board",
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P. Larkin — 24/May/96

(Dr. P. A. Larkin, Ph.D., Chair) (Date)

Whereas the Study Board is satisfied that this publication has been reviewed for scientific content and for immediate health implications,
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this publication be released to the public, and that this publication be designated for: **[ ] STANDARD AVAILABILITY [ ] EXPANDED AVAILABILITY**

Lucille Partington — May 29/96

(Lucille Partington, Co-chair) (Date)

Robert McLeod — May 21/96

(Robert McLeod, Co-chair) (Date)

SEDIMENT DYNAMICS AND IMPLICATIONS FOR SEDIMENT-ASSOCIATED CONTAMINANTS IN THE PEACE, ATHABASCA AND SLAVE RIVER BASINS

STUDY PERSPECTIVE

Industrial activity within the Northern River Basins Study (NRBS) area has been limited primarily to exploitation of fossil fuels and forestry resources. Mining and agriculture are other significant activities, but are less extensive and of less concern regarding point source pollution and effects on people and wildlife. The expansion of forestry activities and development of a large pulp and paper industry has led to increasing public concern over cumulative impacts of these and other developments on the health of northern ecosystems.

Many of the contaminants of concern in the study area have a strong affinity to sediment. As a result, the distribution, pathways and fates of many contaminants are closely related to the dynamics of the riverine sediments.

This report was undertaken after the sediment and sediment-associated contaminant sampling field programs were completed. As such the report provides a retrospective review of river processes affecting sediment-associated contaminant dynamics.

Related Study Questions

4a) *What are the contents and nature of the contaminants entering the system and what is their distribution and toxicity in the aquatic ecosystem with particular reference to water, sediments and biota?*

4b) *Are toxins such as dioxins, furans, mercury, etc. increasing or decreasing and what is their rate of change?*

14) *What long term monitoring programs and predictive models are required to provide an ongoing assessment of the state of the aquatic ecosystems? These programs must ensure that all stakeholders have the opportunity for input.*

The report concludes that while NRBS results have yielded some interesting observations, it would have been most useful for the monitoring and assessment of sediment work to be established prior to any field work being undertaken. The point is made that additional sediment information is likely to emerge that will have some bearing on answering questions previously raised or not yet answered by NRBS. Additional examination by a multi-disciplinary group of the NRBS data is advocated.

REPORT SUMMARY

This report examines the mechanisms of natural riverine sediment production in the Northern River Basins Study area, together with the routine data for suspended sediment in these rivers collected by Water Survey of Canada, as a background for the examination of sediment-associated contaminants in the NRBS area.

The treatment of natural sediments is presented in Chapters 2 (study area description), 3 (data analysis), 4 (time trends) and 5 (sources, pathways and fate of sediments).

The issue of sediment quality is dealt with in Chapter 6 which examines, in general terms, the contaminants associated with industrial activity in the NRBS area and the degree to which these contaminants are adsorbed onto natural river sediment.

With this background information on natural sediments and on industrial contaminants, Chapter 7, the kernel of the report, then examines the interaction between industrial contaminants and natural sediment in the NRBS area, based on previous studies of river water quality and specific projects organized as part of the NRBS investigation.

A synthesis of Conclusions is given in Chapter 8. Recommendations for future monitoring and assessment are provided in Chapter 9.

All tables and figures are provided at the end of the report after the references.

ACKNOWLEDGEMENTS

The following individuals and agencies are acknowledged for their contributions to this report. Richard Chabaylo, of the NRBS Office provided much information and many reports. Erik Ellehoj provided river distance estimates and other GIS products. Bob Crosley (Ecological Research Division, Environmental Conservation Branch, Environment Canada, Calgary) provided details of sampling sites in the NRBS sediment program, provided draft reports on sediment-associated contaminant data from all the NRBS studies, and provided helpful comments on Chapter 7 of this report. Nick Chapin (Water Survey of Canada, Environment Canada, Calgary), supplied discharge data for the period 1990-95 for selected stations in the NRBS area and sediment data for multiple-vertical sampling for the Peace River at Peace River station. M. Oullet of Weldwood of Canada Ltd. Hinton Division provided information on effluent discharges. Please accept our sincere thanks for your contributions.

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1.0 INTRODUCTION

The expansion of forestry activities and development of a large pulp and paper manufacturing industry in the Northern River Basins Study area has led to increasing public concern over cumulative impacts of these and other developments on the health of northern ecosystems. In response to these concerns, the governments of Alberta, British Columbia, Canada and the North-West Territories are undertaking a broad study of the aquatic conditions and environmental needs of the NRBS area. A location map of the Peace-Athabasca-Slave river network is provided in Figure 1.1.

This report provides a review of the suspended sediment regime of the rivers in the NRBS area and examines the implications for sediment-associated contaminant dynamics. This review was undertaken after the field work of the Hydrology/Hydraulics/ Sediment Component of the NRBS was completed. The particular emphasis of the report is on the sediment-associated contaminants derived from point-source industrial activities related to the production of pulp and paper. In addition, natural and anthropogenic sources of hydrocarbon contamination are also examined.

Fine-grained fluvial suspended sediments are a particular area of concern in the NRBS because of the affinity of point-source contaminants from pulp and paper mills and hydrocarbon development with the sediment that is transported and stored in the rivers and lakes of the area. For example, Owens and others (1994) found that the transport of dioxins and furans in the Wapiti-Smoky river system of the NRBS area occurred predominantly in suspended sediments, and that the observed variations in the concentrations of these compounds were due to flow variations.

The hypotheses of the study are as follows:

1. The river systems of the NRBS act as conduits of contaminants;
2. These systems are not inert chemically (i.e. contaminants are transferred between phases with significant sediment-associated and biological phases);
3. These systems are not inert physically;
   - material is dispersed laterally and longitudinally from point sources
   - sediment is added to the system downstream
     - diluting upstream contaminants
     - reactivating old and new deposits that may or may not be contaminated and
     - adding new sources of contaminants
   - sediment is removed from the system through short and long term deposition
   - these processes occur sequentially and/or concurrently and occur at various time and space scales.

4. The contaminant dynamics of the system, and the effects on aquatic and human health, can not be assessed, or mitigated, if the sediment dynamics are not understood.

1.1 Objectives

To address the study hypotheses the following topics are examined:

Chapter 2 Description of the causative mechanisms and boundary conditions affecting the sediment regime

Chapter 3 Description of suspended sediment data availability and fitness for purpose

Chapter 4 Description of the time trends of fluvial suspended sediment dynamics
- on a seasonal (open water and ice regime) and annual basis
- over the long term
- critical event analysis

Chapter 5 Description of sediment sources, pathways and fates of sediments:
- basin wide dynamics
- reach dynamics
- site dynamics

Chapter 6 Sediment quality:
- sediment-associated characteristics of mill effluents
- other sources of contaminants from natural and man made sources
- sediment-contaminant relationships

Chapter 7 Implications for sediment-associated contaminants, and

Chapter 8 Conclusions

Chapter 9 Recommendations for future monitoring and assessment.

1.2 Companion document

A separate document on CD-ROM is also being prepared by Environment Canada, Prairie and Northern Region, Regina to provide background maps, aerial and ground photographs for the Peace-Athabasca drainage. This will show channel changes over the last thirty years, sources of sediment along the main stems and sites of sediment sampling undertaken in the NRBS work. Release is expected later in 1996.

2.0 STUDY AREA DESCRIPTION

This chapter provides a brief overview of the environmental setting of the NRBS area as it affects the production of sediment that is carried by watercourses in the Peace-Athabasca-Slave (PAS) system. A more detailed discussion of sediment sources within the PAS system is provided in Section 5.2.

2.1 Topography

The drainage network of the PAS system is shown in Figure 2.1. The Peace and Athabasca rivers both have their headwaters in the Cordillera and then drain northeastwards towards Lake Athabasca. Most of the drainage network is incised within high-level interior plains (Figure 2.2), though some of the tributaries in the lower courses (e.g. the Wabasca River) flow through lower-lying organic wetland.

The incision of the main stems and tributaries into the Interior Plains is probably the most important control on sediment production in the area. As shown in Figure 2.3, most of the terrain in the PAS system is rolling or undulating. Most fluvial sediment seems to come from bank scour and valley wall erosion by watercourses that have cut down into this undulating surface: thus deep, steep-sided river reaches are likely to produce most of the river sediment..

The nature of the exposed rock and overburden (Section 2.2), is also an important factor of course. In general, though, because the depth of incision of the main stems (and their tributaries) decreases towards the northeast (as the elevation of land decreases), more sediment is produced in the upper parts of the Peace River drainage network. The lower parts, in a generalized sense, act primarily as conduits for the sediment from upstream.

An important point here is the much greater depth of incision of the Peace River (and tributaries) into the plains than that of the Athabasca system (Figure 5.1). Between Bennett Dam and Peace River township, the Peace River is incised more than 200 m into the plains, whereas, in contrast, the Athabasca River valley in its middle reach (at Athabasca) is less than 50 m deep, as it is in fact throughout most of its length, except near McMurray. The origin of this contrast between the two mainstem rivers is linked to the post-glacial drainage evolution of the region (Carson, 1991b, Section 9.1).

This contrast in internal relief between the two basins is reflected in sediment production. The Peace River at Peace River has a specific sediment yield of about 350 t/sq.km./yr (ignoring the land upstream of Bennett Dam). This is about 7x the specific yield of the Athabasca at Fort McMurray.

The other point to be emphasized regarding the Peace system is that virtually all sediment originates from sites downstream of the W.A.C. Bennett Dam. This is not only because of the sediment trapping effect of the dam, but also because of the lower sediment yields of streams draining the more resistant rocks of the Cordillera compared to those that have dissected the Interior Plains.

2.2 Geology

The land surface of the PAS system in Alberta is made up largely of unconsolidated surficial sediment laid down during and after the Pleistocene glacial period. Underneath, at varying depths, is much older sedimentary bedrock (largely Devonian and Cretaceous) which is generally flat-bedded to weakly-dipping. These older sedimentary strata underlie the major part of Alberta, being bounded to the west by the deformed rocks of the Cordillera and to the northeast (essentially east of the lower Athabasca and Slave rivers) by the western margins of the Canadian Shield.

Production of fluvial sediment in the PAS system, being largely from incision of watercourses into the land surface, varies in intensity according to the type and thickness of Quaternary surficial sediments and the strength and type of the underlying bedrock strata where bedrock has been exposed by downcutting.

In the lower reaches of the Athabasca system, for example, the steep trench-like rapids reach upstream of Fort McMurray (Figure 5.1) coincides with relatively resistant sandstones of the Grand Rapids Formation and the tougher shale of the Clearwater Formation (Lower Cretaceous) (Figure 2.4), whereas downstream of Fort McMurray, the Athabasca and its tributaries have incised through Quaternary sediment directly into more easily erodible bituminous sands. Downstream of Fort McMurray, right-bank tributaries tend to have cut down through outwash deposits (Figure 2.5), with little fine-grained sediment yield, whereas left bank tributaries have cut down through finer-grained lacustrine sediment.

In the upper Peace River basin (downstream of Bennett Dam), the Peace and its tributaries have cut down into underlying shale, but most of their valley walls are composed of unconsolidated silt from Quaternary glacial lakes (Figure 2.6). These tributaries are prolific suppliers of fine-grained sediment to the Peace River. Similar glaciolacustrine sediments veneer the lower parts of the Wapiti-Smoky river basins, but the major sediment source here appears to be the underlying bedrock shales. Downstream of Peace River township, the Peace River has cut down through the Quaternary sediment and upper bedrock shale into sandstones of the Peace River Formation and then into shaly silt of the Loon River Formation. These tougher sandstone strata result in a narrow, more trench-like character of the Peace River valley upstream of the Notikewin River confluence.

Overall, therefore, production of fluvial sediment in the PAS system is to a large extent controlled by the type and thickness of strata encountered by watercourses as they have cut down from the land surface first exposed after deglaciation.

2.3 Vegetation

The dominant vegetation cover of the NRBS area is mapped in Figure 2.7. It is largely mixed deciduous forest and bog, except for coniferous forest in the upper Athabasca basin, and agricultural crops in the Grande Prairie and Peace River areas and the lower Pembina valley. Where crops are grown on sloping surfaces, sediment losses can be large, but little investigation appears to have been made regarding how much of this sediment actually reaches streams and rivers. As shown in Figure 2.8, most of these cropped areas have clay or clay loam soils.

2.4 Hydrology

For much of the year the rivers of the PAS system have an ice cover. Ice statistics for the two main rivers are provided in Table 2.1. The shorter ice period on the Peace River is the result of flow regulation at Bennett Dam which has produced significant flow augmentation during the winter months for hydro-electric power generation. Comparisons of the regulated and natural flow regimes along the Peace-Slave rivers are shown in Figure 2.9, taken from Aitken et al. (1995).

Most of the runoff in the basins of the PAS system comes from melting of the winter snow pack, often accelerated and augmented by rainfall. Peak runoff and sediment movement on the larger rivers is usually in June. Tributary streams that do not have headwaters in the mountains often peak earlier in the year (April or May) depending on their elevation. On the Peace River, summer flows upstream of Bennett Dam are used to store water for winter flow augmentation, with the result that summer flows downstream on the Peace and Slave rivers have been reduced significantly following regulation (Figure 2.9). Implications of this reduction for suspended sediment transport in the Peace River are discussed in Section 5.3.2.

Table 2.2 provides a summary of flood information for rivers in the NRBS area. The highest flood peaks on record for the Smoky River and the Peace River at Peace River and Peace Point occurred in June 1990. In terms of understanding the degree of reworking of bottom deposits, and the fate of sediment-associated contaminants in such bed material, examination of the bed of the Peace after these floods might have been highly instructive.

Table 2.3 provides data for natural low flows in the area. The 7Q10 flow is defined as the annual minimum 7-day average discharge below which flows would be expected in only 10% of the years. It is thus a near-extreme (but not the minimum) annual minimum 7-day flow. In the NRBS area such low flows are usually in mid-winter when precipitation in the basins is temporarily being stored in the form of snow and ice. These flows are usually also those with the minimum concentrations of natural suspended sediment, sediment sources being protected by the prevailing ice and snow cover. At this time of the year, therefore, industrial sediment effluent encounters the least amount of natural background sediment to dilute it. Thus, assuming little seasonal change in the amount and toxicity of industrial sediment effluent, this is the time of year when river suspended sediment is most likely to reveal the presence of industrial sediment contaminants.

2.5 Summary

The background material provided above is used more fully in the next three chapters in assessing the production, movement and deposition of fine-grained river sediment in the PAS system.

3.0 SUSPENDED SEDIMENT REGIME: DATA AVAILABILITY AND FITNESS FOR PURPOSE

3.1 Introduction

This chapter addresses the routine suspended sediment sampling program in the NRBS area as undertaken by the Water Survey of Canada (WSC) and cooperators. Chapter 7 addresses issues related to special programs undertaken to measure the quality of suspended sediments and deposited sediments.

3.2 Data Availability

The primary sources of suspended sediment information are Carson (1989, 1990a,b) dealing with the Lower Athabasca basin (Fort McMurray to Embarras), Carson (1991a, 1992a,b) dealing with the Peace and Slave rivers; and Hudson and Niekus (1992) dealing with Alberta rivers at a regional level. Little additional sediment information is available since these analyses (Chapin, 1995). Thus, updating of the sediment regime to mid 1995 would not change conclusions, and is not undertaken given the short time frame available for this study.

There are 80 streamflow measurement stations at which suspended sediment samples have been collected by Water Survey of Canada (WSC) and cooperating agencies in the Athabasca, Peace and Slave river systems in the NRBS area (Hudson, 1992). These stations are all within Alberta (Figure 2.1), with the exception of several stations in the upper Peace River in British Columbia (Carson, 1992b).

Sediment data from the WSC sites are of variable quality, and duration and frequency of sampling. Twenty-three of the Alberta stations are designated "full-program" which means that they have suspended sediment samples collected at sufficiently frequent intervals that daily suspended sediment loads can be estimated (Table 3.1). Load estimates and sediment size distributions (when available) from these stations are published (e.g. HYDAT, 1994). There are a further 34 "miscellaneous" sampling stations which have infrequent samples, but which are sufficient to estimate loads through sediment rating equations (sediment concentration vs streamflow) (Table 3.2). There are numerous other stations with insufficient records to estimate sediment loads (Hudson and Niekus, 1992). Some stations have only one or two years of record with only one or two sediment samples. Sediment size distributions are occasionally determined for suspended samples from miscellaneous stations.

Suspended sediment load records are generally of short duration compared to the streamflow record. Therefore, loads have been estimated for various periods of streamflow record by Carson (1990ab, 1992a) and Hudson and Niekus (1992) (Tables 3.1 and 3.2). Note that apparent inconsistencies in load data for a given station are often the result of different time periods to which the data refer. Carson (1990a, 1990b and 1992a) provided a detailed and critical examination of the published sediment load estimates, and computed alternative best estimates of sediment load for stations in the lower Athabasca and Peace-Slave systems by applying various corrections. These load estimates have the suffix "a1", "a2" or "a3", respectively, as a superscript in Tables 3.1 and 3.2. Hudson and Niekus (1992) provide reconnaissance load estimates which are identified with the superscript suffix "b". The latter estimates are used in the cases where Carson's more detailed analysis is not available.

3.3 Accuracy of Sediment Load Values

In order to compute sediment loads, a representative sediment concentration (in mg/l) is multiplied by water discharge (m^3/s). Both the concentration and discharge are highly variable in time and space. Sediment is sampled relatively infrequently (at best a few times a day, but often on a daily, weekly or longer schedule, or event basis) and water levels are measured essentially continuously. Errors are associated with how well the sediment samples represent the sediment concentration at a given time, and how well these discrete samples represent constantly changing sediment concentrations over time.

For full time stations discrete samples are relatively closely spaced in time, hence can be interpolated to provide a"continuous" record of instantaneous sediment concentration. The interpolation method is subjective. For other "miscellaneous" stations, samples are widely spaced, thus measured concentrations are usually related to discharge through a concentration - discharge rating. Errors can occur at each step of these processes. In this section the sources and magnitudes of errors are examined for the full time stations for which sediment loads are published by WSC. The errors associated with the miscellaneous stations are more difficult to ascertain.

3.3.1. Sources of uncertainty

Various uncertainties exist in the estimation of true concentration in a single vertical at a river through sampling, but in general WSC has good controls for minimizing these errors. The major source of uncertainty in the WSC data base is in the estimation of true mean concentration in the full width of the river cross-section, given that in almost all cases WSC's sampling program is based on sampling at a single vertical. WSC's approach to this problem is to undertake comparative samples for concentration at the single vertical (c(SV) with sampling for mean concentration at multiple verticals in the cross-section (c(MV), on an occasional basis. The ratio of c(MV)/c(SV), often called the k-factor, is then used to adjust the values of the main body of c(SV) values. It will be seen below that on NRBS rivers the data available on k-factors is somewhat meager. In some cases, the variability of the k-factor over time is so limited that this is not a problem; in other cases, it poses real difficulties in the assessment of the accuracy of sediment concentration data (and therefore of sediment loads).

In the main body of analyses of sediment loads referred to in the previous section (even for "full program sediment stations"), the usual approach has been to estimate daily mean sediment concentration through a regression equation on daily mean water discharge, a variable that is, at most stations, monitored on a day-to-day basis. This regression, known as a sediment rating curve, is then used to predict daily mean sediment concentration for those days on which no sampling was done. Adjustments are often made to these values, by time (e.g. month), discharge and other conditions.

Errors in daily mean sediment concentration therefore arise from both the sampling procedure and the regression procedure. In almost all cases insufficient data are available to accurately determine the magnitude and direction of these separate errors. An indirect approach to the problem of random errors in the data has been used by Carson (1989, 1991a). This involves the computation of predicted monthly sediment load (using the regression approach) for those (few) months in which sediment sampling was done regularly and frequently by WSC (usually daily). This is followed by comparison with the computed WSC load. The standard deviation of the differences between these values is then a measure of the probable imprecision in the sediment-regression computed monthly load, at a 68% confidence. The approach assumes that the WSC daily load data are themselves correct. (There is insufficient data to rigorously evaluate the "accuracy" of the WSC stations). As well, this procedure assumes statistical independence among consecutive data sets for a station, an assumption which is not always valid.

It should be noted that the WSC daily load data will themselves contain some error, arising from different sources but primarily from unknown changes in the k-factor and, to a lesser extent, in water discharge data. Errors in water discharge may be significant during breakup conditions. No attempt has been made to assess the full error in the sediment loads arising from both imprecision in the sediment rating estimates and errors in the WSC data: only imprecision for the sediment rating estimates have been determined. The overall probable error values reported in Table 3.1 are subjective estimates.

In addition to these random errors, some of these errors in the WSC data may be systematic rather than random, though frequently the source of such errors is known and attempts are made to remove such bias.

For almost all of the small rivers listed in Table 3.2, no attempt has been made to determine the imprecision of the mean annual sediment loads. However, a letter designation is provided in the table for some of them to indicate the strength of the sediment rating curve used to predict loads at these stations. This subjective scheme identified good (A), fair (B), poor (C) rating relationships, and rating relationships that are unstable over time (U).

3.3.2. Accuracy of mainstem stations

Special attention is given to the mainstem stations because they dominate the sediment budget and because, with two exceptions, the Alberta pulp mills are located on the mainstem rivers.

3.3.2.1 Athabasca River

The data for the Athabasca River at Fort McMurray, when adjusted for month of sampling, provide a good sediment rating equation. The probable imprecision in using this equation to predict annual WSC loads at McMurray is 23% based on data analyzed by Carson (1989). Extrapolating to the mean annual load of 1974-86, and assuming statistical independence which may not be entirely valid, yields a probable imprecision in predicting the mean annual load of about 7 percent. There is additional error arising from the use of k-values based on infrequent sampling, but this is relatively small, and the overall probable error in mean annual sediment concentration is estimated at 10-15 percent.

The data for the Athabasca River at Embarras, the key station for determining the sediment and contaminant flux to Lake Athabasca, are unfortunately the most uncertain of all the mainstem stations in the Athabasca system because of lack of meaningful k-value data during the sampling period. Recent MV sampling indicates that the old SV site (in a side channel) currently needs increasing by more than 30% to make it representative of the full channel width, but the magnitude of the adjustment factor varied between 1.30 and 1.76 in four calibrations in 1989 (Carson, 1990b). The probable error in mean annual load, using a constant adjustment factor of 1.35 during the 1976-1984, period is at least 20 percent.

3.3.2.2 Peace-Slave rivers

No attempt has been made to determine the accuracy of the sediment load data for the Peace River at Dunvegan Bridge and at Peace Point because of the infrequency with which multiple vertical sampling has been undertaken at these sites.

The precision of the 1970-1990 mean annual load for the Peace River at Peace River, based on the sediment rating approach as predictors of WSC monthly loads, is estimated at 6 percent. In part the low error is due to the fact that actual measured WSC loads could be used in most of the months of very high load (at which times the sediment rating markedly over predicted WSC concentrations: Carson, 1992a, p.23).

The accuracy of mean annual load at Peace River is also influenced, however, by the reliability of the WSC loads themselves. The single vertical used for sampling at this site lies, to varying degrees, in the sediment-rich plume of the Smoky River, which enters the Peace River a short distance upstream. Attempts have been made to adjust for the varying plume position in relation to the SV site, but uncertainty still exists (Carson, 1992b, Figure 3.4). It is likely that the true probable error in the 21-year mean annual load is at least 10 percent, even without considering discharge errors during high stages and/or flows.

The precision of the 1970-1990 mean annual load for the Slave River at Fitzgerald is shown in Table 3.1 to be the best of all mainstem sites in the NRBS area. This is largely due to the regular sampling undertaken at this station especially during high-flow events. The actual sediment-rating approach for the site severely under predicted sediment concentrations during high flows but fortunately almost all such months were sampled intensively so that actual WSC loads could be used instead of sediment-rating estimates in these cases. Nonetheless, in the largest single month of predicted sediment load (May, 1974: 50 Mt), no actual sampling was done, and computations had to rely on the predicted sediment value.

The overall high accuracy of the load for this station is also related to its location (actually at Fort Smith, N.W.T.) downstream of rapids which ensures the SV sampling is representative of the full cross-section (Carson, 1992a). In the development of the sediment-rating for this station, it should be noted that the data for some of the early 1970s were ignored because of problems with pump sampling.

3.4 Temporal representation of data

Temporal representation spans a number of issues:

(1) the timing of sampling as it affects the accuracy of the existing data set;

(2) the long-term representativeness of the sampled data beyond the sampled period; and

(3) the accuracy of mean sediment load values for different durations;

These topics are briefly addressed below.

3.4.1 Variability in timing of sediment programs

Some stations were sampled frequently in particular years, and other stations in different years. This makes determination of regional sediment budgets difficult. In the Lower Athabasca, for example, much of the sampling at and below Fort McMurray was done in the early 1970s, most of the tributaries were heavily sampled in the late 1970s, whereas most of the Embarras data are based on sampling in 1976-1984.

In addition, some stations (usually for obvious logistical reasons) have sediment sampling programs that do not cover the entire period in which most sediment is moved, e.g. the Embarras station contains data for April in only 6 of the years in the period 1972-84. Almost all stations have limited, if any sampling, in the autumn and winter periods, i.e. October through March. This is relatively unimportant when the main purpose of the sediment program has been determination of sediment quantity. However, it is precisely at such periods, when levels of background "clean" sediment are low, that contaminant concentrations in sediment are likely to be greatest.

3.4.2 Extrapolation to longer periods

In situations where sediment load data are determined from sediment-rating equations, and where water discharge data are available for a longer period, load data for the sampled period can be extended to the longer discharge record fairly easily. The procedure is reliable provided that the sediment rating equation has been stable over time (though this is not always a safe assumption especially in small basins where land use changes can significantly affect the sediment rating).

In situations where the water discharge record itself is of relatively short duration, the longer-term representativeness of the sampled data are more difficult to assess. This is especially true in small basins where storms of a given magnitude are more infrequent. As an example, more than a quarter of all the tributary sediment delivered to the Athabasca River between the Clearwater River and the Embarras station in the period 1976-86 is estimated to have come from a single small tributary (the Ells River) in a single month (May, 1985), a month when in fact no sampling was undertaken at this station. Thus great care is needed in taking the mean annual load of relatively short periods (less than 20 years) as representative of longer term loads, particularly on smaller rivers, even if the data appear to be relatively accurate for the actual period for which water discharge data are available.

3.4.3 Accuracy of sediment load data for different durations

Accuracy of computed mean sediment loads also depends on the time period under study. Because positive and negative random errors tend to counteract each other, the standard error of mean values is usually smaller in the case of longer periods. As an example, the probable imprecision in using sediment-rating computed sediment loads for a single month in a single year as estimates of WSC sampled loads for the same month was estimated for the Peace River at Peace River (Carson, 1992a) as 33%. The imprecision in the load of a single year ranged from 15 to 25%. The imprecision in the mean load for a particular month in the 21-year period 1970-90 averaged 10%. And the probable imprecision in the mean annual load of the 21-year period was estimated at only 6 percent. Thus, in general, it is only at the level of mean annual loads (over fairly long periods), that meaningful comparison between the sediment loads of different stations is possible.

3.5 Variability in reported values of sediment loads

One point of confusion in dealing with mean annual sediment loads for a given station is that different values are often given, even by the same author, depending upon the purpose of the analysis, the availability of data, and the mode of estimation. For example, Table 3.2 gives the mean annual load of the Athabasca River at McMurray as 5.6 Mt for the period 1976-1984 (based on Carson, 1990b). This allows direct comparison with the station at Embarras, for which 1976-1984 is the longest period available. A later analysis of data by Carson (1992b, p.33) for a sediment budget on the Peace-Slave system required estimation of the 1970-1990 mean annual loads, which yielded a figure of 7.3 Mt at McMurray (reflecting exceptionally heavy loads in some of the additional years). In contrast, Carson (1990a, p.32), using sediment data available to 1987, estimated the mean annual load for the period 1973-1986 as being the best estimate of the long term mean, yielding a load of 6.0 Mt.

In view of the fact that the loads given in most reports are sample statistics being used as estimators of long term loads, and that these statistics change as new data become available (sometimes significantly where the station record duration is short), such inconsistency cannot be avoided, though the confusion can be minimized by reference to the specific years involved.

Sediment load data for the Lesser Slave River have been estimated independently by Hardy BBT Ltd (1989, vol II, p. 5.8). Mean annual load for 1969-1986 was estimated in the range 134 kt to 267 kt. Because few sample data were available for the high-flow range, extrapolation to these levels yields results which vary depending upon the method of analysis. Hudson and Niekus (1992) estimated the load to be 111 kt. The difference in load estimate is because the former analysis fits sediment rating curves through all the data whereas the latter divides the rating curve into low flow and higher flow regimes which causes the curve to flatten out considerably for higher flows.

3.6 Spatial representation

Figure 2.1 illustrates the spatial distribution of sediment stations reported in HYDAT (Environment Canada, 1994). Many of the records are too short to calculate sediment loads easily or meaningfully (Hudson and Niekus, 1992). Figure 3.1 illustrates stations used in this analysis.

In terms of spatial distribution, there are three clusters of stations: around Fort McMurray in the lower Athabasca basin, in the boreal uplands and in the cordillera of the Peace and Athabasca basins (Figure 2.1). There is only one mainstem station (Windfall, 07AE01) in the 1,000 km reach of the Athabasca River upstream of Fort McMurray (07CC02), but several tributary streams are monitored in the upper half of the basin. There are three mainstem stations on the Peace River within Alberta and miscellaneous sites within British Columbia. Only a few tributary streams are monitored in the Peace system within Alberta.

The mainstem sediment stations represent large drainage areas: the Athabasca river at Embarras (07DD01) drains 155,000 km^2, the Peace River at Peace Point (07KC01) 293,000 km^2 and the Slave River at Fitzgerald (07NB01) 606,000 km^2. Because these basins are so large, they consist of several major physiographic regions including mountains, foothills, uplands and plains. About a quarter of the stations have drainage areas exceeding 10,000 km^2, over a third have drainages between 1,000 and 10,000 km^2, and remainder are less than 1,000 km^2. Many of the small basins are experimental watersheds that are quite small (Table 3.1 and 3.2).

As a consequence of the size of the study area and the relative paucity of good sediment data, too little information exists to describe, in detail, the relationships between boundary conditions (topography, surficial materials, land use and energetics described in Chapter 2) and the variability in river channel characteristics and sediment responses. Some discussion of these relationships was, however, provided in the reports by Carson and Hudson-Niekus.

The relationship of stations to sediment sources and sinks and to pulp mill locations is addressed in the following sections.

3.7 Sediment stations in relation to sediment sources and sinks

3.7.1 Athabasca Basin

There are few mainstem Athabasca River sediment stations with sufficient records to provide reasonable load estimates: Embarras at km 459, below McMurray at km 622, at McMurray at km 630, and Windfall at km 1,254 (Figure 3.1). Coverage of the lower basin tributaries between about km 550 and km 630 is relatively dense. For the next 400 km of river reach there is no information. Within this reach, from the Town of Athabasca (km 955) to McMurray, the river is a steep, bedrock-controlled stretch of river, quite unlike the rest of the Athabasca's course. Several tributaries inputs are monitored in the reach from Athabasca (km 955) to the Whirlpool River (km 1,495). These tributaries define some of the major inputs into the Athabasca River.

A summary of mean annual loads is shown in Figure 3.1. The mean load on the Athabasca near Windfall is estimated at 1,299 kt (thousand tonnes), while the comparable load at McMurray is 5,630 kt. The difference is 4,331 kt, of which the monitored tributary stations that lead to this reach account for only 1,096 kt. The rest (3,235 kt), within the limitations of data accuracy, is presumed to come largely from bank scour downstream of these tributary stations and along the main stem.

The above figures mean that the majority of the sediment load at Fort McMurray comes from sources which are unknown. A special study by Hamilton et al. (1985) for Alberta Environment, however, provides some information on these sources. The report describes a detailed synoptic study of NFR loadings (non-filterable residue) in the basin for a 3-day period in each month May-October during 1984. The data are not directly comparable with WSC TSS (total suspended solids) data because of sampling techniques (Linton, Hamilton and Fuglem, 1988), because there was no calibration of the single-vertical sampling site (grab samples from a helicopter), and because the study was forced to assume that steady-state conditions existed during each 3-day period. In addition, 1984 was a year of unusually low sediment production in the Athabasca basin (Table 4.4). Nonetheless the study provides the only synoptic sediment pattern in the basin known to us and for this reason must be examined. The data are shown in Figure 3.2, but discussion is deferred to Section 5.2.1.

The major sediment sink in the Athabasca system is Lake Athabasca itself. The station at Embarras (actually 20 km downstream of Embarras) is ideally located to monitor the inputs to the lake from Athabasca River. The hydrometric and sediment programs at the site were initiated in 1971, but discontinued at the end of 1985, apart from special short-term sediment measurements in 1989 to check the k-factor. As noted previously, partly because of uncertainty in this k-factor, the probable error in the 1976-84 mean annual load of 6.85 Mt is thought to be at least 20 percent (1.4 Mt). In addition the brevity of this 9-year period raises questions as to the long-term reliability of this figure, even if the 9-year mean were accurate. The magnitude of sediment input to Lake Athabasca from Athabasca River is considered more fully in Section 5.2.3.

3.7.2 Peace-Slave system

Within Alberta there are three sediment stations on the Peace River: Peace Point at km 433, Peace River at km 1,042 and Dunvegan at km 1,137. There are a few mainstem stations with miscellaneous records between the Alberta-BC border and Lake Williston: Alces at km 1,259, Taylor at km 1,296 and Hudson Hope at km 1,380. Within Alberta there are few tributary stations in the basin, and several of these are small experimental watersheds. Significant exceptions are the Boyer and Ponton rivers at about km 700 (07JF002 & 3), the Notikewin River (07HC001), Keg River at km 958 (07HF002), and the Smoky and Simonette rivers (7GA01 and 7GF01). The Smoky and Simonette stations are about 340 km and 160 km, respectively, from the Peace River.

Almost all of the load in the Peace River at Dunvegan Bridge (07FD03) is believed to originate within British Columbia, based on observations by BC Hydro (1976), discussed in Chapter 5.

No significant station exists in the basin between Dunvegan Bridge and the Town of Peace River, and the inference that must be made is that essentially almost all the incremental load between the two stations originates in the Smoky River basin, which merges with the Peace main stem just upstream of Town of Peace River. Therefore limited information is available to determine the amounts of sediment supplied within the Smoky River basin, and whether most sediment originates from natural catchments, farmland terrain or manmade point sources. Some general commentary on these sources is made in Chapter 5.

The sediment station at Peace Point was well-located in terms on monitoring sediment delivery by the Peace to the Peace-Athabasca Delta system. The station was difficult to service from Fort Smith (N.W.T.), however, and, given the small difference in load compared to Peace River station, the recommendation was made by Carson (1992b) to discontinue the station.

The station on the Slave River (hydrometric at Fitzgerald; sediment at Fort Smith, N.W.T.) is well-located to monitor sediment delivery from the lower Peace River as well as outflows from the Peace-Athabasca Delta. As already noted, the 1970-90 sediment load for this station appears to have good accuracy.

3.7.3 Peace-Athabasca Delta

Figure 3.3 shows the locations of channels with sediment stations in the Delta. Sediment data are available for the following stations and years operated by Alberta Environment, and published by Water Survey of Canada. Number of suspended sediment samples and grain size analyses done are also given:

Station Name	Record	Sediment samples	Size analyses
Riviere des Rochers at Ben Houle's Cabin	1971-1981	129	13
Revillon Coupe below Riviere des Rochers	1971-1981	99	14
Chenal des Quatres Fourches Below Four Forks	1971-1981	116	16
Mamawi Lake Channel at Dog Camp	1971-1980	69	11
Mamawi Lake Channel at Old Dog Camp	1975, 1978, 1981	33	1
Prairie River near Lake Claire	1971-72, 1976-81	51	2

The limitations in using data from the first three to estimate inputs to the Slave River from Lake Athabasca were discussed by Carson (1992a, p. 53-55).

3.7.4 Sediment stations in relation to pulp mill locations

Ten pulp and paper mills are located in the study area. Details of these mills are provided in chapter 6. Figure 3.1 shows the location of sediment stations (with estimates of long term mean annual loads) and the seven pulp mills located in Alberta.

3.7.4.1 Athabasca basin

All five of the pulp mills in the Athabasca basin are in the middle and upper reaches (Figure 3.1). There are mills on the Athabasca River at Hinton (km 1,400), Whitecourt (two mills), and near Athabasca (km 912). As well there is a mill on the Lesser Slave River. Reliable sediment data are available for the Lesser Slave River about 5 km upstream of the pulp mill. However, there are few mainstem sediment stations near the other pulp mills. There are no mainstem stations above the Hinton mill, but there are some tributary stations. The nearest mainstem station is almost 150 km downstream at Windfall (7AE01 at km 1,254).

At Whitecourt both mills are on the Athabasca River. The Alberta Newsprint mill is located on the left bank a few km upstream of the McLeod River confluence and the Millar Western mill is located on the downstream side of the McLeod confluence on the right bank. The nearest sediment station on the Athbasca River is Windfall which is about 30 km upstream. The nearest downstream station is near Fort McMurray (7CC02, km 630) - almost 600 km away. There is a sediment station on the McLeod River about 30 km upstream of the confluence (07AG04).

3.7.4.2 Peace-Slave basin

In the Peace River basin all the pulp mills are located in the upper basin. Within British Columbia there are two mills above the Bennett Dam at Mackenzie (km 1,631) and one below the dam at Taylor (km 1,296). There are two pulp mills in Alberta: Diashowa-Marubeni 21 km below the Peace River at Peace River sediment station (07HA001 at km 1,042), and the Weyerhaeuser mill near Grande Prairie on the Wapiti River. The latter is about 180 km upstream from the Peace River sediment station (07HA001).

There are no WSC sediment stations on the Peace River near Taylor, but some routine sediment data are available to compute loads and concentrations just upstream and downstream of the Taylor mill (Figure 3.4). The BC Hydro (1976) study provided load data for the Peace River two miles upstream of the junction of the Pine River (on the south bank at Taylor). The mean annual load was given as 2.8 Mt. Added to this is the load for the Pine River itself (3.2 Mt) giving 6 Mt annual sediment load upstream of the Taylor mill.

No data are available immediately downstream of the mill, but the Beatton River joins the Peace on the north bank 15 km downstream. The load of the Beatton at Fort St John (25 km upstream of the confluence) was determined by BC Hydro to be 11.1 Mt. Therefore the load of the Peace downstream of this confluence is estimated at 17 Mt. Thus, clearly, in any attempt to trace pulp-mill contaminants from the Taylor mill in river sediments (or interpret existing contaminant data) great care will be needed in terms of location downstream from the mill and laterally across the river.

Routine WSC sediment data in the vicinity of the mill on the Wapiti River do not exist. Special studies (e.g. Noton et al., 1989) are reported in Chapter 6. The Smoky River's mean annual load is estimated at about 18 Mt, but there is limited information as to the source of this material. The Simonette River (07GF001) contributes about 629kt, and about 478kt is generated in the upper Smoky River above Hells Gate (07GA001) about 340 km above the confluence with the Peace River near Peace River (Figure 3.1).

There are generally good WSC sediment load data at the Town of Peace River, about 21 km upstream of the new Daishowa mill, with good documentation of the cross-sectional variability of sediment concentration arising from the sediment plume of the Smoky River in the right side of the channel. These cross-sectional data on sediment concentration, coupled with data from other sources on the longitudinal extent of the Smoky plume downstream, are essential in the interpretation of data on sediment-associated contaminants from the Daishowa mill.

3.8 Sediment size data

3.8.1 Importance

Sediment size information is important in resolving a number of physical sedimentation issues such as sedimentation rates for water supply filtration, as well as for determination of sedimentation rates in stilling ponds, reservoirs, channel diversions and conveyance channels and for abrasion on pumps and turbines. In addition, sediment size is very important in water quality. Linton (1988) described the direct deleterious effects of sediment on water quality. In addition, the character and quantity of sediment are fundamental concerns in fisheries. Later sections in this report point out the relationship between sediment size and contaminants in terms of the affinity of different compounds to sediment and discuss the role of sediment size in determining the flux of sediments and sediment-associated contaminants through the system.

3.8.2 Data availability

3.8.2.1 Introduction

Sediment size distributions are typically based on sieving for sand and larger material and on the rate of fall through a water column for silt and clay sized material. In the latter it is assumed that the particles are inorganic with a specific gravity of 2.65. However, sediments in reality are a mix of organic and inorganic material, and often consist of clusters of individual particles with a far lower specific gravity. Some of these clusters are robust, such as some soil aggregates, whereas other are fragile, such as flocs in river water. Problems occur in interpreting size distributions because less dense materials and disaggregated materials will be reported as being smaller than heavier or more aggregated particles. This has implications for interpreting sediment-associated contaminants because of the concentrations of many contaminants on finer, organically richer, materials, and because of the increased transportability of smaller sized particles.

Typically silts and clays are transported as aggregrates (small clods of soil), or flocs (which are loosely bound aggregrates of material). If suspended sediments are agitated with sampling and in processing, then flocs quickly break-up into smaller aggregates or individual fine particles (Droppo and Ongley 1989, 1990). The fall velocity of these particles is significantly less than for the aggregates or the flocs.

Experiments of in-situ sediment sizing using a laser particle size analyser in the Athabasca River near Hinton showed dramatic shifts in size distribution between floculated particles and mechanically disaggregated particle sizes. Based on figure 8 in Krishnappen, Stephens, Kraft and Moore (1995) it would appear that the median size of particles (d_{50}) is about 20 microns for dispersed sediments against about 50 microns for in-situ particles. The distribution is highly skewed so that the d_{95} for dispersed particles is about 90 microns whereas ninety five percent of in-situ particles are less than about 380 microns in size.

Similar shifts in reported sizes may result from laboratory procedures. The Regina sediment laboratory (Yungwirth, 1995 pers. comm.) indicate that suspended sediment samples analyzed by WSC have consistently used the Bottom Withdrawal Tube method on the original ("native") water sample with no prior treatment to remove organic material. Size analyses for suspended sediment have consistently been without either mechanical or chemical dispersion. Distilled water may be added to the native water to increase the suspension volume to the standard amount required for analysis. Typically the addition amounts to less than 20% of the final suspension and it is never more than 50 percent. The pipette method is used for size analysis of bed and bank material (Yungwirth, 1995 pers. comm.). Linton, Hamilton and Fuglem (1988), citing Yungwirth (1983 and pers. comm.), state that in the WSC pipette method the sediment water mixture is thoroughly mixed for three minutes and aliquots of the mixture are taken from a fixed depth at a fixed time to estimate fall velocities, hence sizes. As a result aggregates break-up and a finer size material results. Hence, the reported size of sediment in transport and the size of material on the bed and banks actually reflect differences in laboratory procedures as well as differences in sedimentation.

Grain size distribution curves are available for almost all WSC sediment size determinations, but the data are frequently reported in summary form: median grain size, and percentage clay, silt and sand in the cases of suspended sediment. The distinction between silt and clay, which is often the most contaminated fraction, may be an artifact of sample treatment. Samples showing only small amounts of clay in WSC analyses should not be dismissed as unlikely to contain contaminants in situations where the grain size distribution is largely a floc size distribution.

The data on percentage sand are particularly important, perhaps, because this fraction is generally assumed to be inert in terms of contaminant adsorption. Thus it is sometimes suggested that percentage sand data might be used to adjust routine contaminant data (e.g. ng contaminant per gm of sediment) in order to facilitate interpretation of within-river variability of contaminant levels in situations where variable amounts of background sand confuse the picture. This assumption is evaluated in later chapters.

Lastly, it should be noted that, partly because of budget limitations, only a small percentage of suspended sediment samples are actually analyzed for grain size characteristics. In addition, most analyses are restricted to samples with total concentrations >300 mg/L because of the unreliability of results at lower concentrations.

The Sediment Data Reference Index for Canada 1988 (WSC, 1990) lists the following data on number of sediment samples collected and number analyzed for grain size:

Station Name	Record	Sediment samples	Size analyses
Athabasca near Windfall	1974-88	82	1
Athabasca at McMurray	1966-88	950	51
Athabasca at Embarras	1971-85	985	36
Riviere des Rochers	1971-81	129	13
Peace at Dunvegan Bridge	1975-88	84	6
Peace at Peace River:	1966-88	1,816	224
Peace at Peace Point:	1967-88	122	36
Slave at Fitzgerald	1971-88	2,231	92

Use of these limited data to partition mean annual sediment load into sand and silt-clay, for example, is in many cases clearly fraught with uncertainty. In some cases the magnitude of this uncertainty could be determined, in others insufficient data are available even for this.

It should be noted that few data are available to assess the seasonality in grain size characteristics of suspended sediment because of the restriction of analyses to samples with total concentrations greater than 300 mg/L. Thus the grain size of winter samples is rarely known, though it would be expected that silt and clay would dominate the sediment at this time of year, rather than sand, given the lower flows in most rivers. This may not be true on the Peace River given the augmented winter flows since the construction of Bennett Dam. Virtually all samples collected on the Peace River are, as elsewhere, in the period May through September.

3.8.2.2 Athabasca basin

All single-vertical samples on the Athabasca recorded "at" and "below" McMurray were actually taken on the bridge at McMurray above the Clearwater confluence. The grain size data basis is therefore actually larger than indicated above (87) with reasonably good accuracy for mean data (standard error of mean in parentheses) at the SV site:

clay 23% (0.7); silt 56% (0.7); sand 21% (0.9)

Unfortunately, however, the SV site is not representative of the full cross-section, based on the only multiple-vertical sampling which was subjected to grain size analysis. This was done at high flow in August 1989. It showed a dramatic increase in concentration, primarily the sand fraction, from the right bank to the left (Figure 3.5), as expected from the bend geometry of the site (Carson, 1990a, p.8). The k-value for the SV site, for the full sediment, amounts to 1.09, meaning that concentration at the SV site (in the right half of the channel) needed to be increased by 9% to make it equivalent to the cross-section mean. However, the k-value for the silt-clay load was only 1.02, while the k-value for the sand fraction was 1.44. In view of the varying bed-geometry at the site in the years of sediment sampling, together with the varying strength of cross-currents in the bend during different flows, it is clear that application of the grain size breakdown for the SV site noted above to the whole river section is likely to entail appreciable uncertainty.

On the Athabasca at Embarras, the mean grain size breakdown of the suspended load (with standard errors) has been determined (Carson, 1990a) as:

clay 34% (1.5); silt 59.5% (1.0); sand 6.5% (0.9)

showing a marked fining of the sediment compared to the Athabasca at McMurray. However, virtually all of these samples were collected in a small side channel (Figure 3.6: SV site 1989) well separated from the main flow. This channel is known to have, at present, lower concentrations than the main channel, and it is suspected that most of this difference lies in the sand fraction. The very limited data available are not conclusive. Carson (1990a, p.35) concluded that "In the absence of additional MV samples at Embarras between 1976 and 1984, it is probably prudent to avoid making any comment at all on the grain size composition of the sediment load (for the full cross-section of the Athabasca at Embarras)".

For the record, Table 3.3 shows the varying sand component of all SV data at Embarras. Neither high mg/L sand concentrations, nor high %sand values show any obvious consistent relationship to the total sediment concentration at the SV site. There must be some suspicion, given that the Athabasca is a sand-bed river in this reach (unlike at McMurray), that variability in the %sand values partly reflects changing sand-bed geometry as it varies within floods, between floods, as well as seasonally and annually, and partly reflects variation in depth of sampling (closeness to the bed) from time to time.

3.8.2.3 Peace-Slave system

The grain size breakdowns for SV samples at the three lower mainstem stations in this basin (with standard error values) are:

Peace River (7HA01):	clay 28% (0.7);	silt 53% (0.6); sand 19% (0.7);
Peace Point (7KC01):	clay 41% (2.1);	silt 50% (1.7); sand 9% (1.2);
Slave River (7NB01):	clay 45% (1.4);	silt 45% (0.8); sand 10% (0.8);

Within the limits of the statistical accuracy of the data, the last two sets are essentially the same, indicating the marked fining in the suspended load between the Town of Peace River (where the mainstem bed is gravel) and the lower river (sand bed except for the rapids reach above Fort Smith).

At the Town of Peace River there is a tendency for the %sand to decrease as overall sediment concentration increases, but the relationship is weak. The sand concentration varies throughout the range 0%-50% when total concentrations are less than 2000 mg/L, but above 2000 mg/L most %sand values are less than 20%.

The cross-sectional representativeness of these data from the Peace River site are difficult to assess. The total concentration of suspended sediment from multiple vertical sampling across the river has ranged between 53% to 135% of that determined at the SV site. However, only one record has been found where grain size data were determined concurrently from MV sampling and from the SV site. This was on June 4, 1970, with a concentration of 1631 mg/L (MV) and 2505 mg/L (SV): the % sand at the MV site was 28% and that at the SV site was 27%.

Data have been collected for grain size at just the multiple verticals across the Peace River at Peace River, however, on 10 other occasions. They are summarized in Table 3.4. The pattern shown is complicated. In general there is a tendency for % silt-clay to rise towards both banks, presumably indicative of slightly weaker boundary shear stress there (and thus less ability to support sand in suspension). Apart from that pattern, the % silt-clay value may be roughly uniform across the channel (71 July, 73 April and 82 May), increase towards the right bank (70 June, 72 May and July, 77 May and 81 May) or increase towards the left bank (71 June, 74 May).

Similar uncertainties exist for the Peace Point data. Only four MV samples were subjected to grain size analysis, and all of these were related to the 1970-73 SV site (Figure 5.4). SV samples from then on were taken in deep water flow rather than at the edge of the sand bar as in the earlier period.

The SV grain size data on the Slave at Fort Smith, in contrast, do seem representative of the full river section because of the good mixing in the rapids upstream. The data are, however, unusual in some respects. Three-quarters of all the grain size data for the Slave River at Fort Smith were obtained in the single year, 1987, a year which provided a large range in discharge and sediment concentration.

This intensive sampling in 1987 provided a good indication of changes in grain size with flow intensity and overall sediment concentrations. Prior to the high flows of August that year, %sand ranged from 7% to 32% (in total sediment concentrations ranging 77 mg/L to 724 mg/L), but, with the onset of high flows, % sand abruptly decreased to less than 4% (in total concentrations greater than 6000 mg/L). The %sand then returned to 8%-17% as total concentrations decreased to 200 mg/L to 200 mg/L. This kind of temporal variability, at the scale of individual events, needs to be borne in mind any discussion of the degree to which sandy suspended sediment may mask contaminants.

3.9 Adequacy of WSC data for contaminant study

Though the WSC sediment data are relatively scant in most parts of the NRBS area, and subject to constraints in many cases regarding accuracy, temporal and/or spatial representativeness, they do, nonetheless, provide useful information in several important respects.

- They provide adequate data to compute the long term suspended sediment flux to Lake Athabasca and the rest of the Peace-Athabasca Delta and Great Slave Lake, the ultimate long term sinks for most of the sediment.

- The sediment load data for the mainstem stations are also sufficiently accurate for the purpose of determining the amount of dilution of sediment-associated contaminants with background sediment gleaned from diffuse natural sources. This is important in assessing the ability to detect contaminants in the river sediment even in situations where they must be present. This issue will be addressed in Chapter 7.

- Lastly, data from multiple-vertical sampling across the channel at mainstem stations are an important guide in determining where, within the cross-section, sampling for contaminants should be undertaken, and indicating how much cross-sectional variability there is likely to be. Some aspects of this have been discussed earlier in the chapter.

4.0 TIME TRENDS IN SUSPENDED SEDIMENT DYNAMICS

4.1 Seasonality of sediment production

Almost all of the annual sediment flux in the river systems of the NRBS area occurs in a short period in the spring and early summer. Two conditions determine this regime: sediment supply and stream competence. From a discussion of observations in the regime of Albertan rivers (Hudson 1989), the following points illustrate the governing situation in the study area.

Erosion of material from the river bed, banks and valley walls characteristically produces high sediment concentrations on the rise to flood peak with greatly diminished concentrations on the recession. The greatest concentrations are observed on the first of a series of flood peaks. Subsequent flood peaks generally produce successively lower concentrations. These differences are attributed to sediment supply and exhaustion phenomena of the sediment sources.

Sediment supplies are built up during low flow periods as the result of weathering and mass wasting of the river banks and valley walls. This material accumulates along the stream margins and on the bed during low flow conditions. These conditions are particularly active with freeze-thaw cycling and wetting and drying cycles. During winter the bank materials are frozen in place. In the spring the accumulated material on the river bed and banks is easily removed because it is fragmented. In addition, with spring thaw, saturation of bank and valley walls occurs, which may result in mass movements in to the stream channel. These materials are easily removed by flood flows and exhaustion of this readily available sediment supply rapidly occurs. Once the readily erodible material is flushed from the system, more resistant deposits are exposed to fluvial erosion (Carson, Taylor and Grey, 1973; Hudson, 1982; Van Sickle and Beschta, 1983), and sediment concentrations decrease.

During winter, streamflow diminishes greatly with the lowest streamflows being recorded in the late winter. Groundwater is a major source of this streamflow. Sediment concentrations are small because most sediment sources are frozen. Thus contaminated sediment from pulp mills and other point sources are likely to be detected much more readily in the suspended sediment during winter samples, and in the bed sediment at the end of winter before breakup.

These points are discussed with particular reference to the Peace, Athabasca and Slave river system in the following sections and the next chapter.

4.1.1 Athabasca basin

The mean monthly loads for the main river stations in the lower Athabasca basin are shown in Table 4.1, and the median concentrations in Table 4.2, bearing in mind that sampling in winter is very limited (generally less than 12 sampled days during October through March).

The peak Clearwater load is in May while on the Athabasca River at McMurray it is in June, the lag in the main stem reflecting delayed runoff from snowmelt in the Rocky Mountain headwaters.

Sediment concentrations and loads, however, are not perfectly in phase with runoff production: on the Athabasca, peak monthly sediment concentration occurs in June (as with sediment load) prior to peak monthly discharge in July. While this is consistent with the discussion in Section 4.1, it has been suggested that much of the May load is from mid-basin sources such as the McLeod and Pembina catchments (Carson, 1989), though data have not been analyzed to verify this. The issue is pursued further in Chapter 5.

Median sediment concentrations, as reported by WSC, are in the range 230 mg/L to 280 mg/L during May-July on the Athabasca at McMurray compared to less than 15 mg/L during December through March.

Small streams in the lower basin show greatest sediment concentrations during spring breakup in April, but daily loads are higher during May when flows are larger. Computations of the percentage of the sediment load delivered to the McMurray-Embarras reach of the Athabasca River by tributaries (in contrast to the main stem above McMurray) show that this amounts to about a third in April-May, decreases to less than 5% in June-July, and increases to about 40% in October when the Clearwater River load is almost as great as that coming from the main stem.

No analysis appears to have been done of the seasonality of sediment concentrations and loads in the upper Athabasca basin.

4.1.2 Peace-Slave basin

Analysis of seasonality of sediment production in the Peace-Slave system has been restricted to the four mainstem stations, and even then, essentially only for Peace River at Peace River and Slave River at Fort Smith. These are summarized in Table 4.3.

There is a sharp peak in monthly load at Peace River in June (when runoff is also at a peak) whereas on the Slave River (where runoff also peaks in June) there is little difference in sediment load between May and June. Monthly sediment concentrations (load divided by flow) also peak in June at Peace River, but in May on the Slave River. All these comparisons are subject to imprecision of the order of 10-20 percent. In addition, as noted previously, the largest predicted monthly load on record for the Slave River was in May 1974 when no actual sampling was done. The differences between the two stations in terms of timing of peaks are therefore probably insignificant statistically.

Sediment concentrations given in Table 4.3 for winter months seem unusually high compared to stations in the Athabasca basin and elsewhere in northern Canada. The values are almost certainly too high having been estimated by regression analysis (sediment rating) based on channel discharge.

In the case of the Slave River this was the only method possible because no actual samples have been taken at that site during November through March. The large winter channel flows in the

Peace (since regulation in 1968), together with a sediment rating based primarily on spring and summer flows, have therefore probably led to overestimating of winter concentrations.

At Peace River, predicted winter concentrations, at 30-60 mg/L, are also surprisingly high, and are also probably overestimates. The 84 actual WSC sampled concentrations in December through March averaged 29 mg/L. Downstream, at Peace Point, the eight winter WSC samples averaged 38 mg/L. Thus even WSC winter samples on Peace River are significantly higher than on the Athabasca River (less than 15 mg/L). The reason for the discrepancy has not been examined, but the higher concentrations on the Peace may result from increased channel velocities during winter following augmentation for power production upstream.

4.2 Year to year variability

Annual sediment conditions on most rivers vary significantly, which is the reason, of course, why sediment collection and discharge monitoring programs need to cover many years if meaningful long-term average data are to be determined. This is especially true on small rivers. It should be noted that, in general, year-to-year variability in sediment loads is primarily the result of annual variability in runoff production.

4.2.1 Athabasca basin

Annual suspended loads for the Athabasca at Fort McMurray are presented in Table 4.4 (Col. 3) for 1970-87 (Carson, 1990a) and show the typical skewed distribution. Annual loads exceeded the mean in 10 of the 18 years, but the largest load (in 1971) was estimated at 20 Mt, more than three times the mean. The same year was also well above-average on the Clearwater River, but peak load on the Clearwater occurred in 1974. Peak annual load in the period 1970-87 on the Athabasca was almost 13x the smallest annual load.

Analysis of data for 10 smaller tributaries in the lower basin (Carson, 1990a), in the shorter time period 1976-87, showed a larger range in their combined sediment loads, peak load (1985) being 33x the minimum annual load (1981). The range becomes even greater for individual basins. As already noted, 1985 was a year of severe sediment production on the Ells River, a left bank tributary to Athabasca River downstream of Fort Mackay. The annual load on the Ells River in 1985 was estimated at 558 kt, more than 5x the next previous high (1984) in the 1975-86 period, and 230x the minimum annual load (1980).

No published data have been found for other stations in the Athabasca basin, except for the Lesser Slave basin (Hardy BBT, 1989).

4.2.2 Peace River basin

Estimated annual sediment loads for Peace River at Dunvegan Bridge, at Peace River, at Peace Point, and for the Slave River at Fort Smith are given in Table 4.5. The 1990 load at both upper stations was the peak in the period 1970-90 (only available to 1975 at Dunvegan Bridge), whereas at Peace Point the peak was 1972 and on the Slave it was 1974. Again it should be remembered that the imprecision in sediment rating loads of individual years is of the order of 15-25%, not including other sources of error, so that some of these differences may be statistically invalid.

At all three stations on the Peace the peak annual load is only about 11x the minimum annual load in the period; on the Slave it is only 8x, presumably reflecting losses to Lake Athabasca in high-flow years and gains from the lake in low-flow years.

The limited annual variability on the mainstem stations, compared to that on smaller rivers (as noted for the Athabasca) should not be viewed as trivializing the amount of sediment reworking that takes place in these high-flow years, however, as will become apparent in the next section.

4.3 Critical events

Rivers can move large amounts of sediment (sometimes major portions of their loads) in a matter of weeks or even days, these events often producing major changes to channel geometry, reworking of existing channel sediment, and deposition of new sedimentary deposits.

WSC produces summary statistics for many of its stations which indicate sediment conditions in the peak 4 days ("Best 1%") in each year. Unfortunately, the analysis is only available for raw, unadjusted WSC data at stations where full-program sampling has been done. This means that the data have not always been corrected for unrepresentativeness of the SV sampling site; nor are data available for years in which limited or no sampling was done, but for which runoff data are available so that sediment rating estimates of concentration and load could be computed.

The peak period sediment data for Athabasca at McMurray for 1973-1986 are shown in Table 4.6. The data indicate that, for sediment concentration, in most years the peak 4-day mean was no more than 12x the mean value for the year; and for sediment load, that the peak 4-day period accounted for only 4-17% of the annual load in that period. The data may, however, be misleading because they do not include the high-load years of the early 1970s. No equivalent data exist for 1971, but July in that year produced 61% of the suspended load for the year.

Similar data have not been found for Peace River, though the raw WSC data would have been misleading anyway given the need to adjust all the loads at the town of Peace River by a flow-variable k-factor. However, some indication of the significance of critical events is provided by the June 1990 sediment data for that river. At the town of Peace River, the daily mean measured concentration on June 14 was 9450 mg/L and the sediment load on that day was 13.5 Mt. The estimated load for the previous day was 15.9 Mt. Thus in two days, the total load was almost 30 Mt, only slightly less than the mean annual load.

On the Slave River at Fort Smith, in the same flood, the measured concentration peaked at 8950 mg/L (June 19) and the total suspended load on that day and the next amounted to 12.7 Mt. In contrast to Peace River, this is substantially less than the mean annual load. In fact the sediment moving along Slave River during the 10-day flood was significantly less than at Peace River indicating sediment loss in the reach, probably mostly into Lake Athabasca (as discussed in the next section) when reverse flows from Peace River into Lake Athabasca took place over a period of five days. The significant point here, from the standpoint of sediment deposition, is that it is only in extreme floods that sediment movement from Peace River into the lake occurs. Between 1970 and 1990, reverse flows occurred in only 9 years, with large volumes of water being involved in only four of those years.

The marked changes in the grain size of suspended sediment that can occur within large floods has already been noted in the case of the Slave River (Section 3.7.2.3). Similar changes are also known in the composition of bed material, though few data are available in the NRBS area.

In terms of sediment-associated contaminants in the bed sediment of these rivers, it should be clear that presence or absence may be determined not only by where sampling is done, but also when it is done. In the aftermath of floods that have involved a great deal of channel reworking (and deposition of new relatively clean sediment from natural sources), contaminated sediment may be very difficult to detect. The converse is true after several years of low flow with limited sediment movement, especially if the spring freshet is weak.

5.0 <u>SEDIMENT SOURCES, PATHWAYS AND FATES</u>

5.1 Introduction

Meaningful discussion of sediment sources, the pathways used by rivers to move entrained sediment and the sinks in which such sediment is deposited requires separate treatment at different scales.

At the basin-wide scale in the Athabasca-Peace system, it is true to say that sediment is primarily entrained in the upper parts of the basin and is deposited within the lower parts, particularly over very long time scales (thousands of years and beyond). Expressed differently, over the long term, the upper basin is one of net erosion and the lower basin is one of net deposition. The key word is "net" : deposition also occurs in the upper basin, but the amount of erosion exceeds the amount of deposition.

Thus, as sediment moves from the upper basin to the lower basin, there will be reaches en route in which sediment is still being deposited, even though net deposition may be nil, and the reach is in equilibrium or even showing net erosion. This is important in the context of sediment in the effluent from pulp mills, which tend to be located in the upper and middle reaches. Just because the lower basin is the area of net deposition, does not mean that most of the sediment entrained in the upper and middle basins is actually deposited in the lower basin.

Typically sediment, depending on the grain size, moves in pulses from one sediment source to a sediment sink some distance downstream, at which place the sediment may remain in storage for tens, hundreds or even thousands of years, before being reactivated as a sediment source and moved downstream again. This general model applies even to fine-grained sediments, though the distance of travel tends to be much greater in these cases.

This chapter therefore treats the entrainment, movement and deposition of sediment at three different scales: basin-wide; reaches; and site dynamics.

5.2 Basin-wide dynamics

5.2.1 Athabasca basin

As discussed in Section 3..1, and illustrated in Figure 3.1, almost 35% of the roughly 7 Mt sediment in the Athabasca passing Embarras into Lake Athabasca originates upstream of sediment stations in the upper basin, mostly in the basin upstream of Windfall, but with a large tributary component from the Pembina River at Jarvie. Almost 50% originates in the middle basin between these stations and Fort McMurray.

Unfortunately, very little is known about the actual sources of these sediments, though the two main contributors in the upper basin are likely to produce sediment of radically different caliber. The Athabasca River near Windfall is a wandering, gravel-bed channel with sandy-gravelly banks. Only one suspended sediment sample during 1974-84 had a concentration greater than 1,000 mg/L, with 28% sand. This is the only grain size information available for the suspended sediment (WSC, 1990). The Pembina River at Jarvie, in contrast, is an irregularly meandering sand-bed river, often highly sinuous, with cut banks of silt and sand. In many places the sandy bed material is only a veneer over stiff glaciolacustrine clay. Bank erosion appears to be a major source of sediment in Pembina River at least in the lower reach of the river between the Paddle River and the Athabasca River. Eight samples at the Jarvie station in 1976-83 had concentrations above 1,000 mg/L. The sand fraction in the five samples analyzed ranged from 10% to 19 percent (WSC, 1990).

The difference in sediment produced between these two main sources may be important in terms of variability in the quality of the suspended load in the middle reach of the mainstem Athabasca at different times of the year. The sediment input from the Pembina results from high spring melt flows, that may be enhanced by rain to produce large floods, and summer rainstorms. Upper Athabasca runoff is delayed because of elevation and is derived initially by upper foothill and mountain snowmelt, and later in the spring and throughout the summer by glacial melt, both of which may be enhanced by rain.

It is not known how much of the 3.2 Mt of sediment that is entrained between the upper basin stations and McMurray originates in bank erosion of similar glaciolacustrine and alluvial sediments. In particular, the contribution of sediment from the steep bedrock reach between the Town of Athabasca (km 955) and McMurray (km 630) is unknown.

The surveys by Hamilton et al. (1985), reported in Section 3..1 provide some information, subject to the caveats previously noted. They confirm the importance of the Pembina River inputs in May and June (Figure 3.2), but also reveal the significant input from the House River, entering the Athabasca about 140 km upstream of McMurray. This was the largest tributary supplier of sediment to the Athabasca in June and September, and second only to the Clearwater River in July. As a percentage of the load from upstream, the House load in June and July amounted to only 4-8%, however, and presumably would be much smaller in normal to high-flow years. The main point to emerge from Figure 3.2 is probably the large unexplained load (presumably bank erosion) entering the Athabasca river in the steep reach between Athabasca (km 955) and Fort McMurray (km 630). In June, for example, only 15 % (8,200 t/day out of the 54,500 t/day) increment between the two stations could be attributed to sampled tributary inputs.

In the Lower Athabasca river basin (Carson, 1989), most of the tributary streams are deeply incised in their lower reaches into Quaternary surficial sediments of silty-clays or sands and into older underlying strata including the oil-bearing sands. On the basis of maps and photographs, it seems probable that most of the sediment transported in these tributaries is derived from the channel banks and valley walls, especially in the reaches near the Athabasca River where the valley sides are tall, steep and subject to lateral scour at meander bend sites. Sediment yields in these tributaries can therefore be expected to be controlled more by the length of the incised reach than by overall terrain steepness or basin area. This conclusion is supported by the analysis of

Hudson (1982) who showed that the sediment load of the Muskeg River (07DA08, 1,460 km^2, load 0.9 kt) was derived almost exclusively from channel sources.

How much of this sediment in these tributaries actually moves in suspension, as distinct from bed load, appears to depend upon the fineness of the sediment contributed to the stream, and this varies among the tributaries. Some indication is provided by the surficial deposits map (Figure 2.5), but local detail is important (e.g. maps by Hamilton and Mellon, 1973), and the texture of the underlying weak sediments, where exposed in river banks, can be just as important as that of surficial deposits.

Analysis of 1976-84 sediment loads of the Athabasca River at McMurray and at Embarras and for all the major tributaries to the reach between the two stations was undertaken by Carson (1990a). The analysis indicated that channel scour, bank erosion and valley-wall undercutting along the main stem between McMurray (km 630) and Embarras (km 459) produced more suspended sediment than the combined total delivered to the reach in the same period by all tributaries. The conclusion must be regarded as tentative, however, given the uncertainty in the sediment load data for Embarras noted earlier in this chapter.

In terms of an overall sediment budget for the Athabasca basin, it is clear that almost all of the sediment that is discharged by the Athabasca River into Lake Athabasca is ultimately from the basin upstream of Fort McMurray, and largely from the reach between Windfall and McMurray.

The mean annual sediment load at Embarras for 1976-84 was estimated at 6.85 Mt. Annual sediment inflows to Lake Athabasca from the Athabasca River were estimated by Neill et al. (1981) for three years as 3.3 Mt (1976), 5.3 Mt (1975) and 8.2 Mt (1973). For various reasons, these figures seem too low as indicators of mean annual sediment input (Carson, 1992a, App. II). A figure of 9 Mt was put forward as an estimate of the 1970-1990 mean suspended load delivered to the lake from the Athabasca River, based on a predicted load at McMurray for the same period of 7.3 Mt (Carson, 1992b, p. 33), though the long term mean lake input from the river may be nearer 8 Mt.

5.2.2 Peace-Slave basin

Similar conclusions seem to be applicable in the Peace-Slave basin, though the uppermost station on the Peace River in Alberta (at Dunvegan Bridge) has a mean annual load of 15.6 Mt, an order of magnitude greater than the comparable station on the Athabasca River (near Windfall).

Most of the sediment load at Dunvegan appears to be derived from bank erosion and valley-wall slides and gullies on tributaries leading to the Peace River in the reach immediately below Bennett Dam. As indicated in Figure 5.1, the much greater sediment loads on the Peace River than in the Athabasca River are consistent with the much greater depth of incision of the Peace River into the surrounding Alberta Plateau.

Little sediment appears to be supplied between the provincial border and Dunvegan Bridge, the mean annual load at the border as reported by BC Hydro (1976) being essentially the same as at Dunvegan Bridge. Analyses by BC Hydro (1976) also indicated that 11 Mt of the 16 Mt of suspended sediment moving across the provincial border in the average year originates in a single tributary, the Beatton River which enters the Peace River just downstream of Taylor, B.C., about 18 km upstream of the BC/Alberta border.

Somewhat contrary conclusions were reached by Shaw et al. (1990) who reported the results of once-a-month synoptic surveys during 1988. They commented: "average concentrations of suspended solids in the main stem increased gradually from 41 mg/L at the BC-Alberta border to 408 mg/L at Peace Point" (Figure 5.2).

The study by Shaw et al. (1990) showed peak concentration was 176 mg/L near the border on May 9 and 830 mg/L near Dunvegan Bridge on the same day. Both samples were grab samples apparently taken at mid-channel and it is uncertain how representative they were of the full section. This comment is especially important at the provincial border where strong lateral gradients in sediment concentration were reported by BC Hydro (1976) and would be expected on the basis of the huge sediment input from the Beatton River.

The higher sediment yields in the upper Peace basin (compared to the Athabasca) presumably reflect not only the much greater depth of incision of the tributaries, but also the weaker sediment strata (much of it being soft shale) as well as more extensive areas of fine-grained glaciolacustrine sediment into which banks are cut. Downstream of Fort St. John (B.C.), large amounts of sediment are also supplied by erosion of extensive areas of farmland (Figure 2.7). The magnitude of this problem is being assessed by Agriculture Canada but no estimates of inputs to the river system are yet available.

The mean annual sediment load for Peace River at Peace River is more than double that at Dunvegan Bridge (33.7 Mt). Almost all of this is assumed to come from the Smoky River and its tributaries, the basin of which accounts for more than 90% of the incremental basin area between Dunvegan Bridge and the town of Peace River. Annual sediment yield (per unit area) from the Smoky River basin averages 330 tonnes per sq. km., essentially identical to that for the Peace River basin between Bennett Dam and the provincial border, but only half that of the Beatton River.

Downstream of the Town of Peace River, sediment inputs to the river decrease abruptly. This is attributed to the marked flattening of the gradient of the main stem (and tributaries) and the decrease in depth of valleys in the lower-lying terrain. The increase in mean annual load between Peace River and Peace Point is only 2.7 Mt and the statistical significance of this difference is uncertain given the unknown precision of the data for Peace Point. The same comment applies to the Slave River at Fitzgerald which has a mean annual load 3 Mt less than that at Peace River.

Few tributary inputs are measured over the reach between Peace River and Peace Point. The major inputs are from the Ponton River (7JF03: almost 500 kt for a yield of 198 t/km^2/y) and the Notikewin River (7HC01: 220 kt, 47 t/km^2/y). The loads and yields from the Keg (7HF02: 3 kt/y, 4.7 t/km^2/y) and Boyer (7JF02: 12 kt, 1.8 t/km^2/y) are low. The high loads from the Ponton are thought to result from significant channel downcutting near the confluence with the Peace River.

Again it should be noted that comments regarding the small increase in load between Peace River and Peace Point do not agree with the findings of Shaw et al. (1990), given in Figure 5.2. The low sediment input from the Smoky River (averaging 89 mg/L) in that diagram is particularly misleading. Discharge data from the WSC gauge on the Smoky River at Watino show that the mean discharge in 1988 was the lowest on record since 1915 so that the 1988 sediment inputs from the Smoky would be similarly completely unrepresentative of the long term.

5.2.3 Peace-Athabasca Delta area

Only one analysis of sediment data to estimate how much of the Athabasca River sediment moves through Lake Athabasca into Slave River is known (Neill et al., 1981). Based solely on data for the Riviere des Rochers outflow channel, they estimated the outflow (as a percentage of sediment inflow to the lake) as 79% in 1973, 55% in 1975 and 61% in 1976.

Doubts have been raised regarding the adequacy of these data for this purpose (Carson, 1992a, p. 54). In addition, it was felt that the inflow loads computed by Neill et al. were too low, so that the percentage outflow was probably lower than indicated above. How these estimates might change with the inclusion of the other two outflow channels, and with application to years of high sediment flow rather than the three "low to average" years used (Table 4.4), are questions that do not seem to have been addressed.

As noted earlier in this report, the long term mean annual load for the Athabasca entering Lake Athabasca is thought to be about 7 Mt to 8 Mt. Assuming an outflow percentage to Slave River of 67% as suggested by Neill et al. (1981), the net sediment influx to Lake Athabasca from Athabasca River would be about 2.5 Mt, and the outflow from the lake would be about 5 Mt per year.

These data also imply that the mean annual sediment load on the Slave at Fitzgerald should be about 5 Mt higher than for the Peace at Peace Point. As already noted, the mean annual suspended load on the Slave has been estimated at 3 Mt lower than that at Peace Point. This implies an average annual loss of sediment to the delta area from the Peace River of about 8 Mt during the period 1970-1990 (to which the sediment load data refer). This figure seems somewhat high given that flows on Peace River have been regulated since 1968 and overbank flooding has been almost non-existent since regulation (Spitzer, 1992).

Some of the 8 Mt amount must result from error in the difference in loads computed for Peace Point and for the Slave at Fitzgerald: in fact the probable imprecision in the difference between the two stations is roughly the same as the magnitude of the difference.

Nonetheless it is evident that substantial loss of sediment does occur between Peace Point and Fitzgerald as indicated by data from the record flood of late June, 1990 (Carson, 1992a, p.49-52). The sediment load at Fitzgerald during June 1990 was 41 Mt, this being 10 Mt less than determined for Peace Point. Normally little statistical significance can be attached to comparisons of individual months, but the sampling coverage at both sites was unusually good during the high-flow periods, and it is unlikely that the error in the difference is more than about 3 Mt. This implies at least 7 Mt of deposition in the delta area in that event.

No detailed analysis has been made of where this deposition of sediment between Peace Point and Fitzgerald occurs. Much of it appears to occur in Lake Athabasca through reverse flows in the outflow channels during major floods on the Peace River. Carson (1992a, p.44-45) estimated that up to 5 Mt of sediment may have moved into Lake Athabasca from Peace River in each of the years 1972, 1974 and 1979. Spitzer (1992) noted that in the June 1990 floods, sediment and log debris from Peace River were apparently moved well into Lake Athabasca as far as the William River mouth.

It seems likely, however, that some of this sediment loss is also occurring as deposition within the Peace River channel downstream of Peace Point, though this is conjecture. Additional discussion of this possibility is provided in the next section.

5.3 Sediment dynamics at the reach scale.

As expected from the variable gradients in their long profiles (Figure 5.1), the Athabasca and Peace rivers both portray radically different reach characteristics between their sources and their confluence.

5.3.1 Athabasca River

Between the Weldwood pulp mill near Hinton (km 1400) and the new mill just downstream of the Town of Athabasca (km 955), the Athabasca River is a wandering gravel-bed river, well-described and photographed in the Whitecourt reach by Kellerhals et al. (1972, their Figure 3.3). Median bed material diameter is in the range 40 mm-55 mm. Large bars of gravel are common in the river eventually becoming wooded islands and forcing water to undercut banks elsewhere to provide enough channel cross-section area to carry the flow. Fine-grained sediment on the bed is uncommon, but can be found in the lee of gravel bars, especially where trapped by uprooted trees. Side channels between islands and bars will sometimes become plugged with fine sediment as well. The river gradient is reported by Kellerhals et al. (1972) as being about 1.3 metre per km between Hinton and Whitecourt, decreasing downstream to about 0.3 m per km at Athabasca. The amount of fine-grained sediment in the bed would therefore be expected to increase down the reach.

Downstream, between the Town of Athabasca and Fort McMurray (km 630), good descriptions of the channel reach have not been found. The river gradient is steeper than that upstream and appears to mark a new post-glacial reach of the river. Inspection of topographic sheets indicates that over much of this reach, the river is incised in a meandering bedrock gorge, and the channel is presumed to be largely non-alluvial. The mean gradient is reported by Kellerhals et al. (1972) to be 0.67 m per km (with many rapids), compared to 0.3 m/km upstream and 0.24 m/km at McMurray.

The flattening of the river, where it is joined by the Clearwater just downstream of McMurray (Figure 5.1) is quite abrupt (the mean gradient between McMurray and Fort Mackay being about 0.14 m/km), and coincides with a marked change in character of the channel and valley (which becomes much wider). While gravel is still found on the bed surface downstream of the Clearwater confluence, it is much finer (median about 12 mm diameter) and seems to be primarily in mid-island bars. Elsewhere the channel is dominated by sand Some of this is brought in by the Clearwater River, but most is presumed to result from deposition of part of the suspended load of the Athabasca River itself. Photographs of recent bar deposits in the Fort Mackay area show essentially all sand except for thin layers of silt-clay.

Between Fort Mackay and Embarras airport, the river slope decreases further to about 0.1 m/km and the entire character of the channel has become much more alluvial. The river here has become reasonably sinuous with occasional well-developed meanders. A well-defined floodplain of silt and sand has been built-up in most places, but elsewhere the river abuts the main post-glacial sandy terrace level (on which Embarras Airport stands) directly, separated by a prominent bluff. The bed is sandy throughout with a median particle diameter reported by Kellerhals et al. (1972) as 0.19 mm, and believed to be quite deep. No data on bed material appear to have been published by WSC, but internal files show samples ranging from 0.25 mm to 0.45 mm in median diameter. Sediment in some of the side channels (Figure 3.6) is likely to be finer, but no data are available to assess this speculation.

Downstream, river gradient becomes much gentler still as the river approaches Lake Athabasca. Kellerhals et al. (1972) report the mean gradient below Embarras Airport to be only 0.03 m/km in the delta area. Bed sediment is expected to become much finer as silt and clay settle out in the more slowly flowing water. The delta continues to extend into Lake Athabasca e.g. the Canadian Wildlife observing station is now about 2 km upstream.

5.3.2 Peace-Slave rivers

The downstream change in reach conditions on the Peace River is not unlike that on the Athabasca River (Figure 5.1). Between Hudson Hope (just downstream of the Bennett Dam in British Columbia) and Carcajou, the river is essentially gravel-bedded; downstream it is sand-bedded.

Kellerhals et al. (1972) report the mean gradient between Hudson Hope and Carcajou to gradually decrease from 0.49 m/km to 0.21 m/km; between Carcajou and Peace Point it averages 0.055 to 0.085 m/km, ignoring the falls of Vermillion Chutes where the river is caught on bedrock.

Sediment data from Shaw and Kellerhals (1982), given in Figure 5.3, indicate changes in bed material size through the gravel-bedded reach, averaging about 30 mm median diameter in the upper parts to less than 20 mm downstream of Town of Peace River where the Smoky River joins the main stem.

At Peace Point, the bed material is described by Kellerhals et al. (1972) as "shallow sand with local gravel over easily erodible rock". Bed sediment data reported by WSC in the early 1970s indicate the bed material to be well-sorted medium sand with median grain diameter generally in the range 0.25 mm to 0.30 mm. The October 1973 survey just upstream of Peace Point is summarized in Figure 5.4: the expected fining of the bed sediment towards the top of the left-bank bar and into the adjacent backwater channel (where almost 50% of the sediment is silt and clay) is worth noting. It seems likely that a large part of the generally sandy channel downstream of Peace Point may contain such backwater areas in view of the large number of split and side channels shown on the topographic map, but no information has been found to support this view. No other WSC bed sediment data are known for this reach.

The sand bed river of the lower basin meanders quite extensively in places. Here lateral erosion of outer bends is accompanied by deposition on point bars. While this is a natural process in meandering alluvial channels, the large net loss of sediment between Peace Point and the Slave at Fitzgerald, noted in Section 5.2.3, suggests that deposition of suspended load on point bars and in associated side channels may be more pronounced than under normal equilibrium conditions.

The gentle gradient of the river continues (as Slave River) as far as Fitzgerald where water descends over the exposed edge of the Canadian Shield in the 30-km long Slave River Rapids, at the base of which is located the WSC sediment station at Fort Smith (N.W.T.).

There is one important difference between the Peace and Athabasca rivers in terms of deposition of bed material and general bed stability that should be noted. Since 1968, flood flows along the Peace have been dramatically reduced by regulation at Bennett Dam (Figure 2.9). This has had at least two important repercussions on the sediment regime.

One is that sediment concentrations during flood flows in the Peace channel are now higher than they were prior to regulation. This is because most of the sediment is brought in by tributary rivers, and less water is now available from the upper Peace basin to dilute these May-July sediment inputs. It was estimated by Carson (1991a) that sediment concentrations in June at the town of Peace River are approximately double what they were before flow regulation. With higher sediment concentrations, it is likely that sediment is being deposited out of the suspended load more rapidly now than in the past.

The second point, and related to the first, is that the channel of Peace River has shrunk in width since regulation as a reduction in the magnitude of the dominant open-water flow through it. The topic was examined by Kellerhals and Church (1989) in the B.C. reach downstream of Bennett Dam. They noted that, on the basis of "regime theory", a shrinkage in width of about 30% would be expected as a result of the decrease in dominant flow. This shrinkage is taking place today, primarily by abandonment of secondary channels, conversion of gravel bars into vegetated islands, and accretion of sand and silt at bar edges. Thus fine suspended sediment, which might be expected to travel long distances through to the sand bed reach downstream of Carcajou is now, to some degree, settling out in low-velocity parts of the upper main stem. This would be expected to affect the settling out of sediment effluent downstream of the Taylor mill and also the Daishowa mill at Town of Peace River.

A third point, and related to the second, is that sediment loads in the Peace River are probably lower now than prior to regulation. No data exist to verify this point, but, even without sediment trapping behind Bennett Dam (which is believed to be minimal) smaller flood flows downstream of the dam would be expected to result in less frequent and less aggressive bank attack by the river.

5.3.3 Summary comment

Bed conditions are thus known in general terms for most of the main reaches of the Athabasca and Peace rivers. From the standpoint of contaminant research, however, the available data are hardly adequate. How much of the bed downstream of Hinton is subject to settling out of the silt-clay which is the fraction most susceptible to contaminant adsorption? In which reaches, and in which parts of the reach, is fine sediment found? How long does this silt-clay sediment stay in storage? Answers to these questions are hard to find. Some discussion is provided in the next section dealing with site dynamics.

5.4 Site dynamics

5.4.1 Introduction

The reach of the Athabasca River in the vicinity of the Hinton pulp mill has been examined in some detail as part of the NRBS program, primarily by the National Water Research Institute (NWRI).

Krishnappan and Stephens (1995), for example, have examined conditions necessary for deposition of Athabasca sediment on the channel bed and then subsequent resuspension, using a rotating glass flume. This follows similar previous studies of sediment from the Nechako and Fraser Rivers in British Columbia (Krishnappan and Engel, 1994). In tandem with this laboratory work, Krishnappan et al. (1995) conducted a field study of sediment movement along the Athabasca River between Entrance (8 km upstream of the Hinton pulp mill) and Windfall (175 km downstream of the mill). This allowed determination of rates of deposition of sediment in different lengths of the reach.

In addition to this work, Trillium (1995) undertook an analysis of cross-channel patterns of shear-stress distribution at different discharges for the Athabasca River (at the WSC gauging station at Hinton), and also for the Peace River at Peace River, to provide some perspective for the data from NWRI.

These studies are briefly summarized below. The two NWRI studies are available separately as part of the NRBS program. The report by Trillium is provided as Appendix A of this report.

5.4.2 Critical shear-stresses for erosion and deposition of Athabasca river sediment

Fluid shear stresses in flowing water arise from the higher velocity of one layer of fluid above the layer below. Such stresses are important in the movement of suspended sediment because recent work by various investigators, including those at NWRI, has shown that much suspended sediment is actually in the form of flocs. As these flocs settle towards the bed they enter a region of high fluid shear stress which can break up weak flocs and cause dispersal of the finer grains back into the flow above, only the stronger flocs settling out.

The magnitude of the fluid shear stresses near the bed is related to another shear stress, the bed shear stress, which is the downchannel tangential force (per unit area of the bed) between the flowing water and the bed. The magnitude of the bed shear stress is a major determinant of whether or not bed material will be entrained by the flow and reincorporated into the suspended sediment load.

Krishnappan and Stephens (1995) examined the magnitude of bed shear stress at which settling of sediment occurred and then the stress necessary to reentrain sediment into suspension. Flume runs for deposition were done at bed shear stresses in the range 0.121 to 0.324 Pascals (Newtons per square metre of bed) with initial sediment concentrations of 200 mg/L. Some sedimentation occurred in all the tests, amounting to about 25% of the sediment at the highest bed stress and 80% at the lowest bed shear stress. The report concluded that, at a stress slightly less than 0.12 Pa, all the sediment would have settled, and this was the value taken as the critical stress for deposition.

Flume runs were then undertaken to examine the reentrainment of the sediment that had settled on the glass bed. Bed shear stress was incrementally increased from about 0.06 Pa to 0.52 Pa. No erosion of the bed occurred until the bed shear stress was increased to 0.17 Pa, which was taken by the NWRI team to be the critical stress for erosion. However, it should be noted that the rate of bed erosion decreased over time, as the bed shear stress was held constant.

There are, of course, modifications necessary to make the smooth-bed laboratory work applicable to the natural gravel bed of the Athabasca River. Krishnappan and Stephens (1995) suggested that the critical stress values found in the flume would need to be increased by 5x to make them applicable to the natural river. This would produced critical stresses of 0.6 Pa for deposition and 0.85 Pa for resuspension. However, in situations where fine sediment has settled into the spaces between gravel particles on a river bed, it might be argued that substantially higher stresses would be needed to reentrain the fines, comparable with the level of "flushing flows" used in the maintenance of fish habitat.

5.4.3 Summary of the report by Trillium

It appears that, at the time of the work by Trillium (1995), the NWRI report just described was not available, because the computations undertaken by Trillium were based on sediment data from the Fraser River (Krishnappan and Engel, 1994). In this earlier NWRI report, the (field-adjusted) critical bed stress values were 0.28 Pa for deposition and 0.6 Pa for resuspension. The differences do not change the eventual conclusions appreciably.

The analysis of the data for the cross-section on the Athabasca River at Hinton showed that, under an ice cover, bed shear was below the level needed to prevent deposition of sediment at many places on the stream bed. However, under open-water conditions, the bed shear stresses were substantially higher peaking at about 20 Pa in the channel centre at 61% flow exceedance and over 50 Pa at channel centre at 1% flow exceedance.

Notwithstanding the much higher bed shear under open water conditions, shear stresses decrease appreciably towards the bank margins, and on the right side of the river the graphs show a strip up to 10 m wide (about 10% of channel width) in which sediment would be difficult to reentrain at 61% to 35% flow exceedance in the average year, even assuming the low critical stress adapted from the glass flume work. This right bank strip would be wider and persist longer if more conventional flushing flows were needed to clean out sediment.

It should be emphasized that these conclusions apply specifically to the WSC cross-section at Hinton. The same general conclusions are likely to apply throughout the reach downstream until the point is reached where substantial changes in the bed morphometry begin to occur. The actual location of the near-bank area of sedimentation (whether right bank or left bank), its width, longitudinal extent, and the persistence of fine-grained sedimentation will depend on the details of bed morphometry at any cross-section. These are not known except at the WSC gauging section at Hinton.

5.4.4 Field study of the Athabasca River near Hinton

The field study reported by Krishnappan et al. (1995) provides two sets of synoptic data for sediment loads in the reach between Entrance and Windfall based on multiple sampling at four or five transects in the reach.

5.4.4.1 Winter survey

The winter survey (February 1993), at a flow rate of only 29 m3/s at Entrance, showed a relatively high sediment concentration (about 26 mg/L) in the reach upstream of Hinton. The sediment input at Entrance was calculated at 64 tonnes per day, together with an input from the Hinton mill of 3.6 t/d. Of this combined amount, 70% was lost in the 28 km of reach downstream of Entrance, presumably as sedimentation on the bed or incorporated into ice. Ninety percent of the combined sediment input from Entrance and HCE had disappeared by the Berland cross-section, 105 km downstream.

The winter data are therefore consistent with the findings of Trillium (1995), though the matter is not as straightforward as this given that hydraulic conditions were assumed to be the same in the 8-km Entrance-Hinton as downstream. Krishnappan et al. believed that the major factor involved in the precipitation of this sediment was the input of warm pulp mill effluent from the Hinton mill, the organic fibres and bacteria in which would have acted to strength the flocculation in the river sediment with which it mixed. While this view seems a reasonable one to take, given the data, additional verification would be useful for reasons noted below.

The winter cross-sectional distribution of suspended sediment in the Hinton reach is somehat puzzling. Figure 7 of Krishnappan et al. (1995) shows essentially uniform bank-to-bank sediment concentrations of about 26 mg/L at Entrance, decreasing substantially by Obed Bridge. At the latter site, concentrations are 11.5 mg/L in the right side of the channel decreasing to 7 mg/L on the left side. The same right-to-left pattern continues at the Berland site through to Windfall, though this may well be due to clearer inputs from the Berland River along the left bank. No sediment or discharge data were reported for that tributary to verify that assumption.

The asymmetric cross-channel distribution of sediment downstream of Hinton (at Obed) may not be statistically significant given that it is based on one specimen out of four sampled. On the other hand, the possibility of this pattern being related to asymmetry in the HCE plume should at least be considered. Examination of the cross-sectional distribution of AOX at the Weldwood Haul Bridge (1 km downstream of the HCE) in April 1992 by Crosley (1994) shows the HCE plume to the right of channel centre in that reach. Essentially uniform distribution of AOX was found at Knight Bridge 116 km below HCE, but no other data have been seen regarding the downstream penetration of the HCE plume under different flow conditions.

The degree to which asymmetry in the HCE plume persists downstream is important. In the first place it affects where in the river HCE sediments are likely to settle. Secondly, assuming that the HCE plume does indeed hug the right side of the channel in the reach between Hinton and Obed, the higher sediment concentrations on the right side reported by NWRI at Obed then become difficult to explain. This is because, if HCE effluent increases flocculation and deposition, lower concentrations in suspended sediment should develop in and downstream of the HCE plume.

Additional information on the cross-sectional distribution of sediment at Obed under winter conditions would appear to be warranted. Additional information on the length and location of the HCE plume would also be useful.

In addition, as further verification of the view that the HCE effluent precipitates sedimentation in the Entrance-Obed reach during winter flows, it would be instructive to know how much of the sediment load at Entrance had been deposited on the bed before reaching the HCE input site At the moment this is not known because no sampling was done immediately upstream of the HCE influx.

5.4.4.2 Autumn survey

The autumn survey (September, 1993), at a flow rate of 149 m3/s at Hinton, and hence higher bed shear stresses, showed a slightly different pattern. Sediment concentrations in the river upstream of Hinton were actually less than in the winter (about 16 mg/L), but, because of the larger flow, the incoming suspended load above Hinton was much higher at 207 tonnes per day. An input of 3.6 t/d was again noted for the Hinton mill effluent. There is some inconsistency in the data because the combined transport rate at Haulbridge (1 km downstream of Hinton) was computed as 261 t/d. The additional sediment may have been supplied by the right-bank tributary between Entrance and Hinton. Between Haulbridge and the next sampling, at Obed 19 km downstream, 13% of the 261 t/d of incoming sediment had disappeared, presumably through near-bank sedimentation. The data confirm a slower rate of settling-out under the higher discharge of the autumn flow.

The two field investigations thus indicate sedimentation in the reach downstream of the Hinton mill in both autumn and winter. Assuming complete mixing of mill effluent and natural sediment, the settled mill sediment would have been diluted by about 17x in the winter survey and 57x in the autumn survey. In view of the fact that the mean flow at Hinton is less than 150 m3/s from mid-September through to mid-May, it would appear that sedimentation in this reach, on at least parts of the bed, takes place in more than seven months of the year. The key question therefore is not whether sedimentation takes place, but whether the spring freshet is sufficiently strong in every year to remobilize this settled material. Closer attention therefore needs to be paid to the critical bed stress for remobilization of settled fine sediment, especially in the context of a rough gravel bed.

6.0 SEDIMENT QUALITY

6.1 Introduction

To this point sediment has been considered as a physical entity. Sediment as a physical entity refers to the quantity, size and type of sediment as it influences the physical, chemical and biological characteristics of water. In its own right sediment may be considered a contaminant that affects specific land and water uses. In addition, chemicals and wastes are assimilated onto and into sediment particles. Thus, sediment becomes a carrier and storage agent of contaminants such as pesticide residue, absorbed phosphorus, nitrogen and other organic compounds, and pathogenic bacteria and viruses.

The objective of this chapter is to examine how and why river sediments become contaminated with contaminants. The primary focus is on pulp mill contaminants. Other sources of contaminants are discussed if they have similar sediment-associated contaminant "signatures" and may be confused with, or have similar effects to, pulp mill effluents.

In order to understand the sources, pathways and fates of sediment-associated contaminants, the following issues must be addressed:

(a) What are the sources of contaminants, the rate of discharge and types of contaminants discharged by the pulp mills in the study area?

(b) What are the other sources of contaminants from natural and man made sources (e.g. hydrocarbon seeps; the oil sands and other industries);

(c) How are these sources different from, or similar to, pulp mill signatures and pulp mill effluent behavior; and

(d) What are the rates and circumstances of sediment contaminant association, including:
- how long does it take in time and space for partitioning (adsorption) to the sediment fraction
- what fraction of the contaminants partition to sediments
- what are the preferred size fractions and physio-chemical characteristics of sediments that determine sediment-contaminant associations
- what are the life expectancies of contaminants on sediment as submerged and emergent deposits
- can the contaminant be re-mobilized from sediment
- what are the breakdown products of these contaminants?

This chapter describes the above attributes of the sediment - contaminant issue and the following chapter discusses sediment -contaminant interactions in the Peace, Athabasca and Slave river system.

6.2. Types of pulp mill effluent contaminants

Seven pulp and paper mills in Alberta and three in British Columbia discharge effluents into the Peace, Athabasca and Slave river systems (Table 6.1 and Figure 6.1). There are two types of mills: bleached kraft mills (**BKMs**) and bleached chemi-thermomechanical pulp (**CTMP**) mills. McCubbin and Folke (1993) indicate that the bleached kraft mills use quite similar processes and discharge generally similar effluents. The principal difference among the kraft mill processes that affect effluents characteristics is that the mills at Peace River have extended cooking oxygen delignification systems while the other kraft mills use traditional pulping and bleaching processes. The bleached chemi-thermomechanical pulp (CTMP) mills do not use chlorine compounds, rather they produce mechanical pulps and bleach them with a hydrogen peroxide process.The newsprint mills manufacture mechanical pulp, with some use of small quantities of chlorine-free bleaching ("brightening") agents.

Mechanical and bleached kraft type operations, which are the categories of mills in the NRBS area, have complex effluent discharges. Alsberg and others (1993) state that in bleachery waste more than 300 low-molecular compounds have been identified, but only a few have been found in organisms that have been exposed to discharges. However, pulp and paper effluents are often only characterized chemically by a limited range of parameters. Wastewater permits often include Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (EOD), Total Suspended Solids (TSS), Colour, Adsorbable (Extractable or Purgeable) Organic Halogens (AOX/EOX/POX), chlorinated phenolics, PolyChlorinated Dibenzo-p-dioxins and Dibenzofurans (PCDD/PCDF) and heavy metals (McCubbin and Folke 1993).

McCubbin and Folke (1993) state that the conventional bleaching process of kraft mills is the source of about half of the Biochemical Oxygen Demand (BOD), all of the organochlorines, most of the colour and much of the toxicity in typical bleached kraft mill effluent. All the mills in the NRBS area have effective primary and secondary effluent treatment systems.

By world standards, the effluent standards of these mills are very good to equalling the best in the world (McCubbin and Folke 1993). Adsorbable Organic Halogen (AOX) is a measure of chlorinated organic substances formed by chlorine chemicals in bleaching of pulp, and has been employed as an indicator of water quality. AOX has been reduced from up to 10 kg/tonne of pulp to less than 2 for the Alberta mills, and are less than 1 kg/tonne for some mills (McCubbin and Folke 1993). SEPA (1993) state that in bleachery discharges from conventional bleaching extractable organically-bound chlorine (EOCI) makes up 2-3% of AOX. With newer technology, this amount is reduced to less than 1%. However, less than 10% of the EOCI in sediments have been identified . The persistent fraction was on average 12% in sediment in Swedish coastal sites (SEPA 1993).

Production figures and effluent discharge are summarized in Table 6.1. Although concentrations and loadings of effluent contaminants are documented in the Northdat data base (Agra 1994), the limited time frame for the preparation of the present report has prevented detailed examination of these data. However, these figures are required in order to ascertain the probability of detection with various sediment loadings in the river system.

Short-term time trends in contaminant discharge occur. The rates of effluent discharge provided in Table 6.1 indicate the rate of discharge for normal operations. These rates vary with shut downs and for episodic higher inputs. For example, the discharge of suspended solids for Weyerhaeuser at Grande Prairie ranges from 0 to 10,744 kg/day, with a median of 1,622 and standard deviation of 1,542 kg/day (based on data extracted from Northdat).

Longer term trends also occur. Pastershank and Muir (1995) note that the pulp and paper industry reduced the use of molecular chlorine to achieve 1994 Canadian Environmental Protection Act (CEPA) regulations. Weyerhaeuser at Grande Prairie (on the Wapiti River) implemented a 25% substitution of molecular chlorine with chlorine dioxide in 1989, 70% in early 1991, and 100% during the summer of 1992. In June of 1993, Weldwood at Hinton shifted from 45 to 100% chlorine dioxide substitution. These changes in the pulp bleaching process were expected to reduce the concentrations of PCDD/Fs discharged to the Wapiti and Athabasca rivers and to reduce the quantities available to riverine biota (Pastershank and Muir 1995).

6.3 Sources of contaminants found in pulp mill effluent

Many persistent organic compounds are formed by incomplete combustion. Natural sources include forest fires, volcanic eruptions and enzyme formation in organisms (SEPA 1993). In addition, long range atmospheric transport of organic contaminants occurs to areas where such compounds are not used. As a result, similar contaminant signatures to pulp mill effluents may be produced from other sources. To distinguish the role of pulp mills in the contamination of the study area the alternate sources of contaminants must be identified and evaluated in the same terms as the pulp mill effluents. Key questions include what are the other sources of contaminants from natural and man made sources; and how are these sources different from, or similar to, pulp mill signatures and pulp mill effluent behavior.

6.3.1 Dioxins and furans

While bleach kraft mills are a source of lesser chlorinated dioxin and furan congeners (e.g. tetra and penta) (Amendola 1987), combustion is the most common source of the more highly chlorinated congeners (e.g. hepta and octa) (Czuczwa and Hites 1986, in Sekela and others 1994). In the Fraser River, Sekela and others (1994) suggest that highly chlorinated congeners may be from surface runoff originating from slash burning of clearcut logging and forest fires and from combustion of waste wood material in the beehive burners of saw mills. Additional sources include waste combustion, metal processing, cement and lime ovens, and coal energy plants (SEPA 1993). All of these activities take place in the study area (Figure 6.1).

Atmospheric transport may play a significant role of distributing these compounds into the river system with wet and dry deposition.

Sekela and others (1995 draft) state that prior to 1991, wide use of pentachlorophenol as a wood preserver was the largest chemical source of dioxin and furan contamination (CEPA 1990). Use is now limited by regulation, but dioxins and furans have been observed to leach from wood utility poles and railway ties (Wan and Oostdam 1995). Sekela and others continue that CEPA (1990) indicates that PCBs represent the most significant potential source of furans to the Canadian environment (CEPA 1990) and that the second largest chemical source of dioxins is the pesticide 2,4-D which is used as a herbicide in Canada.

6.3.2 Chlorinated phenolics

In addition to pulp and paper mills, chlorinated phenolics may be derived from wood treatment, and agriculture (Health and Welfare Canada 1980). In addition, chlorinated phenolics occur in sewage effluent and in drinking water that contains phenols (USEPA 1979).

6.3.3 Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs from natural sources include forest fires, biosynthesis by plants and bacteria and diagenesis (combustion of organic material over a long period at low temperatures) (Water Quality Branch 1993b). Anthropogenic sources include creosote treated products (CEPA 1994), spills of petroleum products (CEPA 1994), urban runoff (Boom and Marsalek 1988), industrial combustion, slash burning and automobile exhaust (Water Quality Branch 1993b). As a result, PAH concentrations are significantly higher around major urban areas (SEPA 1993). In the lower Thompson River, Sekela and others (1995 draft) state that the inverse relationship between flow and total PAH concentration in suspended sediment suggests that municipal and industrial sources provide a much larger PAH load than atmospherically derived PAH.

Petroleum extraction and processing occurs throughout the study area, with a particular concentration in the mid and lower Athabasca River basin (figure 6.1). Tar sands mining and natural seeps of oils sands are a known source of PAHs in the system.

6.3.4 Resin acids

Sekala and others (1995 draft) cite references indicating that numerous resin acids have been identified in mechanical pulping effluents, bleached kraft mill effluents and effluents of other wood processing. Biological treatment of pulp mill effluents greatly reduces effluents concentrations, but resin acids have been detected in the final effluent of pulp and paper mills in the Fraser River. The amounts are particularly high in concentrated effluents from mechanical mills (McCubbin and Folke 1993). Resin acids are naturally occurring compounds in wood resins, particularly in pine and spruce, but Crosley (1995) points out that chlorinated resin acids appear to be derived only from pulp mills.

6.3.5 Polychlorinated Biphenyls (PCBs)

PCBs were widely used in industrial applications, but since 1980, PCBs have been used only in closed electrical equipment such as transformers (Environment Canada 1980). However, these "sealed systems" are known to leak (SEPA 1993). Other sources include the aqueous fraction of final effluents of kraft pulp and paper mills (Merriman 1988), sewage treatment plant effluent (Derksen, 1995, pers.comm.), landfill leachate (Hammond 1972) and long range aerial deposition (CCME 1987).

6.3.6 Metals

Most trace metals found in surface waters are products of weathering of metal bearing rocks and soils (Sekela and others 1995). Anthropogenic sources include metal plating plants, sewage treatments plants, and atmospheric deposition. Metals, such as aluminum, cadmium, zinc and mercury, are either not used in NRBS area mills, or are in sufficiently small concentrations to comply with receiving water quality objectives without any dilution (McCubbin and Folke 1993).

The metal of primary concern in the NRBS is mercury. Donald and Craig (1995) reviewed existing data bases and concluded that mercury is ubiquitous in soils and sediments of the earth (the average mercury content of Canadian soils is 81μg/kg) and therefore expected to be found in the study area. Mercury levels in lake sediments from northern Manitoba ranged from 60 to 124 μg/kg which is less than the draft guidelines of 170 μg/kg (dry weight). Levels found in NRBS range from 27 in the headwaters of the Peace River (in Lake Williston) to 123 μg/kg in the western part of Lake Athabasca. The average concentration of total mercury in the Athabasca river from the mouth (km 0) to Hinton (km 1,253) was 52.6 μg/kg (range 43 to 59 μg/kg); the levels were similar upstream and downstream of the pulp mills.

6.4 Sediment-contaminant relationships for pulp mill effluent

Alsberg and others (1993) indicate that water is not the ideal medium for monitoring organic environmental toxins, since they are usually lipophilic, and thus poorly soluble in water. The degree to which a contaminant separates (partitions) itself from solution and sorbs to another medium such as sediment is usually denoted by a partition coefficient, K_p, given by the ratio of the concentration of the contaminant sorbed to the sediment divided by the equilibrium solution concentration of the contaminant in the solution. It is often found that the magnitude of this partition coefficient is highly responsive to the fractional amount of organic material in the sediment. Another coefficient, K_{oc}, is commonly used to denote this responsiveness, being given by the ratio of K_p to the fractional mass of organic content. Some reported values for K are included in this section.

6.4.1 Dioxins and Furans

Due to their hydrophobic nature (Octanol-Water partition Coefficient: K_{ow} of log 6-7), dioxins and furans (polychlorinated dibenzo-p-dioxins [PCDDs] and polychlorinated dibenzofurans [PCDFs]), have a high affinity for both particulate and dissolved organic carbon (Webster and others 1986; Servos and others 1989). Sediments which have a high organic carbon content and surface area (such as silts and clays) have been shown to be a sink for dioxins and furans (Czuczwa and Hites 1984). Previous studies have shown that furans are detectable in bed sediment material (Mah and others 1989) and dioxins and furans are detectable in suspended sediments in the Fraser river system (Sekela and others 1994).

Pastershank and Muir (1995) note that the two most common PCDD/F congeners found in environmental samples downstream of bleach kraft mills are 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD) and 2,3,7,8-tetrachlorodibenzofuran (2,3,7,8-TCDF). PCDDs and PCDFs are large families of chlorinated hydrocarbons consisting of 75 PCDD and 135 PCDF congeners (each congener having a different Cl substitution pattern). PCDD/Fs display similar molecular, physical and chemical properties. An increase in chlorine substitution of PCDD/Fs is positively correlated to greater hydrophobicity (insolubility in water), lipohilicity (strong affinity for lipids) and environmental persistence.

PCDD/Fs are characterized as environmentally stable and persistent compounds. The two major pathways of degradation of PCDD/Fs in the aquatic environment are photolysis and biodegradation. 2,3,7,8-TCDF has been shown to be photodechlorinated by sunlight in natural waters with a half life of less than one day (Foga 1991; Dung and O'Keefe 1994). Sunlight photo degradation of PCDD/Fs is much more rapid in the presence of dissolved organic materials than in distilled water and is affected by the degree of chlorination of the pollutant of interest (USEPA 1990a; Friesen and others 1990b) (Pastershank and Muir, 1995).

Microbial degradation of PCDD/Fs with one or two chlorines occurs in laboratory incubations. More highly chlorinated congeners are extremely resistant to biodegradation in sediments or water. Slow microbial degradation of 2,3,7,8-TCDD and 1,3,6,8-TCDD (1 to 7% over periods of 588 to 675 days) has been observed in sediment/water incubations under laboratory conditions (Ward and Matsumura 1978; Muir and others 1985). No degradative products were seen for ^{14}C-labelled 1,3,6,8-TCDD or OCDD in sediments after 700 days in a natural mesocosm experiment on a Canadian Shield lake (Servos and others 1992). The major removal process of 1,3,6,8-TCDD in sediments was found to be diffusion back into the water column (Segstro and others 1995). Historical profiles of PCDD/Fs in sediment cores from large lakes show no evidence of transformation of congeners (such as anaerobic dechlorination) over time (Hites, 1990; Pastershank and Muir, 1995).

Sekela and others (1995 draft) calculated dioxin and furan partitioning at McLure and Savona on the Thompson River in British Columbia. The concentration of contaminant in water, as determined by solid phase extraction, was compared to the concentration of the contaminant in the suspended solid phase using the site specific suspended sediment concentration. At McLure the percentage of dioxins and furans partitioning to suspended sediments ranged from 1 to 15 percent and at Savona it ranged from 30 to 83 percent. On the Fraser River, the partitioning of dioxins and furans to suspended sediment ranged from 10 to 82 percent, depending on extraction method and location.

6.4.2 Chlorinated phenolics

Chlorophenolic phase partitioning coefficients were difficult to obtain in the Thompson and Fraser river study due to the low incidence above detection limits (Sekela and others 1995 draft). The percentage in suspended sediment ranged from 0.02% (in 3-chlorocatechol) to 73% (in 3,4,5-trichlorocatechol). Variations in percent partitioning to suspended sediment occurred both between individual compounds as well as with the same compound measured at different sites or at different times of the year. The calculated log K_{oc} results from Sekela and others (1995 draft) in the Thompson River ranged from 4.04 to 5.17. They state that since a log K_{oc} of 3.84 indicates a high potential for partitioning to sediments, all of the chlorinated phenolics detected would be expected to have a high affinity to suspended sediments. However, the phase partitioning data indicated a low incidence of partitioning (less than 1% in the Thompson) which is attributed to low suspended sediment concentrations (0.9 to 3.8 mg/l) at the time of sampling. In the Fraser River log K_{oc} varied from 3.51 to 7.04, and sediment concentrations from 0.9 to 226 mg/l. The percentage partitioning (0.02 to 73%) appeared to be related to sediment concentration, which is expected from the results of Olsen and others (1982) who showed that partitioning of hydrophobic contaminants to suspended sediments is approximately 40% greater at 100 mg/l than at 10 mg/l. In addition, the association of some of the more hydrophobic chlorinated phenolics with dissolved organic material in the water column may increase the apparent solubility of these compounds.

Chlorophenols that are chemically bound to sediments can be released by bacteria in anaerobic conditions, but the process is very slow (SEPA 1993).

6.4.3 Polycyclic Aromatic Hydrocarbons (PAHs)

Partitioning of Polycyclic Aromatic Hydrocarbons (PAHs) in the Thompson River ranged from 0.1% for chrysene to 52% for benzo[ghi]perylene with log K_{oc} ranging from 2.96 for anthracene to 7.3 for benz[a]anthracene (Sekela and others 1995 draft). The range of partitioning values varied from 0.2% for acenaphthene to 91% for chrysene in the Fraser River. Phase partitioning of PAHs to suspended sediment did not appear to be related to total organic carbon or the suspended sediment concentration, but there was an apparent positive relationship between molecular weights and increased partitioning to sediments. This is consistent with the inverse relationship between the solubility of PAHs and their molecular weight (Water Quality Branch 1993b) (Sekela and others 1995 draft).

6.4.4 Resin Acids

Information on partitioning to sediments was not readily available, but the writers understand that there is a strong sediment association (Brownlee, 1995 pers. comm.).

6.4.5 Polychlorinated Biphenyls (PCBs)

PolyChlorinated Biphenyls PCBs have a high affinity for suspended solids, especially those of high organic carbon content (Hamelink and others 1971, in Sekela and others 1995).

7.0 IMPLICATIONS FOR SEDIMENT-ASSOCIATED CONTAMINANTS

7.1 Introduction

Basically two approaches can be utilized in the description of fluvial sediment-associated contaminant sources, pathways and fates: dynamic sampling of fluxes in the river and lake systems, and static sampling of deposited materials throughout the system.

In terms of dynamic sampling, this report has examined sediment fluxes through the use of published material from the conventional Water Survey of Canada suspended sediment monitoring program. In addition, the reach-scale mass balance of suspended sediment undertaken by NWRI was examined in Section 5.5.3. Special sediment-associated contaminant flux measurements were undertaken for NRBS with centrifuge sampling and are discussed below in Section 7.4.

The NRBS program of bottom-sediment sampling for contaminants is examined in Section 7.5.

7.2 Monitoring and Assessment Objectives

The design of a monitoring and assessment program is a multi-step process as outlined by Hudson (in prep.) The process begins with a recognition of the issues. In the NRBS case one of the key issues is the impact of pulp mills on ecosystem health, with particular reference to human health effects. An element of the problem is that people eat fish thought to be contaminated by pulp mill effluents. Thus a fundamental question becomes how do the fish get tainted by contaminants? Hypotheses include contact in the water column, consumption of contaminated flora and fauna, and contact with sediment.

Research has clearly shown that pulp mill and other contaminants can become strongly associated with sediment. How fish get tainted with contaminants is less clear. Possibilities include direct effects such as ingestion of contaminated materials directly or through plants and bottom dwelling insects and animals, and incubation and spawning in contaminated sediments. Indirect effects include sediment induced stress (such as reduced feeding visibility and gill abrasion increasing chance of disease). Thus, not only must the role of sediment be recognized, but the processes governing the interaction must be understood. For example, if incubation of eggs in contaminated sediments were the issue, then a study would be designed to examine interstitial sediment-associated contaminant dynamics in appropriate spawning habitats for appropriate various species.

Study design must be undertaken in the context of the objectives. If the objective is to check for the presence or absence of contaminants, then a spot sampling program of potential hot spots (such as significant depositional environments) may be undertaken. If trends in contaminants over time are the objective of study, then repeat sampling can be undertaken over a period of years, or sediments could be cored to determine contaminant levels of various aged deposits. These approaches however do not necessarily provide an explanation of processes which are required in order to effectively design mitigation measures. For example, the cessation of contaminant inputs from a particular source does not necessarily translate into clean river sediments. Multiple sources of contaminants may exist and old and new sources of contaminants may be buried or removed over time. Thus effective mitigation would require an ability to model sources, pathways and fates of contaminants (including residence times of contaminated sediments) for particular segments of river and sedimentation environments (e.g. over wintering pools, spawning areas and feeding areas), and the evolution of these attributes over time with changing river regimes and contaminant attributes.

Once the objectives of the study have been established, and the appropriate questions posed to address the issues identified, then the sampling scheme is devised. The sediment dynamics and the contaminant dynamics (sources, pathways, flux rates, timing and fates) will determine the actual sampling design where the issues of what is sampled, when is it sampled, where is it sampled, and how is it sampled, are addressed. The essential elements of the contaminant and sediment regimes are discussed in previous chapters.

7.3 Spatial Variability and the Dilution Effects of Background Sediment Inputs

Sediment effluent from pulp and paper mills is discharged into the mainstem rivers of the NRBS system in their upper and middle reaches. In these places the sediment effluent mixes with natural river sediment. Contaminants in the dissolved phase may continue to be adsorbed by suspended sediment in the river, both industrial and natural, but the assumption that seems to be generally made is that adsorption is essentially complete by the time that effluent enters the river.

As the contaminated sediment is moved downstream it mixes with other sediment, largely contaminant-free, supplied by tributaries and channel erosion by the main stem. Thus the concentration of contaminants in the sediment, in say ng of contaminant per g of sediment, would be expected to experience ongoing dilution downstream as more and more natural sediment is mixed with it.

This means that, even without any loss of contaminant from the system, by deposition or chemical alteration, a point may well be reached downstream where contaminant levels have been diluted so much that none is detected (ND). It is instructive to examine this issue quantitatively in order to provide a proper perspective for "ND" data.

The term "sediment dilution ratio" is used here for this purpose, defined as the ratio of "total river suspended solids" to "solids from mill effluent". As an example, Crosley (1994) reports concentrations of total tetrachlorodibenzofurans (T_4CDFs) at the Weldwood mill in April 1992, at 100 pg per gm of suspended sediment. This is 1000x the common detection limit of 0.1 pg/g. Thus, by the time that sufficient sediment has been mixed with the effluent in the main river to reach a sediment dilution ratio of 1000x, masking of these contaminants by background sediment is likely to produce a ND result. The question now arises as to how much of a sediment load is needed to produce this extinction.

The suspended solids loading of the Weldwood plant in 1992 was about 4.5 tonnes per day (Mackenzie, 1993; actual monthly loadings varied from 2.4 to 6.3 t/d), equivalent to a monthly solids effluent loading of 135 t/m. Thus, assuming no additional inputs (or losses) of the contaminant downstream, extinction of the contaminant (ND reading) would occur once river loads had built up to 4,500 t/d or 135 kt/m. Data published by Nanuk (1985), and shown in Figure 3.2, indicate that in 1984 total river suspended load (increasing in the downstream direction) had reached more than 4,500 t/d in the Athabasca River even before the Berland River in June and by Athabasca township in July, but didn't reach this level anywhere during May, September and October. Thus detection of this contaminant in suspended sediment would be likely only for relatively short reaches of river downstream of Hinton in June and July, though throughout the full length of the river in the lower flows of autumn and winter.

The location of the start of ND readings, however, will vary with different contaminants. Crosley (1994) reports total tetrachlorodibenzodioxins (T_4CDD) concentrations (spring 1992) in the Hinton combined effluent (HCE) as 30 pg/g so that, with the same detection limit as for T_4CDFs, the critical sediment dilution ratio for ND readings is now only 300x, equivalent to 1,350 t/d. Examination of the data from Nanuk (1985) (Figure 3.2), indicate that loadings greater than this value prevailed throughout the river downstream of Hinton in June, downstream of the Pembina confluence in July and September, but not until Fort McMurray in October, and hardly attained at all in early spring (May) flows anywhere on the river. Thus the spatial window for detection of total T_4CDDs is substantially smaller than for total T_4CDFs, though still extensive in winter flows.

At the downstream end of the Athabasca River, allowing an additional 4.5 t/d for the effluent from Alpac (Mackenzie 1993), there should be a combined loading of mill effluent of 9.0 t/d or about 0.3 kt per month. Examination of the monthly mean river suspended sediment loads on the lower Athabasca River (Table 4.1) shows that in June, with loads of 2,000 kt, the sediment dilution ratio would be in excess of 6,000x with detection virtually impossible, assuming the same effluent contaminant concentration and detection limit. In winter, with loads of about 1 kt/mo, the sediment dilution ratio is only about 3x in the lower reach which allows detection. However, such long distances of travel are highly unlikely under an ice cover given the propensity of sediment to settle out at low flows or adhere to ice.

Thus detection of total tetrachlorodibenzofurans in the suspended sediment of the <u>lower</u> Athabasca River is highly unlikely at any time of the year based on these data.

The above comments are for illustrative purposes only, being based on April 1992 mill loadings and 1984 river sediment loadings, but they provide some perspective for the NRBS program.

This sediment masking - the dilution of contaminants in sediment below the detection limit - is even more pronounced in the case of the Peace River system because of the much greater background suspended sediment loads. Taking, simply for illustrative purposes, the same T_4CDF concentration in the effluent from Weyerhaeuser on the Wapiti River, with an effluent solids load of 4 t/d (Mackenzie 1993) or 130 t/mo, extinction would occur in a total river suspended sediment load of of 130 kt/mo. In the Peace River at Peace River in the average June, the monthly load is about 11 Mt (Table 4.3) equivalent to a sediment dilution ratio of almost 100,000x or almost 200x the level at which ND is virtually certain. During winter, with total river suspended loads of the order of 200 kt/mo, the sediment dilution ratio is still 1,500x, or 1.5x the level at which detection is improbable. With a quadrupling of the mill effluent load from the Daishowa plant, winter time detection would be more likely in the reach downstream, assuming that contaminant concentrations in the Daishowa effluent are also comparable with those at Weldwood.

Upstream in the Smoky River catchment there are few longterm data to make reliable comments. However, the sediment loads in the lower Smoky are on average about half those at Peace River implying that detection of organochlorine compounds is about twice as likely.

The most likely reach to encounter contaminants is obviously in the Wapiti River itself into which the Weyerhaeuser mill discharges. Data from Noton et al. (1989) indicate that, in March 1983, mill effluent averaged about 0.6 cubic metres per second with a suspended sediment concentration (NFR) of 156 mg/L. This amounts to about 8 t/d. The total sediment loading in the Wapiti River downstream was only slightly higher than this with a sediment dilution ratio of less than 2x. In the Smoky River at Watino, the suspended loading in March 1983 was about 35 t/d, producing a sediment dilution ratio of less than 5x in the lower Smoky River.

To summarize, while contaminants are likely to show in suspended sediment in the upper reaches during low flow, in downstream reaches sediment dilution ratios are likely to be too high in many cases to allow this. In these lower reaches, unless special precautions are taken, many contaminants will not be detected in the suspended sediment simply because of masking by background sediment. In theory the solution to this is relatively simple: increase the amount of sediment which is subjected to the extraction procedure so that the detection limit can be lowered to allow detection. Availability of the longterm WSC suspended load sediment data provided in this report does make it possible to determine the detection limit needed and thus the amount of sediment needed in the average year. Ultimately, however, what is needed is sediment data along the course of the river at the same sites as contaminant sampling is done. Ideally the data should be determined immediately prior to the onset of sampling of suspended sediment for contaminant analysis in order to indicate the amount of sediment needed and the duration of sampling to obtain it.

Sampling and analysis thus need careful prior planning. The ultimate key to success is accurate knowledge of contaminant levels in the mill effluent itself.

The previous discussion of course raises the question as to the level of contaminant concentration deemed to be an environmental problem: there is little point in designing investigations to allow contaminant detection at very low levels if these levels have no deleterious effects environmentally. This, however, is an issue beyond the present report.

For the moment it is sufficient to note that, with present detection limits, it seems likely that, for many contaminants, detection within suspended river sediment is only likely to occur during low flows and sometimes within relatively short distances downstream of mills.

The same conclusion would be expected to apply to bottom sediments. Bottom sediments in the lowest reaches of the Athabasca and Peace systems will, in many cases, not show evidence of contaminants found in bottom sediments further upstream simply because of sediment dilution. In particular the large amounts of summer flood deposit (with low contaminant concentrations as just noted) might be expected to mask any contaminated sediment that might have settled out at other times of the year. These conclusions include the two major downriver sinks: Lake Athabasca and Great Slave Lake.

7.4 Dynamic Sampling of Suspended Sediment Contaminants

7.4.1 Overview

Suspended sediment, bottom sediment, benthic invertebrates, biofilm and fish were sampled in late March and April 1992 at seven locations in the upper Athabasca river between Hinton and Whitecourt (Crosley 1994). Samples were collected at a reference site about 7 km above the Hinton Combined Effluent (HCE); at the lower end of the HCE lagoon (km 0); Weldwood Haul Bridge (1 km downstream); Obed Mountain Coal Bridge (48 km downstream); Knight Bridge (116 km downstream) ; and Windfall Bridge (176 km downstream of HCE). Details of the procedures are provided in Crosley (1994), but some of the key points are that sampling was undertaken on approximately the same body of water as it moved downstream (based on the time of travel); water was sampled by magnetic drive submersible pumps for centrifuge separation from a depth of 0.5 to 1.0 m below the water surface from near the right bank; sampling took a minimum of 7 hours (at HCE) and approximately 24 hours at the other sites; the objective was to obtain 100 or more grams of suspended sediment;and sampling was undertaken during winter low flow conditions (discharge varied from 38 to 54 m^3/s)

7.4.2 Evaluation

Some of the difficulties associated with dynamic sampling of suspended sediment in the context of sediment-associated contaminants were addressed at length by Carson (1990c,d). This was illustrated by reference to the dynamic sampling program for hydrocarbon contaminants along the Mackenzie River by the National Water Research Institute in 1985-86. The same problems apply to the NRBS study. Some points from this analysis are incorporated in the following discussion, but a detailed evaluation was not undertaken for this study because of time and budget constraints.

7.4.2.1 Importance of Sediment Loadings

In any dynamic sampling program there may be more than one goal. One aim might be simply characterization of contaminant conditions in different reaches: in this case data giving concentration of contaminant in the sediment (e.g. ng/g) are adequate (provided that they are obtained with careful sampling over time and space). Another key goal, however, is usually an understanding of where contaminants are originating and where they are disappearing. Such issues cannot be addressed with ng/g contaminant/sediment concentration data alone, or with supplementary data for NFR or total suspended solids. Identification of sources and sinks requires data on contaminant loadings, and this, in turn, requires data on river discharge at all sites where sampling is undertaken. The lack of such comprehensive data in the NRBS investigation of contaminants in suspended sediment on the Athabasca River is a severe limitation in the interpretation of the data.

The only discharge data in the report by Crosley (1994) on the April 1992 sampling program between Hinton and Windfall was for the Athabasca River at Hinton, noted to have varied in the study period (March 31 to April 9) between 38 and 54 m^3/s. In the discussion that follows, the effluent from the Hinton Combined Effluent (HCE) is assumed to have been about 1 m^3/s based on usual winter discharges (Noton, 1993). Discharge in the Athabasca River at Windfall at the downstream end of the reach has been made available by the Water Survey of Canada and is reported as rising from 83 m^3/s on March 31 to a peak of 126 m^3/s on March 6 and decreasing to 107 m^3/s on March 9. Thus river discharge at the upstream end of the reach was about 50x that of the HCE flow and at the downstream end it was about 100x.

This discharge information is adequate for assessing contaminant loadings provided that sediment contaminants are thoroughly mixed through the river section (see Section 7.4.2.2a). This was certainly not the case at the Weldwood Bridge site about 1 km downstream of HCE as noted by Crosley (1994), but it is assumed here that the HCE plume was fully mixed by the Obed Bridge site 19km downstream of the HCE. No data for water discharge is available for Obed, however, and it must be assumed that it was the same as at the Weldwood Bridge site (and approximated by the Athabasca at Hinton data).

A second source of data is required, however, to completely determine contaminant loadings. This is the concentration of total suspended solids (or NFR) in the river, because the contaminant loading is given by

$$Lc = 86.4 * Ccs * Csw * Q$$

where Lc is the contaminant loading in kg per day, Ccs is the concentration of contaminant in the suspended sediment (mg/mg), Csw is the concentration of sediment in the water (mg/L), Q is water discharge (m^3/s) and 86400 is the number of seconds in a day. When Ccs is expressed in ng/g, the units of Lc are ug per day; and for pg/g, they are ng/day. Alternatively, the expression might be written

$$Lc = Csw * Ls$$

where Ls is sediment (NFR) loading in tonnes per day, and for Csw in ng/g, Lc is in mg/day.

The remaining missing term in the 1992 study therefore is Csw. These data were not included in the report but (Crosley, 1995, pers. comm.) supplied the following NFR values for raw water samples in the April 1992 survey (means of 6 samplings in 24 hours): upstream control site 8.8 mg/L; HCE 50 mg/L, Weldwood Bridge 22 mg/L, and at Emerson Lakes Bridge (48km below HCE) 6.4 mg/L. Unfortunately, these data are insufficient for modelling of loadings because the Weldwood Bridge sample is unrepresentative of the full river section because of incomplete mixing of the HCE plume, and the Emerson Lakes Bridge sample is not accompanied by the corresponding data for Q. The Windfall Bridge sample (for which there are discharge values) cannot be used because there is no Csw value. Again, these limitations hinder meaningful interpretation,

7.4.2.2 Spatial patterns in suspended sediment contaminants: the Athabasca River near Hinton

An attempt has been made to circumvent the various gaps noted above. Crosley (1994, Table 2) provides data for duration of centrifuge sampling and the amount of wet sediment collected in that time using an intake flow rate of 4 litres per minute. The following concentrations in mg/L wet sediment as well as gm of wet sediment per hour were determined using this method (with the mg/L dry sediment in raw water concentrations noted above given in parenthesis.

Location	Centrifuge wet sediment (mg/l)	Centrifuge wet sediment (g/h)	Centrifuge dry sediment (mg/l)
Upstream control	38	9.1	8.8
HCE	345	83	50
Weldwood Bridge	95	23	22
Obed Bridge	63	15	
Emerson Lakes	35	8.4	6.4
Knight Bridge	26	6.1	
Windfall Bridge	20	4.8	

The ratio of dry mg/L in the raw water to wet mg/L centrifuged ranges from 14% at HCE to 23% for the upstream control and Weldwood Bridge. With the above data for perspective, a subjective ratio of 20% might be taken for Windfall, providing an estimate of dry sediment concentration equal to 4 mg/L, or 45% of the concentration of the upstream control site.

The following estimates of NFR loadings can then be made, taking HCE discharge as 1 m^3/s and Athabasca at Hinton and near Windfall as 39 m^3/s and 110 m^3/s respectively:

Location	Tonnes per day
Upstream control	29.6
HCE	4.3
Windfall	38.0

These values are estimates only, based on the process above, and are provided here primarily to show the approach that could be used if all pertinent data are available at the inlet and outlet sites. However, it is unlikely that the estimates are appreciably in error, and the indication is that, during the dynamic sampling program there is no net loss of NFR between the two main sediment input sites and the outflow site at Windfall.

Unfortunately the above data cannot automatically be taken to mean that all the HCE sediment is moved completely through the reach, because deposition en route could have been compensated by inputs en route, such as sediment exchanges with the bed, bank erosion, or inputs from the Berland River. The data do indicate, however, that the load at Windfall is about 10x that from the HCE so that any interpretation of deposition losses for contaminants that is based solely on concentration data could be misleading.

Turning then to the contaminant concentration values - the third element in the loading expression - allows determination of the contaminant loadings for the input and outlet sites, with NFR loadings taken as 4.3 t/d and 38.0 t/d respectively.

Using the data supplied by Crosley (1994, Table 5) for chlorinated phenolic concentrations at HCE and Windfall Bridge (taken as ug/kg or ng/g), the following loadings emerge (g/day):

Compound	HCE (g/day)	Windfall (g/day)
mono-Cl	1.1	1.7
di-Cl	5.7	2.7
tri-Cl	21.0	1.7
tetra-Cl	1.3	0.1
penta-Cl	0.06	<0.1

indicating 50% losses for di-Cl and more than 90% loss for tri-Cl and tetra-Cl, while an apparent gain exists for mono-Cl. The data confirm Crosley's (1994) conclusions that appreciable losses do occur in the reach and are also consistent, in a qualitative way, with the presence of chlorinated phenols in the bottom sediments (though Crosley (1994) reports no evidence of tetra-Cl in the bottom sediments).

Using data for the polychlorinated dibenzodioxins and dibenzofurans from Appendix B of the Crosley (1994) report, the following loadings (mg/day) emerge:

Compound	HCE (mg/day)	Windfall (mg/day)
Total HxCDD	31	80
Total TCDF	473	350
Total HxCDF	37	87
Total HpCDF	69	171

It is difficult to interpret why three of the four classes should show an increase from the HCE lagoon to the Windfall site, unless this is due to analytical imprecision (but there is a consistency in the trend).

As they stand, the data do seem to indicate a preferential removal of the PDDD/F compounds through the reach past Windfall compared to the chlorinated phenols. These conclusions are consistent with those of Crosley (1994, p. 18), though they go further in the extent to which they emphasize transport through the reach rather than in-reach losses. The conclusions are also graphically evident in Figure 9 of Crosley's (1994) report which shows contaminant concentrations in the Athabasca through the reach below Hinton as being about 10% of those in the HCE: this is consistent with a NFR loading in the Athabasca of 10x that of the HCE.

No attempt is made to pursue other analyses of this type here given the time restraints and uncertainties in the data, some of which have been noted previously. However, for perspective, it is interesting to examine additional NFR data collected in the reach (mid-May 1992) and provided by Crosley (1995, pers. comm.). The discharge data for upstream (Athabasca at Hinton) and downstream (Athabasca near Windfall) are taken directly from WSC files and the HCE discharge and TSS load records from Weldwood plant records (Ouellet 1995). The loading data are computed as follows:

Date	Location	Concentration (mg/l)	Discharge (m^3/s)	Load (t/d)
May 20-21	Upstream control	16	188	260
May 21	HCE	148	1.37	17.5
May 25-26	Windfall	2.4	246	51

According to these data, and unlike the period of April sampling, the mid-May period corresponded to massive deposition of sediment from upstream of Hinton in the reach between Hinton and Windfall. The decreased throughput of sediment in May could be related to the influx of sandier sediment at these slightly higher flows but this is conjecture. What the data emphasize, however, is the variability in the NFR sediment budget for this reach even under roughly comparable flow conditions and time of year. This variability needs to be kept in mind in the interpretation of data from any single window of dynamic sampling. This period was consistent with the two low-flow periods examined by NWRI.

In addition, the data also show the variability in NFR concentration and loadings from the HCE outfall, the May values being almost 5x those of the April sampling. This then raises the question of how representative the window of dynamic sampling for April 1992 is of spring conditions in general. To answer this question, far more frequent data on NFR or TSS for the three sites would be needed. More Sedisampler data for contamainants, while obviously useful, are not as essential in order to provide the perspective sought.

7.4.2.3 Sampling of other reaches

The Hinton reach of the Athabasca River is the only one investigated for suspended sediment contaminants. It is the logical area to start, however, and given the supplementary work needed to provide perspective for the program, it is understandable that similar work has not been undertaken elsewhere. An obvious candidate for similar study would be the Wapiti-Smoky system downstream of the Weyerhaeuser mill. On the whole, however, it seems more appropriate to consolidate interpretation of contaminant movement and settling in the Athabasca reach first (as recommended in Chapters 8 and 9) rather than undertaking a new initiative elsewhere.

7.4.2.4 Sampling accuracy of data

As indicated above, two of the main goals of dynamic modelling are assessing contaminant conditions in different reaches and, through loading data, assessing movement through a river reach. Before either can be done it is necessary to verify that the sampling vertical used in a given cross-section is indeed fully representative of concentrations in the full cross-section at that site. Without this assurance, no reliable conclusions can be reached.

As already noted, Crosley (1994) pointed out that the suspended sediment data at Weldwood Bridge were obtained in a section which, because of its proximity to the HCE site, was not fully mixed in terms of sediment. Since the degree to which the vertical that was sampled overestimated or understimated the mean for the section is not known, no reliable interpretation can be put on the data from this site. Normally Environment Canada does multiple vertical samplings across a river (for total suspended sediment) which would allow an adjustment factor (k-value) to be made to data from the single-vertical site, but this does not appear to have been undertaken.

No information is available for other sites except, indirectly, for Knight Bridge where Figure 8 of Crosley (1994) shows the cross-sectional pattern of AOX (adsorbable organic halogen) in raw river water and compares it with Weldwood Bridge. The observations refer to April 2, 1992 with a river flow of 40 m^3/s. The plume of effluent from HCE is shown to be still quite well-defined near the right side of the channel at Weldwood Bridge, as noted above, but much weaker and channel-centred at Knight Bridge 116 km downstream.

Any sampling of AOX (in mg/L) at the right bank at Knight Bridge would seem to be representative of mean conditions in the channel cross-section there at that time. The assurance from this observation must be tempered somewhat, however, because it does not necessarily mean that right-bank sampling at the section provides representative values of HCE contaminants in the suspended sediment. An asymetry in NFR concentrations in the cross-section if it existed, coupled with a constant pattern of contaminants in the water across the section, would necessarily mean an asymmetry in the pattern of contaminant concentrations in the sediment. For this reason, multiple vertical sampling of TSS or NFR is needed for proper assurance.

Useful, if limited, information is also provided in the two mass-balance studies by NWRI (Krishnappan et al., 1995). In the autumn flow of 149 m^3/s, sediment concentration at Obed showed a mid-channel peak in concentration at 19 mg/L, decreasing to 10-15 mg/L at the margins, with the same cross-sectional pattern persisting as far as Windfall. In the ice-covered winter flow of 29 m^3/s, fewer multiple verticals were taken at each transect. Higher sediment concentrations persisted along the right side of the channel (about twice those on the left side) from Obed all the way down to Windfall. These are discussed further in Chapter 8.

7.5 Bottom Sediment Contaminant Sampling

7.5.1 Overview

Various approaches can be used to characterize the sources, pathways and fates of sediments and sediment-associated contaminants. They include source identification and quantification through aerial photography analysis, fingerprinting sources lithologically and with natural tracers, coring of sediment deposits to develop time trends and surficial sampling (Hudson, 1989). The NRBS contaminant program focused on the latter approaches of surficial bottom sampling in the river system and coring of lake deposits. The following discussion is limited to sediment-associated contaminant sampling in the river system. A commentary on the lake coring is provided in NRBS correspondence (Hudson 1992)

Bottom sediments were collected throughout the study area in the period 1988 through 1995. Details are provided in R.L. & L. Environmental Services Ltd. (1993) and Crosley (1995). The procedures utilized in this sampling were apparently a replicate of earlier sampling by Alberta Environment (1988 and 1989) (AEP samples in Table 7.1).

In the "reach specific survey" (RSS) undertaken by R.L. & L. Environmental Services Ltd. (1993) in the upper Athabasca River during April and May 1992, sediment samples were collected from both erosional and depositional sites. The erosional areas were described as cobble-gravel areas with fine sediment occuring as a film on stones and in interstitial spaces. Crosley (1994) states that the erosional samples were collected with a large stainless steel spoon. Depositional areas, such as small bays or backwaters, with fine textured deposits, were sampled with an Ekman dredge and the upper 5 cm of collected sediment was retained. For each of the six sample reaches of the upper Athabasca River described in Table 7.1, at least 10 individual samples were collected. These 10 individual samples were combined into a composite sample for that sampling zone (or reach). The individual grab samples were all taken within a radius of 50 to 100 m. The samples were mixed prior to splitting for analysis. Additional Ekman samples were apparently taken near Athabasca and a ponar sampler was used to collect bed material from 5 verticals through the cross section at 27 baseline (these samples were reported in field notes but not in the RL&L report).

Seven additional samples were collected in the reach-specific area during September-October 1993. These "Triad" samples were collected for chemical and microtoxicological analyses, and have been reported by Day and Reynoldson (1994). Neither these data, nor the "Synoptic" data for May 1993 have been seen in the preparation of the present report.

Following a review of the initial sediment-associated contaminant sampling, a program to addresses issues regarding spatial representativenes and size attributes was proposed (Hudson 1994). The following elements of this proposal were undertaken in the 1994 and 1995 sampling program (ERD in Table 7.1).

Basin-wide sediment collections in the Athabasca and Peace rivers basins were carried out in October 1994 and May 1995 (Crosley 1995). These collections were undertaken to provide a 1994-95 dataset for comparison with the earlier collections, to determine intra-site variability, and to evaluate the particle size distribution of organic contaminants. A total of 12 locations were sampled (Table 7.1). Composite samples were collected at 6 of the 12 sites. Composite samples were collected by mixing equal aliquots from the upper 5 cm of 10 Ekman dredges collected from 4 depositional areas within each sampling reach. These reaches were up to2 to 5 km in length and were located near to the points specified in Table 7.1. Site-specific details will be provided in the CD-ROM library of maps and photographs being prepared by Environment Canada (Section 1.2). At the remaining 6 sites, discrete-area samples were collected from 10 depositional areas in each sampling reach to determine intra-site variability. Each discrete-area sample was a composite of 5 Ekman dredges of the upper 5 cm of sediment.

7.5.2 Evaluation

7.5.2.1 Spatial trends and representation

(a) Basin and reach scales

One of the objectives of the reports by both Brownlee et al. (1994) and Crosley (1995) was to determine the spatial distribution of contaminants in bottom sediments in the NRBS system (Figure 7.1).

Brownlee et al. (1994), using 1988-92 data, concluded:

"In general, concentrations of compounds from the groups analyzed were low throughout the river basins. The two bleached kraft mills (Weldwood at Hinton; Weyerhaeuser at Grande Prairie) were weak sources of some members of the dioxin/furan group, most notably 2378TCDF, and of the chlorophenolic group. The mills were sources of several resin acids and strong sources of the two chlorinated resin acids, 12/14CDHA and 12,14DCDHA." Regarding the latter point, it should be emphasized again that chlorinated resin acids are exclusively derived from pulp mills (Sekela et al., 1995).

Figures 7.2 and 7.3 show the spatial distribution of 2378 TCDF in 1989-90 and 1992 respectively. The former show a background level of 0.8 pg/g on the Athabasca River above Maskuta Creek (upstream of the HCE), with no data in the key reach below Hinton until about Windfall with a level of 1.4 pg/g, then decreasing systematically to Lake Athabasca (0.4 pg/g). The 1992 survey attempts to fill in the gap on the Athabasca between Hinton and Windfall, showing peak levels of 2.0-2.2 pg/g in that reach compared to 0.1 pg/g at the upstream control site.

The dilution of this compound between the Hinton-Windfall reach (taken as 2 pg/g) and Lake Athabasca (0.4 pg/g) corresponds to a factor of 5x. This is remarkably close to what would be expected on the basis of sediment dilution of any contaminant compound between Windfall and Embarras: the mean annual sediment load increases by a factor of 5.3x between the two stations as indicated in Figure 3.1.

The 1988-89 situation in the Wapiti-Smoky-Peace system (Figure 7.4), however appears much more complicated. An initial peak of 1.5 pg/g 2378 TCDF at Grande Prairie (below the mill) is followed by a value of 3.8 pg/g at the mouth of the Smoky River and then a value of 2.7 pg/g downstream on the Peace River about 130 km downstream of the Smoky. The latter value would have been expected to be about 1.9 pg/g based on complete mixing of roughly equal loads of suspended sediment from the Smoky (3.8 pg/g) and the upper Peace (0.1 pg/g) rivers. The difference between this and the actual value of 2.7 pg/g may be simply a matter of sampling or analytical error.

The more interesting question is why values at the Smoky River mouth and the middle Peace River should be more than double the peak at Grande Prairie and 5x to 8x the values along the Smoky between Grande Prairie and the junction with the Little Smoky River. This question does not appear to have been addressed. It would require close examination of intra-site variance in order to assess whether these between-site differences are statistically significant. The statistical data presented by Crosley (1995) show values of coefficient of variation (CV) for total PCDD/F only, and are based on only 3 sub-sites. These CV values ranged between 12% and 101%. Using an average value of 50%, the differences just noted (5x and 8x) would appear to be highly significant statistically. However, it seems likely that the CV would be higher for individual congeners than for total PCDD/F compounds, therefore the matter remains unresolved.

Crosley (1995), using 1994-95 data, concluded:

- Total and chlorinated resin acid concentrations on the Athabasca River both peaked at the site downstream of Hinton (Emerson Lakes), these being 7x-8x the level below Alpac, with little change at Fort McKay. Chlorinated phenolics showed the same pattern though the decrease in the lower reaches seemed to be smaller;

- Total resin acids peaked on the Peace River above the Smoky River, this concentration being 4x those below Ft Vermillion. Chlorinated resin acid concentrations, however, peaked in the Wapiti, with insignificant amounts elsewhere. Chlorinated phenolics were similarly highest in the Wapiti but showed erratic changes down the course of the Peace River.

- Chlorinated resin acids were significantly (5x-10x) higher in the Athabasca than in the Peace system, but little difference could be found in the chlorinated phenolics.

- Levels of individual PCDD/F compounds were essentially at or less than the detection level of 0.1-0.2 pg/g everywhere except Athabasca River downstream of Hinton.

The general trend to highest concentrations downstream of Hinton on the Athabasca is consistent with the sediment dilution effect noted previously. However, intra-site variance was so high in many cases, that quantitative comparison of mean values between sites may not always be reliable.

Again, the situation in the Peace River system is more complicated with fluctuations in total chlorinated phenolics along the system from the Wapiti (35 ng/g), Smoky mouth (14 ng/g), Peace River below Daishowa (16 ng/g compared to 5 ng/g above the Smoky) then down to 5 ng/g on the Peace above Notkewin R. and back up to 25 ng/g on the Peace River below Fort Vermilion. This raises various questions of interpretation. In part, the variability seems to be related to changing composition of the chlorinated phenolics with mono-Cl dominating in the Wapiti and rapidly being lost, while tri-Cl assumes major importance at Fort Vermilion with little upstream.

(b) Site scale

An additional goal of the report by Crosley (1995) was determination of within-site variability in bottom sediment contamination. Initially this was done by sampling in 10 depositional sub-areas within a 3 km reach of the Peace River downstream of Daishowa, each of the 10 sub-areas being a composite of 5 Ekman dredge samples. The protocol was then extended to five other sites but done in spring rather than autumn. His main conclusions were:

- Variance was much higher in the sand fraction than in the silt-clay component, the contaminant concentrations to some degree being correlated with organic carbon concentration in the sand fraction (possibly woody material);

- Within-site variance tended to be higher with resin acid concentrations than PCDD/Fs or chorinated phenolics and least with PAHs.

As an example, the average coefficient of variation for resin acids was 155% in sand fractions and 36% in silt-clay fractions. The sand fraction produced, on average, about 50% of the resin acids in bottom samples, the amount ranging from 11% (in the lower fine-grained reaches) to 79%. Using Peace River below Daishowa as a case study for intra-site variance, total resin acids in the sand fraction varied between a minimum of 89 ng/g and a maximum of 4204 ng/g in the 10 sub-areas, while they ranged 576 ng/g to 3602 ng/g in the silt-clay fraction. Because of the high cost, no other contaminants were examined for intra-site variance at Daishowa.

These data thus provide some perspective for the broad span in 95% confidence levels reported for the main body of data which were based on composite samples from only 3 sub-areas.

The data also raise the question, however, as to the rationale for using mean values based on composite samples. In reaches where there are pockets of contaminated bottom sediment, it could be argued that what really matters is the degree of contamination in these pockets rather than some reach-average. Assuming that these local pockets correspond to particular sedimentological and morphological settings, these could be delineated prior to sampling in order to attain the most efficient and informative experimental design. No maps at the site scale were provided in the report by Crosley (1995), but hopefully they will be included in the CD-ROM library noted in Section 1.2.

As a corollary of the discussion in the last paragraph, however, the question should at least be raised as to whether the spatial trends (or lack of trends) reported for sample mean values at the basin and reach scales (in the previous section) would have been repeated if attention had been focussed on data from individual sub-areas rather than composite samples.

7.5.2.2 Temporal representation

(a) Seasonal variability

The report by Crosley (1995) provides data which tend to support the view that concentrations of contaminants in bottom sediments are less in spring (after ice-out) than in the previous autumn. Data were available for 1994-95 at two sites (Athabasca R. below Alpac and Wapiti R. near the mouth) and are consolidated in Table 7.2. Unfortunately, no data for successive autumn-spring sampling could be found in earlier reports. Comparison of autumn and spring samples with gaps of one or more years could be misleading for reasons given below.

Inspection of preliminary WSC discharge data for stations close to these two sites (not available to Crosley at the time of his report) showed the following pattern. On the Athabasca River at Athabasca, discharge at the time of the May 12 sampling was 232 m^3/s, slightly less than an early May peak of 271 m^3/s, and about 2x the January-February flow, but substantially less than the peak August 1995 flow of 2160 m^3/s. The May flow at the time of sampling was about one third of the longterm May average flow (675 m^3/s) so that the conditions should not be considered to be those corresponding to the spring freshet. On the Wapiti River near Grande Prairie, the same basic comment holds to some extent. Discharge at the time of the May 10 sampling was 195 m^3/s, 20x the flow in January and February, but less than the peak May flow of 491 m^3/s on the 16th, which was the peak daily flow in 1995 (though itself small, having been exceeded 23 times in the 31-year period 1960-90). The May 10 flow, however, was only slightly less than the longterm May flow of 256 m^3/s.

These discharge data thus indicate that the period of bottom sampling in spring 1995 did not occur after significant post-breakup flows, and this raises the question as to why contaminant concentrations were so much lower than in the previous autumn. Crosley (1995) makes an observation that may well be relevant here. In discussing the fact that spring samples were generally coarser than autumn samples, he notes that this may have been an artifact of the sampling methodology: whereas 4 depositional areas were sampled at the two stations in autumn, 10 were sampled in the spring. "Increased coarseness in the May samples may be a result of the necessity to sample some less-than-ideal (less fine) depositional areas during the second survey to fulfill sampling requirements." (p12). The same conclusion may be applicable to contaminants within the sediment.

Any analysis of this possible seasonal change, however, needs accurate knowledge on the sub-areas sampled and the flow-history of the areas in the last 12 months. Crosley (1995) comments that "samples were generally taken from shallow-water areas near the shore, but occasionally recently emerged beaches and banks were sampled".

In the Wapiti reach, spring bottom sampling was done at a flow which was sufficiently high that it had not been exceeded since early July of the previous year. Thus these shallow-water and dry-area samples presumably were deposited prior to July of 1994, during the main summer flood flow, and not added to or reworked since that time. The October 8 1994 bottom sampling in the same reach occurred when the flow had been falling, with small reversals, during late summer. These deposits could then correspond to sedimentation during relatively low flows when, perhaps, sediment was dominated more by mill effluent. This is therefore another possible explanation for the higher contaminant concentrations in the autumn-sampled sediments.

In the Athabasca reach below Alpac, spring bottom sampling was done at a flow which (based on Fort McMurray data) had been marginally exceeded for 12 days since April 28, but which prior to that had not been exceeded since early October 1994. In this case the spring sampled bottom sediments may have been deposited during spring (perhaps from a reworking of winter deposits upstream) rather than from the previous late summer.

The discussion above therefore highlights the importance, in any interpretation of seasonal differences in bottom-sediment quality, of knowledge of flow history and of the changing location of sedimentation areas in the reach according to water stage and local boundary shear stress as discussed in Chapter 5. Moreover, in the Wapiti reach, it is also clear, that neither sampling would have involved bottom sediment laid down during winter conditions; and that the spring sampling did not involve reworking of the autumn bottom sediments. In this sense, the sampling sequence is possibly not directly comparable with that on the Athabasca below Alpac.

(b) Year-to-year variance

In his analysis of bottom sediments, Crosley (1995) reported that: "chlorinated resin acids in sediment were detected in significantly lower concentrations at most sites than were found in 1988-92" but that "PAH concentrations were similar to those found in 1988-92 at most sites. Increases in concentration of selected PAHs during that time period were noted at the Peace River above Smoky River." "A pattern of continuing improvement in PCDD/F quality was noted at most sites, with the exception of the Peace River above Smoky River, where some evidence of degradation was noted."

Because of uncertainty in analytical precision, Crosley (1995) did not speculate on the reasons for this overall improvement in the quality of bottom sediment, nor for the apparent exception to the trend shown at the Peace River site above Smoky River. However, the results are consistent with the expected changes resulting from the modification of chlorine treatment in the kraft mills. Some care is needed, however, before accepting this as a cause-and-effect phenomenon for reasons outlined below.

The baseline samples for this time-trend analysis were taken in autumn 1988. This year was one of exceptionally low spring runoff in both the Athabasca and Smoky river basins, though the flow was "normal" in the upper Peace because of regulation from Bennett Dam. Assuming that the spring freshet is the normal mechanism for cleaning bottom sediment of much its over-winter accumulation of fine sediment (and associated contaminants), autumn levels of contaminants in bottom sediments might be expected to decrease in proportion to the strength of peak flows in the previous spring. With this perspective it should be anticipated that contaminant levels in bottom sediments in late 1988 would have been unusually high, except in the upper Peace River.

An analysis has therefore been made of more recent discharge data at sites and in years for which more recent contaminant sampling has been undertaken. The results for 2378-T4CDF are summarized in Table 7.3.

As noted by Crosley (1995), the pattern on the Peace River above the Smoky River is different from the others with concentrations of all four PCDD/F congeners analyzed showing increases from Sept. 1988 (when the site had the lowest PCDD/F values of all sites sampled) to Oct. 1994 ranging from 2x to more than 6x. However, the values for both years were based on a single composite sample, and the statistical significance of the difference is unknown. Peak summer discharge was not substantially lower in 1988 than in 1994, consistent with the hypothesis above.

In contrast, on the Wapiti River, where contaminant levels were substantially higher in 1988 than 1994, peak spring flow was, as expected, significantly lower in 1988 than 1994. These two sites therefore suggest that caution is required in the interpretation of time trends in contaminant data when this is done without knowledge of flood history.

At the other two sites, however, it is clear that the trend cannot be attributable to differences in flood history. The peak 1994 flow on the Smoky was only marginally higher than the 1988 flood peak, and on the Athabasca near Windfall, the peak 1994 flow was actually less than the 1988 peak. Thus, overall, the differences between contaminant concentrations in 1994 and 1988 do not appear to be related to flood history in any obvious way.

There is one further point to consider in this context. This is that the control site on the Athabasca (above the HCE) also showed a dramatically lower 2378TCDF concentration in 1995 than in 1989 with higher peak flows in 1989 than in 1994. No comment on this was found in the report on the 1994/95 bottom sampling, but it would seem to be a very relevant piece of data.

The other interesting issue on the Wapiti, Smoky and Peace river is the effect of the record 1990 flood in terms of reworking bed sediments and contaminants and creating extensive new deposits. No information appear to be available to address this topic. This is unfortunate because significant removal, dispersion, dilution and burial of old contaminated beds is likely to have occurred in this flood event.

8.0 CONCLUSIONS

This chapter lists the various conclusions to emerge from this report in the context of the two main study questions that have been examined:

4-a What are the contents and nature of the contaminants entering the system? Describe their distribution and toxicity in the aquatic ecosystems with particular reference to water, sediment and biota.

4-b Are toxins such as dioxins, furans, mercury etc., increasing or decreasing and what is their rate of change?

8.1 NRBS Question 4-a

8.1.1 Presence of contaminants in river sediment

Contaminants that are found in pulp mills in the NRBS area have also been found in both suspended sediment and bottom sediment in rivers downstream of these mills. These include dioxins, furans, chlorinated phenolics and chlorinated resin acids. Of these, only the latter appear to be uniquely derived from pulp mills (specifically bleached-kraft mills).

The concentrations found were generally considered to be low, with the exception of some of the resin acids. We are not aware of any work done to assess the biological significance of these concentrations, i.e. whether the levels found pose a risk of serious contamination of the food chain.

It should be noted that, whereas bottom samples have been taken throughout both the Athabasca and Wapiti-Smoky-Peace systems, analysis of contaminants in suspended sediment appears to have been restricted to the Athabasca reach below Hinton.

8.1.2 Spatial patterns of contaminants in bottom sediments at basin and reach scales

The presence of contaminants is particularly evident in the reaches immediately downstream of the bleached kraft mills: the Weldwood mill at Hinton on the Athabasca River, and the Weyerhaeuser mill at Grande Prairie on the Wapiti.

In reaches further downstream (below Fort McMurray on the Athabasca and below Town of Peace River in the Wapiti-Smoky-Peace river system) contaminant concentrations are much less likely to exceed detection levels because of the mixing with large amounts of cleaner natural sediment. This sediment dilution effect appears to be stronger in the Athabasca.

In the Wapiti-Smoky-Peace system, the downstream decrease in at-a-site mean values of contaminant concentrations along the course of the river is much more variable. No attempt appears to have been made to evaluate the statistical significance of this downstream pattern (at the level of individual congeners) or examine the reasons for the pattern if it is the result of more than simply high intra-site sampling variability.

8.1.3 Spatial patterns of contaminants in bottom sediment at site scale

Not a great deal of information is available on this topic because of the strategy, for cost reasons, of pooling sediment specimens into a composite sample at each site. Some, limited, data are available from the study by Crosley (1995) to address the issue of intra-site variability. This variance is high. As a result, standard errors of some of the mean values at a site are also high making comparison of downstream trends uncertain.

The question needs to be addressed, in any case, as to whether the use of composite samples is a meaningful approach. The strategy can certainly mask local "hot spots" at a particular site and lead to dubious comparison of different sites, even when the standard error of site means is low.

In addition the relevance of the composite sampling approach to food chain issues is not at all clear. From a fisheries standpoint, for example, the river bed is made up of distinct habitat types, some of which are used by fish for specific purposes and some of which are used very little, depending, of course, on river stage. In terms of spawning salmonids, for example, what presumably matters is contaminant levels in the interstitial fines within gravel in that habitat with specific depth-velocity requirements for spawning.

It is acknowledged that composite sampling seems a logical and economic first-stage approach to the problem, and will highlight obvious widespread areas of contaminant deposition. But for reasons just noted, care is needed in the interpretation of the results, and local pockets of contamination may be missed in such an approach.

The importance of the winter ice period needs to be emphasized because this is when the relative importance of pulp mill effluent in the total sediment is at a peak. It is also a period in which sedimentation can take place over large parts of the channel bed, based on the NWRI findings and the analysis by Trillium (1995). In this context, the relevance of open-water sampling of bottom sediments in spring and autumn to the spatial disposition of winter sedimentation (especially in the context of fish habitat) should perhaps be addressed.

8.1.4 Seasonality of deposition of contaminated sediment

The initial deposition of pulp mill sediment, at least during low autumn and winter flows, appears to be restricted to a relatively short reach immediately downstream of the effluent site. This comment is based on the study by Krishnappan et al. (1995) in the Hinton reach previously discussed. In stronger flows, contaminated sediment is moved further downstream: this involves dilution of concentrations with background sediment, together with some additional input of the same contaminants from non-pulp-mill sources.

In the typical year, it would appear that sediment from the Hinton Combined Effluent would mix with natural sediment and settle on parts of the bed for at least 7 months.

The assumption is usually made that during the spring freshet this settled sediment would become resuspended, mixed with background sediment from upstream, and transported far downstream. Such resuspension from a gravel-bed may, however, require fairly high flushing flows which may not occur in the near-bank areas each year. The possibility of mixed HCE and natural sediment staying on the bed in certain areas for more than one year should therefore not be dismissed with the data presently available.

8.1.5 Impact of HCE inflow on sedimentation in the Athabasca River

The laboratory study by Krishnappan and Stephens (1995) included two tests, at a flume bed shear stress of 0.26 Pa, in which pulp mill effluent was introduced into the flume at a concentration comparable with the effluent concentration in the natural river. In the absence of effluent, the initial sediment concentration of 250 mg/L was reduced by settling to a steady state concentration of 85 mg/L, amounting to 66% of the sediment settling. In the presence of mill effluent, the steady state concentration was 65-70 mg/L, amounting to 72-74% of the sediment settling. Though there is clearly increased settling in the presence of mill effluent, the increase is relatively small.

In the winter survey on the Athabasca River, Fig. 7 of the report by Krishnappan et al. (1995) indicates that the amount of sediment deposited in the reach between Entrance and Obed was at least 70% of the incoming sediment loads (combined Entrance and HCE load). The argument that most of this deposition is due to precipitation by the pulp mill effluent may well be true. However, given the limited changes noted in the laboratory, this argument cannot be considered conclusive at present. It is especially unfortunate that no measurement of sediment load was made in the Athabasca just upstream of HCE.

The undertaking of a transect immediately upstream of HCE would have provided data on how much of the settled sediment in the Entrance-Obed reach had settled upstream of the HCE input. This in turn would have provided a much less ambiguous assessment of the effect of HCE inflow on sedimentation downstream.

8.1.6 Fate of suspended sediment contaminants below pulp mills

Ideally, the mass-balance approach used for suspended sediment by Krishnappan et al. (1995) would also have been used in examination of contaminants adsorbed to the suspended sediment in the study undertaken at low flow (39 m^3/s at Hinton) in April 1992 in the same reach. Unfortunately gaps in the necessary data at most points in the reach (in discharge and sediment concentration) make it difficult to pursue a mass-balance approach accurately. Some analysis was done in Section 7.4.2.1, however, in comparing inputs from the HCE and from the Athabasca upstream with the outflow from the reach at Windfall, 176 km downstream.

These data showed slightly more sediment leaving Windfall than being supplied by the Athabasca and the HCE at Hinton, a marked contrast to the two periods noted in the sediment study by Krishnappan et al. (1995). The data do not necessarily mean that all HCE sediment is transported past Windfall because of the possibility of extra sediment being picked up en route, or supplied by small tributaries, to compensate for sediment deposited.

Examination of loadings of chlorinated phenolics at HCE and Windfall, in fact, showed that most of these compounds were not evident in sediment moving past Windfall, suggestive of sediment deposition, or breakdown of the phenolics. In contrast, mg/day loadings of most dioxin and furan groups showed higher values at Windfall than in the HCE. Unless this is the result of analytical imprecision, it appears to imply acquisition of these compounds in sediment along the reach. No attempt appears to have been made to address this contrast between the two sets of contaminants.

8.1.7 Representativeness of suspended sediment-contaminant study

Useful information has been provided by the sediment-contaminant mass balance, although as just noted some issues remain unresolved. Perhaps the key question, however, is whether the sampling period used for the sediment-contaminant study is really representative of late winter or early spring conditions. The period used was one which turned out to involve no net settling of sediment in the reach. This is a marked contrast to both of the sediment studies undertaken by NWRI which showed appreciable net sedimentation. It is also a marked contrast to conditions only six weeks later in 1992 when sampling again showed much lower sediment loads at Windfall than at Hinton.

It is therefore questionable as to how valid any interpretation is of the sediment-contaminant mass balance study, given that the sampling period seems to have been atypical.

Moreover in any assessment of the representativeness of such a mass-balance study, attention must also be paid to the magnitude of the HCE sediment outflow. In the April 2, 1992 study HCE produced 4 t/day of suspended sediment, but March-May HCE sediment loadings ranged from 1 to 20 t/day.

If HCE sediment effluent causes flocculation of background sediment, thereby accelerating the settling of both, as suggested by Krishnappan and Stephens (1995) and Krishnappan et al. (1995), the magnitude of the HCE input is an important variable in any assessment of the mass-balance of the Hinton reach. In this respect, the April 1992 study seems to have been reasonably representative, however, because average daily HCE loadings in 1992 were 5.0 t in March, 5.8 t in April and 6.5 t in May.

Lastly, given the importance of the ice-cover period, a contaminant mass-balance in winter would have useful.

8.1.8 Sediment contamination and sediment size

As previously noted, there is a general assumption that contaminants preferentially adsorb to the finest sediment grains (clay size) and that the sand component is likely to contain little contamination.

Presumably for this reason, early analysis of bottom sediments (Brownlee et al., 1994) was done only on the size fraction that passed through a 0.06 mm sieve, i.e. on the silt-clay fraction. This raises two questions: (a) whether it is valid to ignore the sand fraction; (b) whether a further breakdown of silt versus clay would have been beneficial.

The later study reported by Crosley (1995) included a specific attempt to examine the first of these issues. The results were quite variable.

Concentrations of PAH in sand tended to exceed those in silt-clay. The same was true of total resin acids, where concentrations in sand exceeded those in silt-clay at four of six sampling locations. The results for the resin acids were thought to be the result of organic materials (e.g. fragments of pine needles) in the sand. Examination of the data for individual compounds, however, reveals that some compounds were consistently more abundant in silt-clay (including the chlorinated resin acids) and others more abundant in the sand. In some cases high standard errors render comparisons unreliable.

Concentrations of chlorinated phenolics and PCDD/F were generally higher in silt-clay than in sand. The former were 1.2x to 2.6x higher in the fine fraction and the latter varied between 1.1x and 3.8x higher at the four sites examined.

In short, it is clear that the sand fraction cannot be ignored completely, but in those contaminants most directly related to pulp mill effluent, the concentrations in silt-clay are distinctly higher in general. This means that downstream (and cross-stream) variability in concentrations of contaminants in <u>total fine sediment</u> (less than 2 mm) could be produced simply by variability in the proportion of sand in the sediment mixture. This point must obviously be borne in mind in interpretation of spatial (and temporal) trends if analyses have been done on the full sediment mixture.

The finding raises the question of whether the same pattern exists <u>within</u> the silt-clay fraction, i.e. higher concentrations in the clay component than in the silt; and whether variability in contaminant concentrations also reflects, in part, the proportion of the fine fraction that is clay. This issue may be less relevant, however, because the NWRI investigations showed that most silt-clay sediment in the Athabasca was in the form of mixed silt-clay flocs rather than discrete particles. In other words, even silt-rich sediment might be composed dominantly of clay size grains. Nonetheless an attempt to examine the degree of correlation between contaminant concentration in the silt-clay fraction and the %clay in that fraction would seem to be instructive. It might be examined if not already done.

8.2 NRBS Question 4-b

8.2.1 Available data on time trends in contaminant levels

The only attempt known to us to examine this question in the context of sediments is the report by Crosley (1995) on bottom sediments collected in 1994-5 and compared with data from sediments collected in 1988-92. This report summarized results as follows:

- high detection levels prevented evaluation of the time trend in chlorinated phenolics;

- PAH concentrations were generally similar between the two data sets;

- concentrations of PCDD/F were lower in the second group of samplings on both the Athabasca River and in the Wapiti-Smoky-Peace system, with decreases of 67-99 percent; the lone increase was on the Peace River upstream of the Smoky River;

- concentrations of total chlorinated resin acids were also significantly lower at the five sites for which data were available, with decreases of more than 75 percent;

- concentrations of total resin acids showed no consistent trend, and at two sites (on the Peace River) were substantially higher (4x and 51x) in the second group of samplings.

These findings were based on comparison of samples from which the sand fraction had been removed.

The decrease in PCDD/F and in chlorinated resin acids is consistent with expectations based on the substitution of molecular chlorine with chlorine dioxide in 1989-91 at the Weyerhaeuser mill on the Wapiti River and similar changes at the Weldwood Mill on the Athabasca River in 1993.

8.2.2 Interpretation of time trend data

Notwithstanding the impressive decreases shown, there are several problems in the acceptance of these time trend data as statistically significant changes, and additional difficulties in relating the trends to changes in the quality of mill effluent.

8.2.2.1 Statistical significance of differences

(a) Almost all the data were derived from a single sample at each site, except for 10 samples at two sites in 1995 for the chlorinated resin acid comparisons. No data were provided for the standard error of these mean values. This, of course, is difficult for the early sampling program which collected only a single specimen at each site. However, the data on intra-site variance in the second sampling could be examined in more detail to assess the utility of applying the coefficient of variation to the first sampling program. In this way, estimates of the standard error of means could be made, and a first-attempt approach could be taken to the statistical significance of the difference between the two sampling periods.

(b) The problem of statistical significance of the differences between the two time periods is compounded by the fact that, in many cases, the sampling reaches used in the two sets of surveys were not the same (Crosley, 1995). Thus the standard error of the mean is not controlled solely by intra-site variance but also inter-site variance in a given length of river.

8.2.2.2 Interpretation of time trends

(a) In terms of attributing these differences to changes in mill effluent it would be instructive first to examine the chemistry of the mill effluent directly over this period, rather than only examining differences in the sampling period in riverine sediment samples. No report has been seen in the preparation of the present report which provides such information. Yet such information would seem to be essential for meaningful interpretation.

(b) Though the samplings on the Athabasca River always included an upstream control, little attention appears to have been paid to the time trend in this control reach. It is remarkable, in fact, that between the 1989 sampling and the 1995 sampling there was a decrease of 94% in the concentration of 2378-T4CDF, with virtually all of the decrease being found in the 1992 sampling as well. All other PCDD/F concentrations, as well as total chlorinated resin acids, were below the detection limit in all three samplings so that no trend is indicated in those cases. Some effort needs to be directed to explaining this change at the control site. It is difficult to understand how improvements in water effluent chemistry could be transmitted to sediment upstream.

No upstream control site was adopted on the Wapiti-Smoky-Peace flow route, although the site on the Peace immediately upstream of the Smoky confluence might be considered a control.

(c) As suggested in Section 5.5.2, it seems likely that in years of weak spring and summer flow, sediment that has settled out in the previous winter may, in fact, remain on the bed throughout the following fall and winter. This is of some importance in comparing sediment concentrations between two years. Samples collected in years after a weak spring-summer flow would be expected to have concentrations that are higher, perhaps substantially, than samples collected after a strong spring-summer flood that has moved and dispersed the winter-settled sediment and diluted it with background sediment. The problem is that the critical discharges for resuspension have been estimated only at Hinton and at Peace River, and even these are subject to uncertainty for reasons given in Section 5.5.2.

In the case of the Wapiti-Smoky-Peace system, two points in particular need emphasizing.

One is that 1988, the base year for the time-trend comparison in most of this drainage, was a year of exceptionally low spring runoff so that it is unlikely that there was any movement of winter-settled sediment prior to the autumn sampling. For this reason, then, it would be expected that contaminant concentrations in the bottom sediments would be higher than in most years. It is fortunate that sampling was also done in 1989 on the Wapiti (and on the Smoky) because the spring flood in this year was comparable with the 1994 spring flood (even greater in the case of the Wapiti). Thus the comparison between the 1989 and 1994/5 data should not be affected by the considerations just mentioned.

A second point is that 1990 was a year of record summer floods on the Wapiti-Smoky-Peace system. On the Wapiti the annual peak flow was the highest on record in 1990, whereas that in 1988 was the lowest on record in the 1962-1990 period. This level of flow in 1990 had not been approached since 1982. On the Smoky, the 1990 flood peak was also higher than anything in the period 1955-90, though it had been approached (to within 75%) in 1987. On the Peace River at Peace River the 1990 flood peak was, again, the highest in the 1958-90 period, and 45% higher than the 1987 flood peak.

In the 1991-1995 period, the highest peak on the Wapiti (in 1991) was only 21% of the 1990 peak; the highest peak on the Smoky (also in 1991) was only 29% of the 1990 peak; and the highest peak at Peace River (1994) was only 30% of the 1990 peak.

It is to be expected that the 1990 flood on the Wapiti and downstream completely reworked the bed sediment, dispersing fines far downstream, mixing them with natural sediment. Sediment laid down on the falling limb of this flood would be expected to have been almost free from contaminants. How long it would take to attain contaminant levels in the bed sediment comparable with those in 1989 (ignoring the 1988 levels which are likely to have been extreme for reasons just given) is difficult to assess and would presumably depend on distance downstream of the Weyerhaeuser mill.

(d) An additional point relates to the texture of the sediments. The possibility that % clay in the silt-clay fraction affects contaminant levels has already been noted. It would be instructive to examine the %clay values in the 1988-89 samples and compare them with those of the 1994-95 samples. A major flood such as the 1990 event can produce significant changes in bed texture.

8.2.3 Assessment

The above caveats are not raised as a challenge to the view that there may have been a real improvement in contaminant levels in the Peace-Athabasca bed sediments between 1988 and 1995, and that such a change is due to improvements in mill effluent during this time.

The various points are raised to illustrate that such a conclusion cannot be unequivocally argued at this point in time, and to provide a perspective for reexamination of the existing data and for collection of new data.

9.0 RECOMMENDATIONS FOR MONITORING AND ASSESSMENT

This chapter deals with NRBS question 14: What long term monitoring programs and predictive models are required to provide an ongoing assessment of the state of the aquatic ecosystem? The suggestions are made primarily in the context of the sediment component of that ecosystem.

9.1 Biological significance of different levels of contamination

It is assumed that studies have been undertaken to examine the concentrations at which different contaminants in the sediment adversely affect aquatic biology. We have not seen reports on such studies nor reference to them in any of the reports dealing with sediment contaminants. It seems important, in order to put all the sediment-contaminant work in perspective, that the results of such studies be examined before further work on sediment-contaminant analsis is done. If such studies have not yet been done, it is clearly important to begin them.

9.2 Time trends in sediment-contaminant concentrations in pulp mill effluent

No analysis has yet been found of the time trends in sediment-contaminant concentrations in the pulp mill effluents during the period 1988-1995. Such an analysis is essential to proper interpretation of time trends in contaminants in the bottom sediments of the rivers downstream of these mills. It is recommended that, if this work has not already been done, such analysis be undertaken to provide a proper perspective for the bottom-sediment contaminant investigations.

9.3 Surficial bottom-sediment contaminants

As noted in Section 7.2.5.1(a), the downstream pattern of contaminant concentrations in bottom sediments in the Wapiti-Smoky-Peace system shows strange variability. This is especially true with the chlorinated phenolics with different species being lost and gained irregularly. It might be useful to have some attention directed to this finding.

Additional bottom sampling has apparently been done in the Wapiti and Smoky rivers as part of the pulp mill licensing agreements, but has not been seen in the preparation of this report. These data should be examined.

The report by Crosley (1995) is especially useful in addressing the intra-site variance of some of these data. However, there is scope for substantially extending this statistical analysis as noted in Section 8.2.2.1.

9.4 Modelling of settling and resuspension of fine sediment

Work done to date on this topic has been, in some respects, of a preliminary nature.

The distribution of bed shear stress provided by Trillium (1995) is based on one-dimensional flow. Many gravel-bed rivers show well-developed two-dimensional variability in topography, often in the form of alternating riffles and pools, quite distinctive in terms of fish habitat. Depending upon the flow intensity, sedimentation may take place on side bars associated with the riffles or in the pools. Shear stress patterns are complicated by convergence and divergence of the flow. As noted by Trillium (1995) two-dimensional flow computer models do exist for this kind of situation, but require detailed adaptation to the particular bed configuration of each channel.

The work by NWRI, reported by Krishnappan and Stephens (1995), dealing with critical shear stresses for deposition and resuspension was based on flow in a glass-sided and glass-bedded flume. Even with the scaling adjustments used, there must still be some concern that the computed stress for resuspension is too low for a gravel-bedded river.

It would be useful to explore both of these points further. This could be done in a flume study with a rough bed (simulating gravel) moulded into the two-dimensional pattern of bedforms found in the Hinton reach of the Athabasca River. The flume trials could then examine both the distribution of shear stress over the bed at different stages and the critical stress for resuspension. Alternatively, or in addition, observations in the field in the Hinton reach could address the same issues.

9.5 Deep bottom-sediment contaminants

Existing sampling of bottom sediments on the rivers has focussed on surficial sampling. It would be instructive to examine the reach downstream of all mills, on aerial photographs (followed by field verification), to ascertain whether any sites exist which would be suitable for examination of longterm sediment accumulation, ideally extending back to the pre-mill period. This would provide relatively unambiguous evidence of changes in the quality of bed sediment. Such coring would need to be done within 100 km of mills to avoid problems of detection arising from dilution of mill sediment with background sediment.

9.6 Suspended sediment mass-balance studies

The interesting observations provided by the two NWRI suspended sediment mass-balance for the reach between Entrance and Windfall in terms of settling of sediment downstream of the HCE suggest that additional work of this type be undertaken. Two points in particular warrant examination.

9.6.1 Impact of HCE inflow on sedimentation

The suggestion has been made by NWRI that HCE sediment combines and flocculates with sediment from upstream leading to accelerated sedimentation downstream. The suggestion seems reasonable but requires further verification as noted in Section 8.1.5. In particular repeated multiple vertical samplings immediately upstream of HCE, as well as at Entrance and at Obed bridge, are needed to assess how much of the sediment loss in the Entrance-Obed reach is actually occurring downstream of the mill.

Additional information on the length and cross-sectional distribution of the HCE plume downstream of Hinton under different flow levels and severity of ice conditions either needs to be made available or determined if not available.

9.6.2 Duration of settling of sediment in the reach downstream of the HCE

At present only two surveys of sediment mass balance in the Entrance-Obed-Windfall reach have been undertaken (September and February). Both showed net sedimentation in the river reach. Yet the incomplete data for the sediment-contaminant mass-balance of April 1992 showed no net sedimentation. Additional surveys would provide a much better perspective for assessing the duration in the typical year in which sediment from the HCE settles out in this reach.

9.6.3 Nature of future sediment mass-balance surveys

The work recommended above would not have to be as comprehensive as the NWRI study. Sampling could be restricted to a cross-section at Entrance, to one just upstream of the Hinton Combined Effluent, to the HCE (data supplied by Weldwood) and to the Obed Coal Mines bridge.

A small current-metering program on the few tributaries between Entrance and Obed would allow assessment of how small the error would be in assuming a constant flow rate through the reach given by the WSC gauge at Hinton (and the HCE discharge in the lower reach).

Multiple-vertical sampling would need to be done at both Entrance and Obed, as in the NWRI study but preferably with five verticals at each transect, to ensure accuracy in the sediment loadings.

Such a program, carefully undertaken in terms of times of sampling (in terms of fluctuations in HCE output and travel time between the three stations), and done under representative conditions throughout the year, would provide a much better perspective for the interpretation of data from the past sediment-contaminant studies, as well as any in the future.

Assuming that the Hinton WSC discharge and the HCE outflow are the only discharge data needed (and readily available), the only work involved is sampling, filtration, and interpretation. It would be appropriate to solicit the cooperation of WSC in this matter, given that the Hinton data could become part of a sediment file for the existing WSC station.

Any additional sampling at the WSC station on the Athabasca near Windfall, as part of the regular miscellaneous program at that station, should be encouraged to coincide with times of sampling at Hinton (allowing for the time of travel).

9.7 Sediment-contaminant mass balance studies

In the event that additional studies are done of sediment-contaminants in the suspended sediment load, in terms of addressing the issues of sources and fate of these contaminants, it is essential that they are done as part of a proper mass-balance methodology. This means that data are required for loadings of contaminants and not just concentrations.

In addition, given that work to date emphasizes the winter ice period as that part of the year in which localized sedimentation below pulp mills is most important (and when such river sediment has the highest relative concentration of pulp mill sediment) it would seem appropriate to ensure that the next contaminant mass-balance study be done under winter conditions. Some data exist from more traditional water quality studies in the winter (e.g. Noton and Shaw, 1989), but we have not seen comparable data for winter sediment quality.

9.8 Screening marker for pulp mill contaminants

In addition, while work to date has tended to use total resin acids as a screening marker of bleached-kraft pulp mill effluent, based apparently on cost considerations, careful reevaluation of this strategy is needed in view of the presence of natural resin acids (e.g. pine needles) in river sediment. It is worth noting that the highest total resin acids concentration in silt clay bottom sediments in the 1994-95 survey of the Wapiti-Smoky-Peace system was, by far, in the Peace River above the Smoky. At this site, chlorinated resin acids were not detectable: peak concentration of the latter suite of contaminants was in the Wapiti River (Crosley, 1995).

Chlorinated resin acids, which appear to be a specific signature of kraft pulp mill effluent, seem to be a much more logical screening marker, and should be considered as such for any future work.

9.9 Fractionation of sediment mixtures

In view of the cost of laboratory analyses, multi-fraction analyses should be avoided unless justifiable. Apart from the cost of fractionation, multi-fraction contaminant analysis reduces budgetary availability for other types of replication, such as non-composite site analyses.

The data collected in the 1994 bottom-sediment study appear to justify the elimination of the sand fraction and concentration on the silt-clay component. However, to some extent, this conclusion seems to depend on which particular comtaminants are examined. A more detailed analysis of the data than currently available would be worthwhile, complete with standard error limits for mean values, in order to develop guidelines for future work.

The question of variable composition of the silt-clay fraction itself should be addressed in any future work. As noted in Section 8.1.7, as a start it would be instructive to examine this matter further from the data already collected.

9.10 Overall assessment and organization of future studies

The NRBS work has provided some interesting observations, but interpretation of these observations is far from unambiguous. It would have been useful if a monitoring and assessment paradigm had been established prior to any fieldwork. It would also have been useful if an analysis of the physical context had been done prior to any monitoring and assessment rather than after the fact. This prior analysis would have significantly altered when, where and how the sediment-associated contaminants program was undertaken and how the results could be interpreted.

The kind of issues dealt with in this report involve interrelated aspects of chemistry, hydrology, river sedimentology and aquatic biology. The answers to many of the questions raised require information from at least three of these areas of study. When attention is focussed on just one component, or even two, answers are likely to be, at best, incomplete and possibly wrong. It is essential that in the planning of any further studies that careful, and ongoing, coordination is undertaken.

In the same vein, it is apparent that additional information is likely to emerge in the future that will bear upon some of the issues addressed in this report. It is important not to treat each new study in isolation, but to examine the extent to which it provides material relevant to questions previously raised but not yet answered.

Finally, while considerable data have been acquired in the NRBS study, interpretation, as evident at the time of this report, appears to be limited. One of the problems, again, is the multidisciplinary nature of the problem. It would seem sensible, before embarking on any future work, to examine all the NRBS data more thoroughly from a multidisciplinary aspect to attempt a more in-depth interpretation than has been done so far, and to use the results (or lack of results) from that overview to guide future work.

10.0 REFERENCES

Agra Earth and Environmental, 1994. Northdat version 1.0. Report to the Northern Rivers Basin Study for Project CW1367.00. 25 pages plus appendices

Aitken, B., Choles, J. and A. Deboer, 1995. Hydrology overview for the Northern River Basins Study. Draft report for the Northern River Basin Study

Alsberg, T., Balk, L., Nylund, K., de Wit, C., Bignert, A., Olsson, M., and T. Odsjö. 1993. Persistent organic pollutants and the environment. Swedish Environmental Protection Agency, Stockholm.137 pp

Amendola, G.D., Barna, R. Blosser, L. Lafleur, A. McBride, F. Thomas, T. Tiernan and R. Whittemore. 1987. The Occurrence and Fate of PCDDs and PCDFs in Five Bleached Kraft Pulp and Paper Mills. Presented at the Seventh International Symposium on Chlorinated Dioxins and Related Compounds. Las Vegas, Nevada.

B.C. Hydro, 1976. Peace River sites C and E: river regime and morphology. British Columbia Hydro and Power Authority, Hydroelectric Division, Report No. 783

Brownlee, B.G., Telford, S.L., Crosley, R.W., and L.R. Noton. 1994. Distribution of organic contaminants in bottom sediment sin the Peace and Athabsca river systems. Report to the Northern Rivers Basin Study for Project 2321-D1. First Draft

Burkham, D.E., 1985. An approach for appraising the accuracy of suspended-sediment data. U.S. Geological Survey Professional Paper 1333.18 pp

Carson, M.A., 1989. Evaluation of sediment transport data for the Lower Athabasca River Basin, Alberta. Proprietary report for Environment Canada, Calgary, Alberta. March, 1989

Carson, M.A., 1990a. Evaluation of sediment transport data for the Lower Athabasca River Basin, Alberta. Report for Environment Canada, Calgary, Alberta. April, 1990. Published January, 1991

Carson, M.A., 1990b. Sediment budget for the Athabasca River Basin, Alberta, between Fort McMurray and Embarras, 1976-1986. Report for Environment Canada, Calgary, Alberta. April, 1990. Published January, 1991

Carson, M.A., 1990c. Sampling of suspended sediments for water quality applications. Talk presented at Joint Study Team Meeting of Water Resources Branch and Water Quality Branch, Inland Waters Directorate, Environment Canada in Ottawa, February 14-16. Unpublished

Carson, M.A., 1990d. Statistical sampling problems and interpretation strategies in sediment quality studies. Talk presented to Sediment-Water Quality Workshop for Ontario Data Collection Programs, Canada Centre for Inland Waters, Burlington, Ontario, November 2. Unpublished

Carson, M.A., 1991a. Assessment of sediment transport data and sediment budget analysis for the Peace-Slave river system, Alberta: Phase I (Assessment of data). Proprietary report for Environment Canada, Calgary, Alberta. March, 1991

Carson, M.A., 1991b. Applications of geomorphology for Inland Waters Directorate staff: Western and Northern Region. Report for Inland Waters Directorate, Environment Canada

Carson, M.A., 1992a. Assessment of sediment transport data and sediment budget analysis for the Peace-Slave river system, Alberta: Phase II (Sediment loads and regional budget). Report for Environment Canada, Calgary, Alberta. March, 1992

Carson, M.A., 1992b. Assessment of sediment transport data for the Peace-Slave river system, Alberta. User report for Environment Canada, Calgary, Alberta. March, 1992

CCME (Canadian Council of Ministers of the Environment). 1987. Canadian Water Quality Guidelines. Prepared by the Task Force on Water Quality Guidelines of the Canadian Council of Resources and Environment Ministers (CCREM).

Chapin, N.R.F., 1995. Environment Canada, Calgary, Alberta. Personal communication

Crosley, R.W., 1994. Contaminants in abiotic media: NRBS reach specific study area April 1992. Report to the Northern Rivers Basin Study for Project 5313-D1. First Draft

Crosley, R.W., 1995 (October draft). Bottom sediment contaminant surveys of the Athabasca and Peace river basins 1994-1995. Report to the Northern Rivers Basin Study

Czuczwa, J. and R. Hites. 1984. Environmental Fate of Combustion-Generated Polychlorinated Dioxins and Furans. Environ. Sci. Technol. 18(6):444-450.

Day, K., and T.B. Reynoldson, 1995. Ecotoxicology of depositional sediments in the upper Athabasca River. report to the Northern River Basins Study for Project 2326-C119 pp

Droppo, I.G. and E.D. Ongley, 1989. Flocculation of suspended solids in southern Ontario rivers. Sediment and the Environment, IAHS Publication No. 184

Droppo, I.G. and E.D. Ongley, 1990. Flocculation of suspended fine-grained sediment in rivers. National Water Research Institute, Ontario, Contribution #90-78

Environment Canada, 1994. HYDAT CD-ROM. Enviornment Canada, Ottawa

Hamilton, W.N. and G.B. Mellon, 1973. Industrial mineral resources of the Fort McMurray area. In Carrigy, M.A. and J.W. Kramers, 1973, "Guide to the Athabasca Oil Sands area", Alberta Research Council Information Series 65, 123-161

Hamilton, H.R., Thompson, M.V., and L. Corkum. 1985. Water quality overview of the Athabasca River basin. Prepared for Alberta Environment by Nanuk Engineering and Development. 117 pp plus appendices

Hammond, A.L. 1972. Chemical Pollution: Polychlorinated Biphenyls. Science 175:155-156.

Hardy BBT Ltd, 1989. Sediment Transport Analysis: Lesser Slave Basin. Report to Environment Canada, Calgary, Alberta. March, 1989

Hudson, H.R., 1982. Aspects of the hydrologic and sediment regimes of denuded muskeg areas". Proceedings of the Canadian Society of Civil Engineering Conference 1982, Vol. III:1031-1046

Hudson, H.R., 1989. A case study of approaches for determining diffuse suspended sediment sources and processes, in Sediment and the Environment, edited by Hadley and Ongley, IAHS Publ. 184: 85-94

Hudson, H.R., 1990. Hydrologic approach to the prediction of sediment yield: a discussion. Journal of Hydraulic Engineering 116(12), Dec. 1990: 1552-1553

Hudson, H.R., 1992. Lake Athabasca coring project. A memorandum to Dr. Rick Bourbonniere, National Water Research Institute, October 29, 1992. On file at Northern River Basins Study Office. 3 pp.

Hudson, H.R., 1994. Proposal for the 1994 sediment contaminant study. A memorandum to the sediment contaminant working group of the Northern River Basins Study, September 23, 1994. On file at Northern River Basins Study Office. 5 pp.

Hudson, H.R. and F. Niekus, 1992. Regionalization of fluvial suspended sediment loads in Alberta. Report to Environment Canada, Calgary, Alberta, October 1992.

Hudson, H.R., in prep. A paradigm for cumulative effects monitoring and assessment", presented at the International Symposium on Sediment Water Interactions, in draft form for journal publication

Kellerhals, R., Neill, C.R. and D.I. Bray, 1972. Hydraulic and geomorphic characteristics of rivers in Alberta. Alberta Research Council, River Engineering and Surface Hydrology Report 72-1

Kellerhals, R. and M. Church, 1989. The morphology of large rivers: characterization and management. In D.P. Dodge (Ed.), Proceedings of International Large Rivers Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences, 016, 31-48

Krishnappan, B.G., and P. Engel. 1994. Critical shear stress for erosion and deposition of fine suspended sediments in the Fraser River. Environment Canada Fraser River Action Plan Report 1994-13, 10 pp

Krishnappan, B.G., Stephens, R., Kraft, J.A., and B.H. Moore. 1994. Size distribution and transport of suspended particles in the Athabasca River near Hinton. NWRI Contribution 94-112, National Water Research Institute, Burlington, Ontario, Canada. 33 pp

Linton, L.R., H.R. hamilton and M., Fuglem. 1988. Similarities in estimates of suspended sediment between Water Quality Branch and Water Resources Branch for sites in the Saskatchewan River basin. Environment Canada Sediment Survey Section Report IWD-HQ-WRB-SS88-5, 62 pp, appendices

Mathews, W.H., 1978, Surficial geology of Charlie Lake map-area, Peace River District, BC. Map 1460A, Geological Survey of Canada

McCubbin, N., and J. Folke. 1993. A review of the literature on pulp and paper mill effluent characteristics in the Peace and Athabasca river basins. Northern Rivers Basins Study Project Report No. 15, Edmonton, Canada, 85 pp., appendices

Mackenzie, I., 1993. Personal communication. Alberta Environmental Protection, Edmonton

Merriman, J. 1988. Distribution of Organic Contaminants in Water and Suspended Solids of the Rainy River. Water Poll. Res. J. Canada. 23(4):590-600.

Neill, C.R., Evans, B.J. and A.W. Lipsett, 1981. Circulation of water and sediment in the Athabasca Delta area. Alberta Oil Sands Environmental Research Program, Project WS 3.3.1

Noton, L. R., 1993. Personal communication. Alberta Environmental Protection, Edmonton

Noton, L.R. and R.D. Shaw, 1989. Winter water quality in the Athabasca River system, 1988 and 1989. Environmental Quality Monitoring Branch report, Alberta Environment, Edmonton

Noton, L.R., Anderson, A.M., Reynoldson, T.B. and J. Kostler, 1989. Water quality in the Wapiti-Smoky river system, downstream of the Proctor and Gamble pulp mill, 1983. Environmental Quality Monitoring Branch report, Alberta Environment, Edmonton

Olsen, C.R., N.H. Cutshall and I.L. Larson. 1982. Pollutant - Particle Associations and Dynamics in Coastal Marine Environments: A Review. Marine Chemistry. pp 501-533.

Ouellet, M. 1995. Weldwood of Canada, Hinton Division. Personal communication

Owens, J., Swanson s., and D. Birkholx. 1994. Bioaccumulation of 2,3,7,8-Tetrachlorodibenzofuran and extractable organic chlorine at a bleached-kraft mill site in a northern Canadian river system. Environmental Toxicology and Chemistry 13(2):343-354

Pastershank, G.M., and D.C.G. Muir. 1995. Contaminants in environmental samples: PCDDs and PCDFs downstream of bleached kraft mills Peace and Athabasca rivers, 1992. Northern Rivers Basins Study Project Report No. 44, Edmonton, Canada, 56 pp., appendices

R.L. & L. Environmental Services Ltd. 1993. Benthos and bottom sediment field collections, upper Athabasca River, April to May 1992. Northern River Basins Study Report # 2. Northern River Basins Study, Edmonton, Alberta, February 1993

Sekela, M., Brewer, R., Baldazzi, c., and G. Moyle. 1995. Survey of contaminants in suspended sediment and water in the fraser River basin. Environment Canada, North Vancouver, British Columbia. Draft Report. 199 pp and appendices

Sentar Consultants. 1994. Ecotoxicology of pulp mill effluents in the Athabasca, Peace and Slave rivers: synthesis report. Northern River Basins Study Project 2112-B1/C1 Report

Servos, M., D. Muir and B. Webster. 1989. The Effect of Dissolved Organic Matter on the Bioavailability of Polychlorinated Dibenzo-p-dioxins. Aquatic Toxicology 14:169-184.

Shaw, J. and R. Kellerhals, 1982. The composition of recent alluvial gravels in Alberta river beds. Alberta Research Council Bulletin 41

Shaw, R.D., Noton, L.R. and G.W. Guenther, 1990. Water quality of the Peace River in Alberta. Environmental Quality Monitoring Branch report, Alberta Environment, Edmonton

Spitzer, M.O., 1992. Environment Canada, Calgary, Alberta. Personal communication

SEPA 1993. Persistent organic pollutants and the environment: the environment in Sweden- status and trends. Swedish Environmental Protection Agency Report 4246, 137 pp

Trillium, 1995. Deposition and resuspension of fine-grained sediments. Contract report to Environment Canada, Winnipeg by Trillium Engineering and Hydrographics Inc.

Water Quality Branch. 1993a. Ambient Water Quality Criteria for Chlorophenols. Ministry of Environment, Lands and Parks. Water Management Division. British Columbia.

Water Quality Branch. 1993b. Ambient Water Quality Criteria for Polycyclic Aromatic Hudrocarbons. Ministry of Environment, Lands and Parks. Water Management Division. British Columbia.

Webster, G., M. Graham, J. Sarna and L. Muir. 1986. Dissolved Organic Matter Mediated Aquatic Transport of Chlorinated Dioxins. Chemosphere 15:1379-1386.

WSC, 1990. Sediment Data Reference Index, Canada 1988. Water Survey of Canada, Ottawa, 1990

Yungwirth, R., 1995. Personal communication. Water Survey of Canada, Sediment Laboratory, Environment Canada, Regina

2.1 Ice statistics for the Athabasca and (regulated) Peace rivers (based on Aitken et al., 1995)

Station	Average Freeze up Date	Average Breakup Date	Average Duration of Ice Cover
Athabasca River			
Near Jasper	Nov 12	Mar 21	128 days
Near Hinton	Nov 10	Apr 7	149 days
At Windfall	Nov 6	Apr 21	169 days
At Athabaca	Nov 8	Apr 20	164 days
Below Ft. McMurray	Nov 3	Apr 24	173 days
Peace River			
At Hudson Hope	N/A	N/A	no ice
At Taylor	N/A	N/A	no ice
At Dunvegan			
Peace River	Jan 1*	Apr 10*	98 days
At Fort Vermillion			
At Peace Point	Nov 20*	Apr 28*	160 days

* These dates are preliminary

2.2 Flood information table for rivers in the NRBS area (based on Aitken et al., 1995)

STATION NAME	Average Flood Peak (m^3/s)	Yield (m^3/s per 10 km^2)	Highest Recorded Discharge (m^3/s)	Date	Ratio Peak to Mean
Peace River at Hudson Hope	3931	5.62	8810	June 1964	2.24
Peace River at Peace River	7769	4.18	16500*	June 1990	2.12
Peace River at Peace Point	7087	2.42	12600	June 1990	1.78
Pine River at East Pine	1657	13.69	3960	July 1965	2.39
Smoky River at Watino	2756	5.48	8620	June 1990	3.13
Wabasca River at Wadlin Lake Rd	618	1.73	1690	Apr 1974	2.73
Athabasca River near Jasper	445	11.47	642	June 1984	1.44
Athabasca River at Entrance	830	8.49	1200	June 1972	1.45
Athabasca River near Windfall	1226	6.26	2070	June 1960	1.69
Mcleod River near Whitecourt	574	2.79	1780	June 1980	2.61
Pembina River at Jarvie	291	1.95	974	Apr 1974	1.81
Lesser Slave River at Hwy #2A	90	6.31	146	July 1979	3.10
Athabasca River at Athabasca	2082	2.22	5440	June 1954	3.35
Clearwater River at Draper	419	0.63	790	Apr 1974	1.62
Athabasca River below McMurray	2590	1.36	4700	July 1971	5.30
Slave River at Fitzgerald	6928	1.14	11200	Apr 1974	1.62

* the highest stage recorded at Peace River was in February 1992 due to an ice jam event

2.3 Natural low flow data for rivers in the NRBS area (based on Aitken et al., 1995)

Location	7Q10 (m^3/s)	Minimum Daily (m^3/s)	Years of data	Date of Minimum
Peace River Basin				
07GE001 - Wapiti River near Grande Prairie	6.86	4.02	33	Feb 19 1961
07GJ001 - Smoky River at Watino	22.9	14	36	Dec 12 1956
Athabasca River Basin				
07AD001 - Athabasca River at Hinton	16.7	7.08	58	
07AE001 - Athabasca River at Windfall	28.6	19.3	17	
07BE001 - Athabasca River at Athabasca	51.1	42.2	59	Jan 18 1953
07DA001 - Athabasca River below McMurray	109	88.6	32	Jan 18 1988

Table 3.1 Mean annual suspended sediment load estimates for "full" sediment stations

Station Name	ID	Km upstream	Area (km^2)	Load (tonnes)	Period-Imprecision
Athabasca River Basin					
Cache Percotte Creek near Hinton	7AD03	1,400	7	14[b]	
Whiskeyjack Creek near Hinton	7AD04	1,400	3	3[b]	
Wampus Creek near Hinton	7AF03	1,421	25	356[b]	
Deerlick Creek near Hinton	7AF04	1,421	14	246[b]	
Eunice Creek near Hinton	7AF05	1,421	17	188[b]	
Driftpile River near Driftpile	7BH03	1,176	837	226,000[b]	
Swan River near Kinuso	7BJ01	1,145	1900	315,000b	
Lesser Slave River at highway 2A	7BK06	1,083	14400	111,000[b]	
Clearwater River at Draper	7CD01	~630	30800	430,000[a2]	1970-84, 10-15%
Athabasca River below Ft. McMurray	7DA01	622	133000	6,060,000[a2]	1976-84, 10-15%
Poplar Creek near Fort McMurray	7DA07	609	151	1,100[a2]	C U
Athabasca River at Embarras Airport	7DD01	459	155000	6,850,000[a2]	1976-84, > 20%
Peace River Basin					
Peace River at Dunvegan Bridge	7FD03	1,137	130000	15,600,000[a3]	
Smoky River above Hells Creek	7GA01	1,378	3840	478,000[b]	
Spring Creek near Valleyview	7GF02	1,242	112	4,420[b]	
Wolverine Creek near Valleyview	7GF03	1,242	11	139[b]	
Spring Creek (upper) near Valleyview	7GF04	1,238	33	37[b]	
Bridlebit Creek near Valleyview	7GF05	1,231	20	20[b]	
Rocky Creek near Valleyview	7GF06	1,231	19	22[b]	
Horse Creek near Valleyview	7GF07	1,242	4	14[b]	
Peace River at Peace River	7HA01	1,042	186000	33,700,000[a3]	1970-90, > 10%
Peace River at Peace Point	7KC01	433	293000	36,400,000[a3]	1970-90
Slave River Basin					
Slave River at Fitzgerald	7NB01	253	606000	33,600,000[a3]	1970-90, 5-10%

Table 3.2 (page 1) Mean annual suspended sediment load estimates for "miscellaneous" sediment stations

Station	ID	Km upstream	Area (km^2)	Load (tonnes)	Period/ Imprecision
Athabasca River Basin					
Whirlpool River near the mouth	7AA09	1,495	598	77,600[b]	
Wildhay River near Hinton	7AC01	1,418	959	31,300[b]	
Athabasca River near Windfall	7AE01	1,254	19600	1,300,000[b]	
McLeod River above Embarras River	7AF02	1,335	2560	142,000[b]	
McLeod River near Whitecourt	7AG04	1,245	9100	194,000[b]	
Freeman River near Ft. Assiniboine	7AH01	1,173	1660	112,000[b]	
Lovett River near the mouth	7BA03	1,428	101	2,310[b]	
Pembina River near Entwistle	7BB02	1,263	4420	63,100[b]	
Paddle River near Rochfort Bridge	7BB04	1,226	625	28,700[b]	
Little Paddle River near Mayerthorpe	7BB05	1,225	298	5,820[b]	
Paddle River at Barrhead	7BB06	1,179	2390	42,900[b]	
Pembina River at Jarvie	7BC02	1,126	13100	672,000[b]	
East Prairie River near Enilda	7BF01	1,217	1460	485,000[b]	
West Prairie River near High Prairie	7BF02	1,219	1160	183,000[b]	
Pine Creek near Grassland	7CA05	951	1450	6,830[b]	
Athabasca River at Fort McMurray	7CC02	630	99700	5,630,000[a2]	1976-84, 10-15%
Hangingstone River at Ft. McMurray	7CD04	634	959	47,000[a1]	1976-86, A
Beaver River near Fort MacKay	7DA05	588	454	1,500[b]	
Steepbank River near Fort McMurray	7DA06	601	1320	12,300[a]	1976-86, B
Muskeg River near Fort MacKay	7DA08	573	1460	900[a]	1976-86, C
Hartley Creek near Fort MacKay	7DA09	572	358	300[a]	1976-86, C
Joslyn Creek near Fort MacKay	7DA16	567	257	6,300[a]	1976-86, AU

Table 3.2 (page 2) Mean annual suspended sediment load estimates for "miscellaneous" sediment stations

Station	ID	Km upstream	Area (km²)	Load (tonnes)	Imprecision
Athabasca Basin (continued)					
Ells River near the mouth	7DA17	567	2450	86,900[a]	1976-86, A
Beaver River above Syncrude	7DA18	603	165	1,500[a]	1976-86, B
MacKay River near Fort MacKay	7DB01	574	5570	1,100[a]	1976-86, A
Dover River near the mouth	7DB02	579	963	524[b]	
Dunkirk River near Fort MacKay	7DB03	650	1570	2,100[a]	
Firebag River near the mouth	7DC01	525	5990	26,000[a]	1976-86, A
Peace River Basin					
Peace River at Hudson Hope	7EF01	1,380	69900	~0[a]	
Halfway River at the mouth	7FA01	1,347	9400	2,100,000[a]	
Moberly River near the mouth	~7FB08	1,343	1840	200,000[a]	
Beatton River near Ft. St. John	7FC01	1,305	16100	11,100,000[a]	
Kiskatinaw River near the mouth	~7FD01	1,300	4370	2,200,000[a]	
Peace River at Taylor	7FD02	1,296	97100	2,800,000[a]	
Peace River above Alces River	7FD10	1,259	118000	16,400,000[a]	
Simonette River near Goodwin	7GF01	1,203	5050	629,240[b]	
Notikewin River at Manning	7HC01	958	4680	220,404[b]	
Keg River at Hwy 35	7HF02	699	667	3,159[b]	
Boyer River near Fort Vermillion	7JF02	707	6650	12,407[b]	
Ponton River above Boyer River	7JF03	707	2440	484,948[b]	
Birch River Basin					
Birch River below Alice Creek	7KE01	539	9860	288,694[b]	

A denotes a good sediment rating; B a fair rating; C a poor rating; U denotes instability in the rating relationship over time

Year	mg/L suspended sediment	% sand	mg/L sand
1973	1420	17	241
1977	854	2	17
	569	12	68
	891	5	45
	696	6	42
	564	12	68
1979	345	13	45
	776	10	78
	868	8	69
	420	12	50
	422	17	72
	401	3	12
	604	6	36
1980	2220	2	44
	2240	2	45
	1030	2	21
	320	6	19
	480	3	14
	500	2	10
1982	1940	12	233
	894	24	215
	445	3	13
1983	648	13	84
	391	6	23
1984	853	4	34
	849	4	34
1985	1410	5	71
	1380	5	69
	1370	4	55
	952	2	19
	584	3	18
	623	1	6
	862	1	9
	869	1	9
	712	1	7
	786	2	16
1989	457	31	142

TABLE 3.3
SAND COMPONENT OF SV SUSPENDED SEDIMENT: ATHABASCA RIVER AT EMBARRAS

Date	Discharge m3/s	sediment mg/L 1 Left	2	3	4 SV	5 Right	Mean
70 Jun 4	3230	877	789	1460	2505	2620	1650
71 Jun 21		2092	2172	1989	1664	1200	1823
71 Jul 14		4783	4600	4580	4074	3488	4305
72 May 24	4470	1056	1300	1325	1499	1525	1341
72 Jul 14	6370	1615	1662	1523	1310	832	1388
73 Apr 28	3450	1186	1203	1130	1118	1154	1158
74 May 14	4960	1398	1562	1642	1760	1587	1590
74 Jul 17	3090	1057	1278	1128	851	407	944
77 May 10	4160	864	1225	1470	1665	1823	1409
81 May 22	3920	725	749	713	760	900	769
82 May 12	3130	1911	2047	1902	1785	1881	1905

		%silt-clay 1 Left	2	3	4 SV	5 Right	Mean
70 Jun 4	3230	76	63	64	73	90	73
71 Jun 21		86	82	77	71	77	79
71 Jul 14		88	87	85	83	85	86
72 May 24	4470	72	62	66	73	77	70
72 Jul 14	6370	66	60	68	72	80	69
73 Apr 28	3450	87	87	90	93	92	90
74 May 14	4960	85	80	77	72	78	78
74 Jul 17	3090	84	81	86	88	83	84
77 May 10	4160	87	69	75	78	83	78
81 May 22	3920	77	75	77	88	90	81
82 May 12	3130	92	85	91	88	86	88

TABLE 3.4

SUMMARY OF DATA FOR SUSPENDED SEDIMENT CONCENTRATION AND GRAIN SIZE
FOR FIVE VERTICALS ACROSS PEACE RIVER AT PEACE RIVER

Note: mean value is simple mean of five verticals and is not weighted by local discharge at each vertical

SV is indicated in approximate position close to vertical #4, but no SV sampling was done on the above occasions concurrently with MV sampling except on June 4, 1970

Month	Clearwater	Athabasca River at McMurray	Athabasca River at Embarras
January	2	1	?
February	1	1	?
March	1	1	?
April	49	227	464
May	118	841	1050
June	62	2154	2083
July	37	1653	1866
August	40	440	660
September	68	280	589
October	29	35	134
November	8	18	?
December	4	3	?
	420	5654	6846

McMurray data adjusted x 1.12
Embarras data adjusted x 1.35
all loads in kilotonnes

TABLE 4.1
MEAN MONTHLY LOADS OF SUSPENDED SEDIMENT, 1976-84
ON ATHABASCA-CLEARWATER SYSTEM

Month	Clearwater 69-87	Athabasca River at McMurray 73-86	Athabasca River at Embarras 76-84
January	8	10	?
February	7	15	?
March	9	10	?
April	53	140	310
May	116	272	178
June	67	311	304
July	72	258	306
August	48	87	159
September	55	52	107
October	40	26	20
November	11	21	?
December	7	7	?

McMurray data adjusted x 1.12
Embarras data adjusted x 1.35

TABLE 4.2
MEDIAN CONCENTRATIONS (MG/L) OF SUSPENDED SEDIMENT ON ATHABASCA-CLEARWATER SYSTEM

PEACE RIVER	Mt	load/flow ratio mg/L	SLAVE RIVER	Mt	load/flow ratio mg/L
January	0.2	43	January	0.5	88
February	0.2	55	February	0.5	87
March	0.2	60	March	0.4	79
April	4.6	970	April	0.8	140
May	7.8	1030	May	9.1	741
June	11.1	1350	June	8.9	634
July	5.1	810	July	6.5	480
August	3.6	760	August	3.5	302
September	0.4	101	September	1.2	125
October	0.3	76	October	1.0	105
November	0.2	48	November	0.7	101
December	0.1	31	December	0.5	94
TOTAL	33.8		TOTAL	33.6	

TABLE 4.3

MEAN MONTHLY SUSPENDED LOADS AND CONCENTRATIONS ON PEACE RIVER AT PEACE RIVER AND ON SLAVE RIVER AT FORT SMITH 1970-1990

Estimated suspended load (Mt)

Year	(1)	(2)	(3)	% (3)-(2)/(3)
70	4.0		4.6	
71	15.3		20.4	Gaps
72	7.7		11.9	
73	4.6	7.5	6.3	-10 ND
74	7.1	8.0	11.6	32 ND
75	2.9	3.9	3.0	-30 OND
76	3.1	4.3	3.4	-27 ND
77	5.4	7.2	8.0	10 JFM ND
78	5.3	6.4	6.3	-2
79	5.9	6.8	8.2	16 JF ND
80	6.7	5.7	9.9	42 JFMAM ND
81	1.3	1.3	1.6	14 JFMA OND
82	6.6	7.3	7.4	2 JFMAMOND
83	3.4	5.0	3.4	-50 JFMA OND
84	2.6	2.6	3.0	15 JFMASOND
85	1.9	2.0	2.5	18 JFMASOND
86	8.1	9.5	9.6	1 JFMA ND
87	1.9		2.4	
1973-86 mean	4.6	5.5	6.0	

(1) : annual load computed by uncrrected sediment rating
(2) : load computed by WSC Calgary for months available. Missing months denoted under "Gaps" column
(3) : annual load computed by open-water sediment rating adjusted with bias and monthly corrections

All loads adjusted x 1.12

TABLE 4.4

ATHABASCA RIVER AT McMURRAY
COMPARISON OF ANNUAL LOADS USING DIFFERENT METHODS

DUNVEGAN BRIDGE		PEACE RIVER		PEACE POINT		SLAVE RIVER	
Year	Mt	Year	Mt	Year	Mt	Year	Mt
		1970	6.8	1970	8.4	1970	10.2
		1971	44.2	1971	35.3	1971	24.5
		1972	75.9	1972	73.9	1972	59.9
		1973	31.8	1973	51.0	1973	43.8
		1974	59.4	1974	70.1	1974	79.8
1975	5.3	1975	11.6	1975	18.7	1975	21.4
1976	31.8	1976	52.1	1976	70.7	1976	48.2
1977	19.0	1977	45.2	1977	42.7	1977	38.3
1978	5.1	1978	10.9	1978	18.4	1978	20.1
1979	10.0	1979	35.0	1979	45.0	1979	37.0
1980	3.0	1980	19.2	1980	6.5	1980	13.0
1981	14.8	1981	20.8	1981	18.5	1981	18.5
1982	8.0	1982	39.9	1982	24.0	1982	34.5
1983	15.3	1983	36.2	1983	40.6	1983	28.6
1984	17.3	1984	24.6	198	30.0	1984	27.1
1985	6.1	1985	15.5	1985	21.0	1985	24.8
1986	6.8	1986	22.5	1986	22.3	1986	22.8
1987	21.8	1987	45.4	1987	44.6	1987	42.3
1988	8.0	1988	12.0	1988	31.6	1988	29.1
1989	4.0	1989	23.5	1989	25.8	1989	27.2
1990	33.4	1990	76.0	1990	65.3	1990	54.9
MEAN	13.1	MEAN	33.7	MEAN	36.4	MEAN	33.6
Std devn	9.2	Std devn	19.8	Std devn	20.0	Std devn	16.4
% st dev	70.2	% st dev	58.7	% st dev	55.9	% st dev	45.1

TABLE 4.5
ANNUAL SUSPENDED SEDIMENT LOADS
ON
PEACE-SLAVE RIVERS
1970-1990

WATER SURVEY OF CANADA
02/12/88 , PAGE 1
SEDIMENT SURVEY SECTION

ATHABASCA RIVER AT MCMURRAY

STATION NO. 07CC002

MEAN CONCENTRATIONS IN MG/L FOR MONTHS JUN TO SEP INCLUSIVE

YEAR	DATE OF MAX (A)	TOTAL PERIOD MEAN VALUE (B)	BEST 10% OF PERIOD STARTING DATE (C)	BEST 10% OF PERIOD MEAN VALUE (D)	BEST 10% OF PERIOD RATIO TO COL. (B) (E)	BEST 1% OF PERIOD STARTING DATE (F)	BEST 1% OF PERIOD MEAN VALUE (G)	BEST 1% OF PERIOD RATIO TO COL. (B) (H)
1973	JUN 17	337	JUN 16	1 641	4.9	JUN 17	4 040	12.0
1974	JUL 17	193	JUL 13	758	3.9	JUL 17	1 330	6.9
1975	JUL 1	230	JUN 27	795	3.5	JUL 1	1 680	7.3
1976	AUG 22	222	AUG 20	744	3.4	AUG 22	1 530	6.9
1977	JUN 3	230	JUN 2	994	4.3	JUN 3	1 920	8.3
1978	JUL 16	304	JUL 14	744	2.4	JUL 16	1 720	5.7
1979	JUN 18	253	JUN 9	773	3.1	JUN 18	1 820	7.2
1980	JUN 9	297	JUN 6	846	2.8	JUN 9	1 570	5.3
1981	JUN 7	112	JUN 1	414	3.7	JUN 7	599	5.3
1982	JUL 8	354	JUL 8	1 299	3.7	JUL 8	2 980	8.4
1983	JUL 23	297	JUL 20	1 101	3.7	JUL 23	1 810	6.1
1984	JUN 4	155	JUN 3	515	3.3	JUN 4	614	4.0
1985	JUN 29	97.1	JUN 27	406	4.2	JUN 29	517	5.3
1986	JUL 20	327	JUL 16	1 962	6.0	JUL 20	4 110	12.6

WATER SURVEY OF CANADA
30/11/88 , PAGE 1
SEDIMENT SURVEY SECTION

ATHABASCA RIVER AT MCMURRAY

STATION NO. 07CC002

LOAD IN TONNES FOR MONTHS JUN TO SEP INCLUSIVE

YEAR	DATE OF MAX (A)	TOTAL PERIOD TOTAL VALUE (B)	BEST 10% OF PERIOD STARTING DATE (C)	BEST 10% OF PERIOD TOTAL VALUE (D)	BEST 10% OF PERIOD % OF COLUMN (B) (E)	BEST 1% OF PERIOD STARTING DATE (F)	BEST 1% OF PERIOD TOTAL VALUE (G)	BEST 1% OF PERIOD % OF COLUMN (B) (H)
1973	JUN 17	5 584 770	JUN 16	3 016 600	54.0	JUN 17	600 000	10.7
1974	JUL 17	3 160 260	JUL 14	1 617 000	51.2	JUL 17	296 000	9.4
1975	JUL 2	3 062 900	JUN 28	1 440 400	47.0	JUL 2	300 000	9.8
1976	AUG 22	2 844 670	AUG 20	1 124 500	39.5	AUG 22	221 000	7.8
1977	JUN 3	3 771 040	JUN 2	2 107 500	55.9	JUN 3	405 000	10.7
1978	JUL 16	4 847 430	JUL 14	1 380 500	28.5	JUL 16	340 000	7.0
1979	JUL 16	4 409 634	JUN 10	1 452 000	32.9	JUL 16	402 000	9.1
1980	JUN 9	5 082 360	JUN 7	2 239 700	44.1	JUN 9	515 000	10.1
1981	JUN 7	1 112 473	JUN 1	501 900	45.1	JUN 7	65 700	5.9
1982	JUL 8	6 384 310	JUL 8	3 543 500	55.5	JUL 8	708 000	11.1
1983	JUL 23	4 505 150	JUL 20	2 066 000	45.9	JUL 23	303 000	6.7
1984	JUN 13	1 978 770	JUN 11	797 900	40.3	JUN 13	85 800	4.3
1985	JUN 29	998 076	JUN 27	524 900	52.6	JUN 29	68 300	6.8
1986	JUL 22	7 498 535	JUL 19	5 809 100	77.5	JUL 22	1 310 000	17.5

TABLE 4.6
ATHABASCA RIVER AT MCMURRAY: PEAK PERIOD STATISTICS FOR SEDIMENT LOADS AND CONCENTRATIONS, 1973-86

Table 6.1 Pulp and paper mills in the Northern River Basins Study area

Company	Location	Receiving River	Production (air dried t/d)		[2]Treatment discharge (m^3/day)	
Alberta						
Weldwood	Hinton	Athabasca	Bleached kraft pulp	1,033	ASB	111,965
Weyerhauser	Grande Prairie	Wapiti	Bleached kraft pulp	861	ASB	60,495
Diashowa-Marubeni	Peace River	Peace	Bleached kraft pulp	794	ASB	63,308
Millar Western Pulp	Whitecourt	Athabasca	Bleached CTMP[1]	611	EA-ASB	12,699
Slave Lake Pulp	Slave Lake	Lesser Slave	Bleached CTMP	232	AST	3,904
Alberta Newsprint	Whitecourt	Athabasca	Newsprint	519	EA-AST	15,612
Alberta-Pacific[2]	Athabasca	Athabasca	Bleached kraft pulp	?	EA-AST	
British Columbia						
Fletcher Challenge	Mackenzie	Peace	Bleached kraft pulp	?		
Fiberco Pulp	Taylor	Peace	Bleached CTMP	?		
Finlay Forest Industries	Mackenzie	Peace	Newsprint	?		

1 CTMP: Chemi-thermomechanical pulp (Based on McCubbin and Folke 1993)
2 Source: Sentar 1994
EA - Extended Aeration; ASB - Aerated Stabilization Basin; AST - Activated Sludge Treatment

Table 7.1
Summary of Bottom Sediment Sampling on the Athabasca and Peace Rivers

Location Program	AEP	RSS	Synoptic	Triad	ERD	ERD
Athabasca River						
Above Hinton	Oct 89	Apr 92	May 93	Oct 93		May 95
Weldwood Haul Bridge		Apr 92	May 93	Oct 93		
Obed	Oct 89	Apr 92	May 93	Oct 93		
Emerson Lakes		Apr 92	May 93	Oct 93		May 95
u/s of Berland River			May 93	Oct 93		
Knight Bridge		Apr 92				
Windfall Bridge		Apr 92	May 93	Oct 93		
Above ANC	Oct 89					
Blue Ridge	Oct 89		May 93			
u/s of Lesser Slave River	Oct 89				Oct 94	
Athabasca			May 93			
Below Aplac					Oct 94	May 95
u/s Fort McMurray	Oct 89				Oct 94	
Near Fort McKay					Oct 94	
u/s Firebag River	Oct 89					
27 Baseline (WBNP)			Mar 93			
Near Mouth (Big Point Ch.)	Oct 89					
Peace River						
Wapiti River near mouth	Oct 89				Oct 94	May 95
Smoky River near mouth	Oct 89				Oct 94	
u/s of Smoky River	Sept 88				Oct 94	
Below Diashowa					Oct 94	
u/s of Notikewin River	Sept 88				Oct 94	
Below Fort Vermillion					Oct 94	May 95
Above WBNP	Sept 88					

TABLE 7.2 DIFFERENCES IN CONTAMINANT CONCENTRATIONS IN SILT-CLAY FRACTION OF SAMPLED BOTTOM SEDIMENTS IN THE NRBS SYSTEM BETWEEN AUTUMN 1994 AND SPRING 1995

Wapiti River near the mouth

Total resin acids	autumn 1033 ng/g, spring 302 ng/g, ratio 3.4x
Total chlorinated resin acids	autumn 21.7 ng/g, spring 4.9 ng/g, ratio 4.4x
Total PCDD/F	autumn 31.3 pg/g, spring 24.4 pg/g, ratio 1.3x

Athabasca River below Alpac

Total resin acids	autumn 342 ng/g, spring 254 ng/g, ratio 1.3x
Total chlorinated resin acids	autumn 12.6 ng/g, spring 9.7 ng/g, ratio 1.3x
Total PCDD/F	autumn 63.6 pg/g, spring 34.2 pg/g, ratio 1.9x

TABLE 7.3 CONCENTRATIONS OF 2378-T4CDF IN SILT-CLAY FRACTION OF BOTTOM SEDIMENTS IN THE NRBS SYSTEM 1988-94 IN RELATION TO ANTECEDENT SPRING FLOOD PEAK

	1988	1989	1991/2	1994/5
Peace River above Smoky River				
pg/g contaminant	0.1			0.2
discharge m3/s	3040			3600
Wapiti River				
pg/g contaminant	36	0.8		<0.2
discharge m3/s	295	903		661
Smoky River				
pg/g contaminant		3.8		<0.2
discharge m3/s		1800		1730
Athabasca near Emerson Lakes				
pg/g contaminant	7.0		2.0	0.95
discharge m3/s	761		1190	579
Athabasca upstream control				
pg/g contaminant		0.8	<0.1	0.05
discharge m3/s		817	975	598

Based on data provided by Crosley (1995)

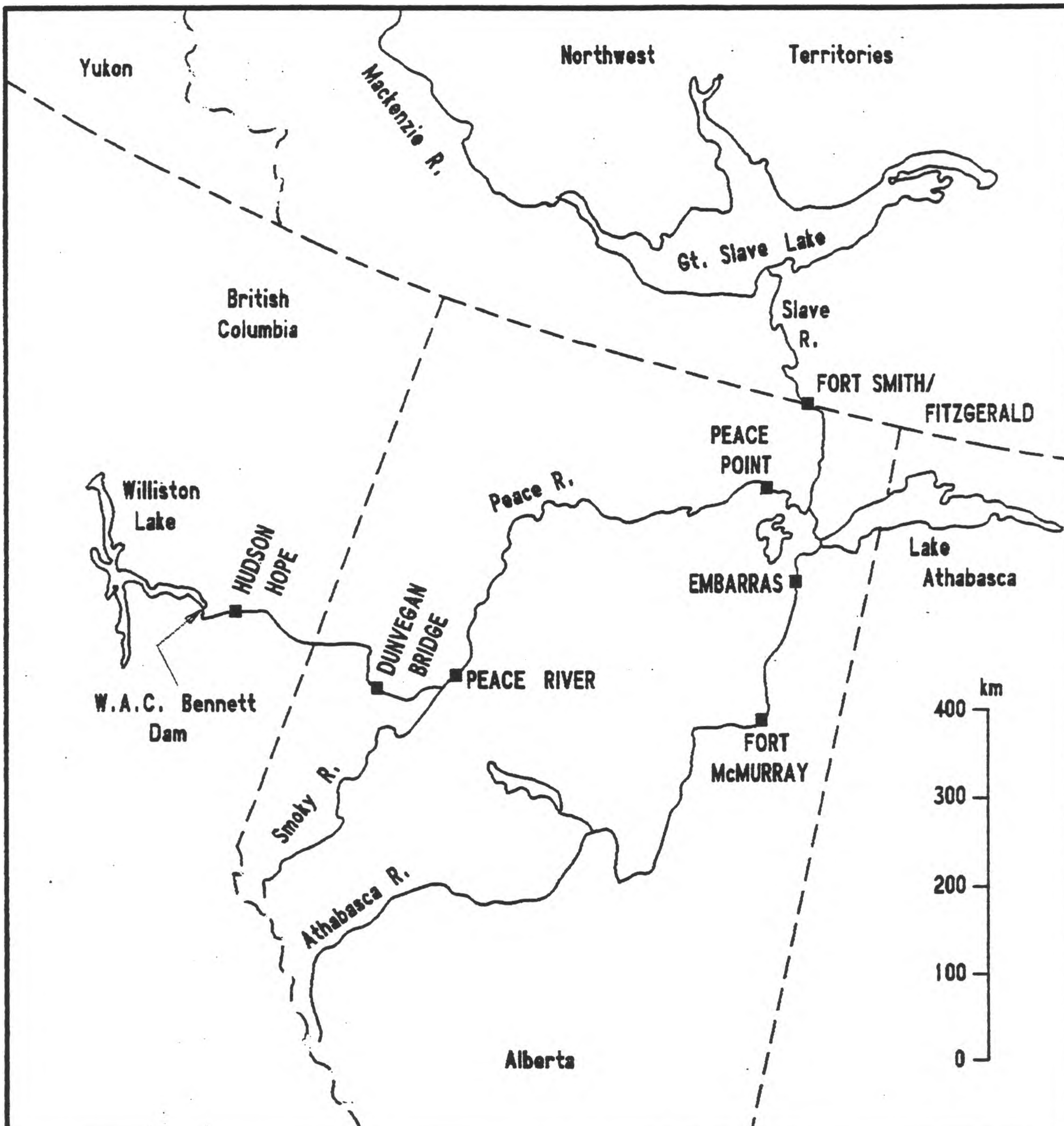
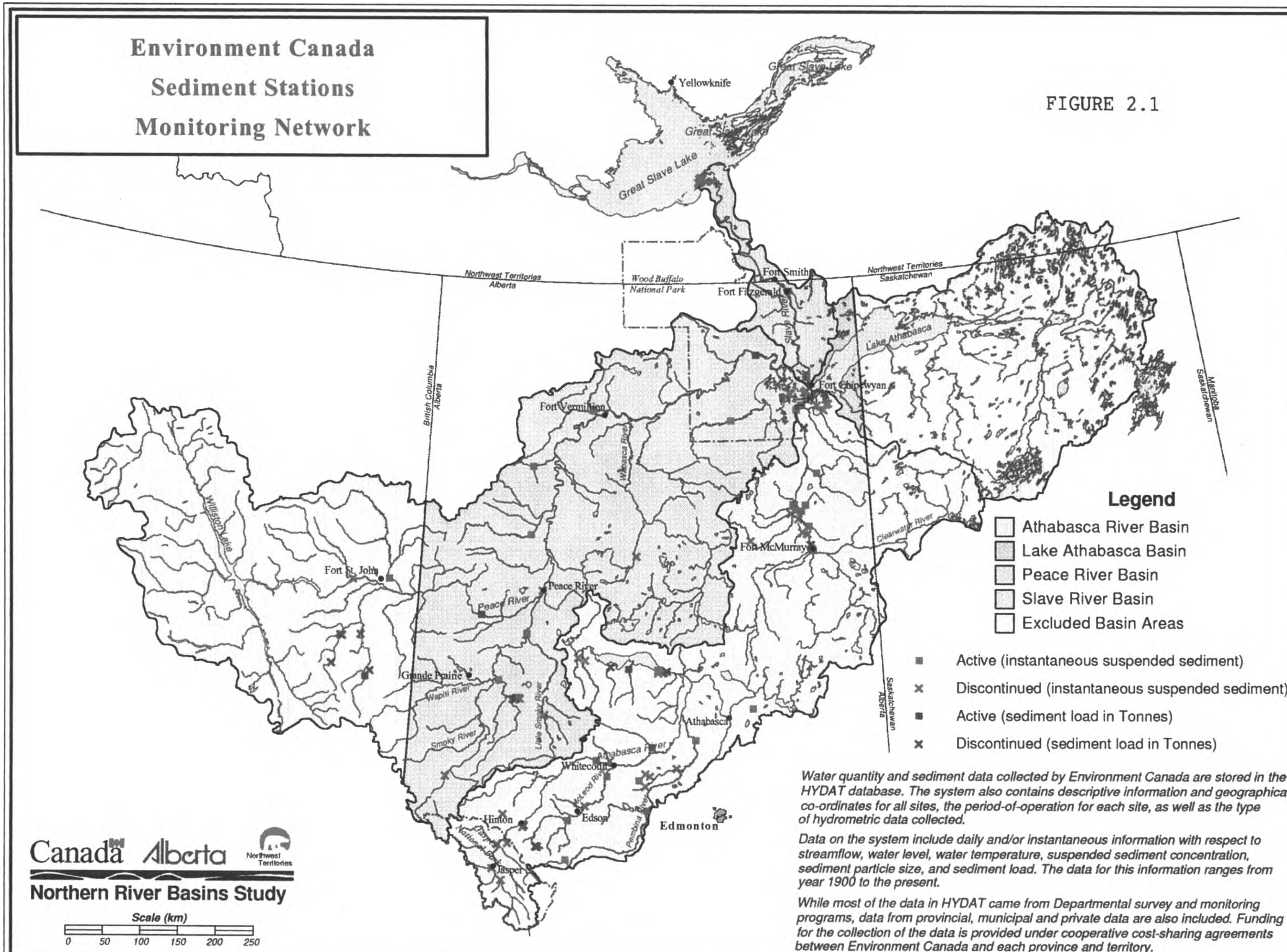


FIGURE 1.1

LOCATION OF PEACE-SLAVE DRAINAGE NETWORK

FIGURE 2.1



Environment Canada
Sediment Stations
Monitoring Network
Yellowknife
Great Slave Lake
Northwest Territories
Alberta
Northwest Territories
Saskatchewan
Manitoba
Saskatchewan
British Columbia
Alberta
Saskatchewan
Alberta
Wood Buffalo National Park
Fort Smith
Fort Fitzgerald
Slave River
Lake Athabasca
Fort Chipewyan
Fort Vermilion
Wabasca River
Fort McMurray
Clearwater River
Fort St. John
Peace River
Peace River
Williston Lake
Grande Prairie
Wapiti River
Smoky River
Lake Smoky River
Athabasca
Athabasca River
Whitecourt
McLeod River
Hinton
Edson
Pembina River
Edmonton
Jasper
Jasper National Park
Legend
Athabasca River Basin
Lake Athabasca Basin
Peace River Basin
Slave River Basin
Excluded Basin Areas
Active (instantaneous suspended sediment)
Discontinued (instantaneous suspended sediment)
Active (sediment load in Tonnes)
Discontinued (sediment load in Tonnes)
Water quantity and sediment data collected by Environment Canada are stored in the HYDAT database. The system also contains descriptive information and geographical co-ordinates for all sites, the period-of-operation for each site, as well as the type of hydrometric data collected.
Data on the system include daily and/or instantaneous information with respect to streamflow, water level, water temperature, suspended sediment concentration, sediment particle size, and sediment load. The data for this information ranges from year 1900 to the present.
While most of the data in HYDAT came from Departmental survey and monitoring programs, data from provincial, municipal and private data are also included. Funding for the collection of the data is provided under cooperative cost-sharing agreements between Environment Canada and each province and territory.
Canada
Alberta
Northwest Territories
Northern River Basins Study
Scale (km)
0 50 100 150 200 250

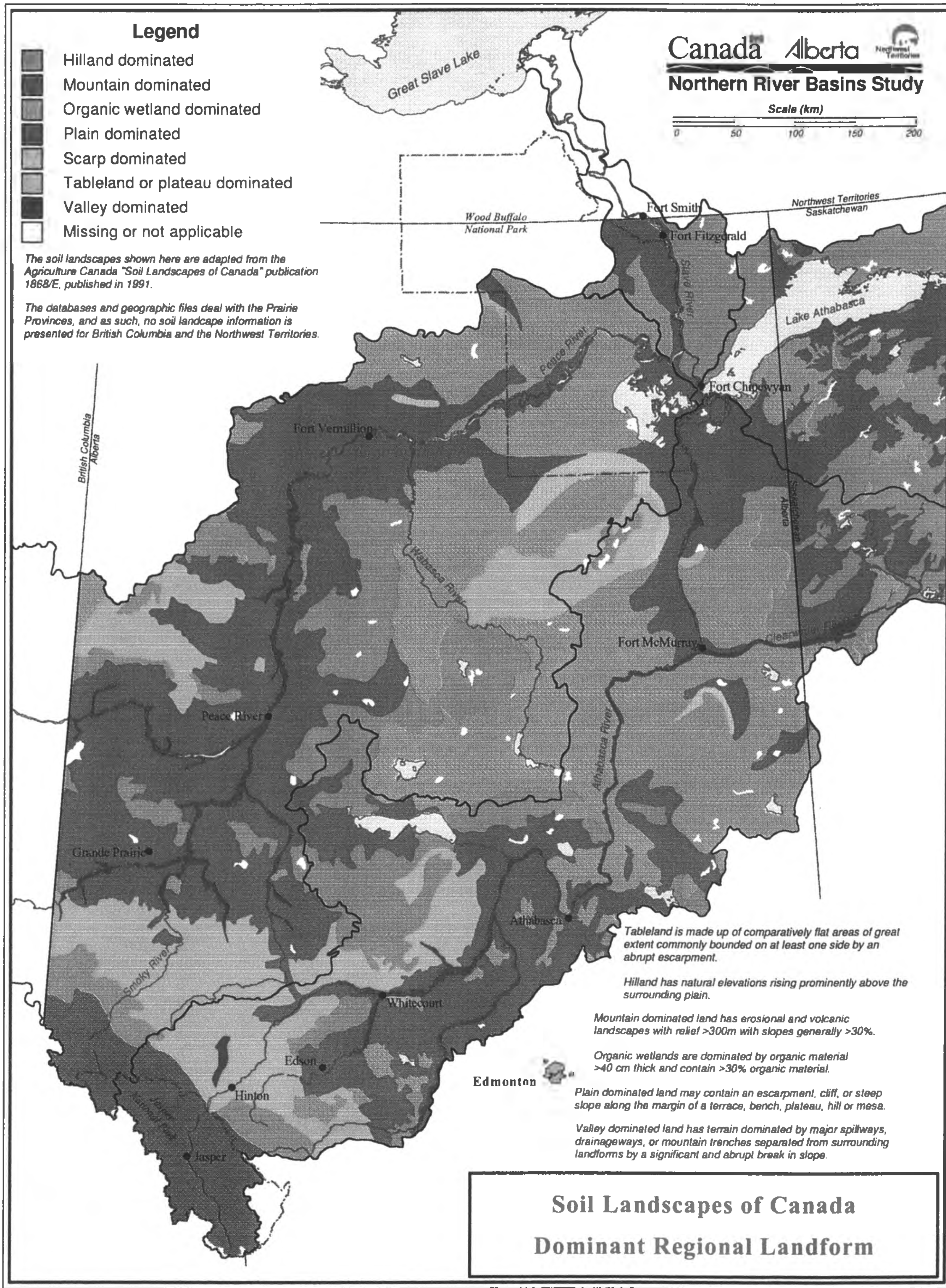
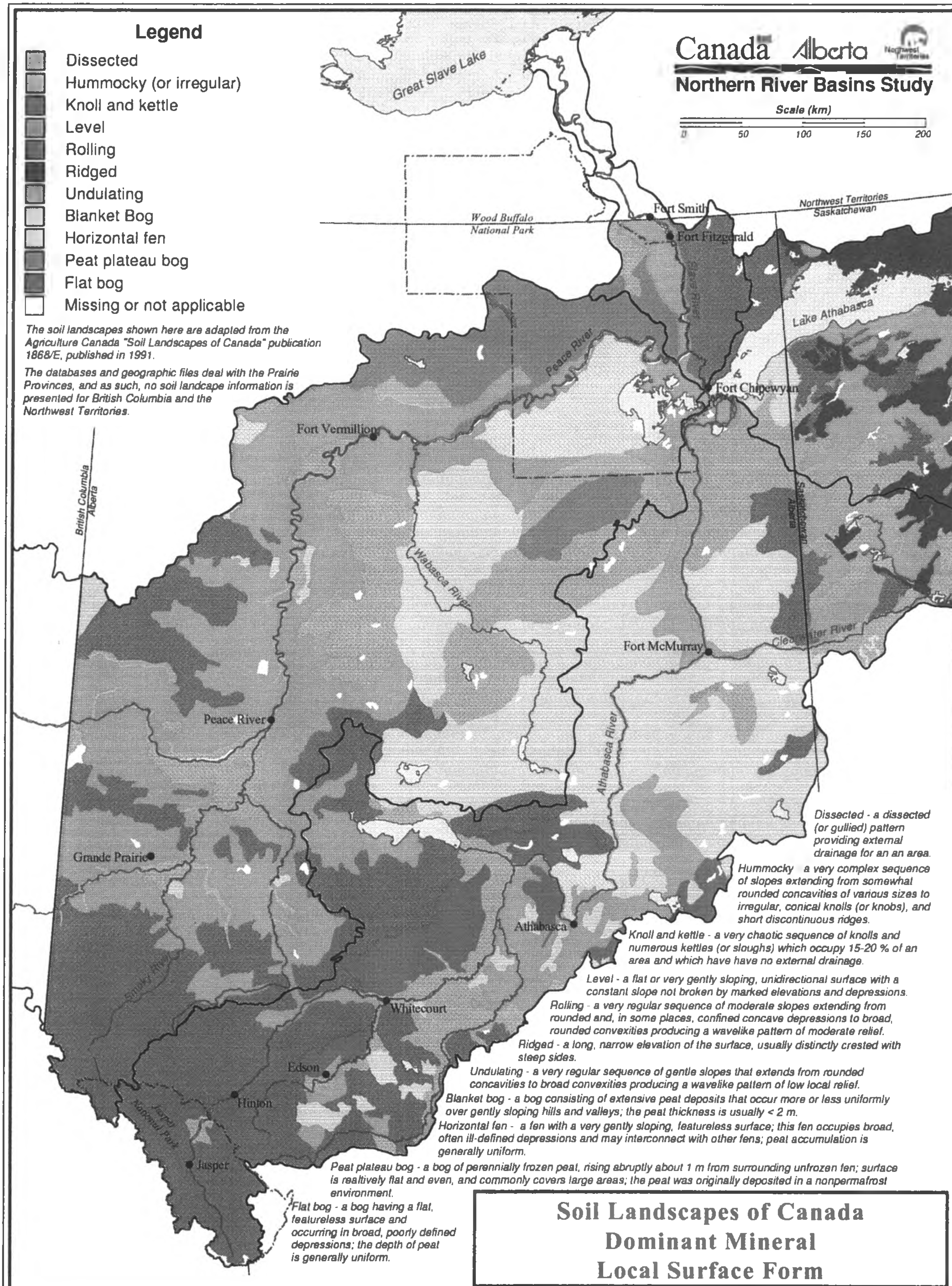

Legend
Hilland dominated
Mountain dominated
Organic wetland dominated
Plain dominated
Scarp dominated
Tableland or plateau dominated
Valley dominated
Missing or not applicable
The soil landscapes shown here are adapted from the Agriculture Canada "Soil Landscapes of Canada" publication 1868/E, published in 1991.
The databases and geographic files deal with the Prairie Provinces, and as such, no soil landcape information is presented for British Columbia and the Northwest Territories.
Canada
Alberta
Northern River Basins Study
Scale (km)
0
50
100
150
200
Great Slave Lake
Wood Buffalo National Park
Fort Smith
Fort Fitzgerald
Northwest Territories
Saskatchewan
Slave River
Lake Athabasca
Peace River
Fort Chipewyan
Fort Vermillion
British Columbia
Alberta
Wabasca River
Saskatchewan
Alberta
Fort McMurray
Clearwater River
Peace River
Athabasca River
Grande Prairie
Athabasca
Smoky River
Whitecourt
Edson
Edmonton
Hinton
Jasper
Tableland is made up of comparatively flat areas of great extent commonly bounded on at least one side by an abrupt escarpment.
Hilland has natural elevations rising prominently above the surrounding plain.
Mountain dominated land has erosional and volcanic landscapes with relief >300m with slopes generally >30%.
Organic wetlands are dominated by organic material >40 cm thick and contain >30% organic material.
Plain dominated land may contain an escarpment, cliff, or steep slope along the margin of a terrace, bench, plateau, hill or mesa.
Valley dominated land has terrain dominated by major spillways, drainageways, or mountain trenches separated from surrounding landforms by a significant and abrupt break in slope.
Soil Landscapes of Canada
Dominant Regional Landform

FIGURE 2.2



Legend
Dissected
Hummocky (or irregular)
Knoll and kettle
Level
Rolling
Ridged
Undulating
Blanket Bog
Horizontal fen
Peat plateau bog
Flat bog
Missing or not applicable
The soil landscapes shown here are adapted from the Agriculture Canada "Soil Landscapes of Canada" publication 1868/E, published in 1991.
The databases and geographic files deal with the Prairie Provinces, and as such, no soil landcape information is presented for British Columbia and the Northwest Territories.
Canada
Alberta
Northwest Territories
Northern River Basins Study
Scale (km)
0
50
100
150
200
Great Slave Lake
Wood Buffalo National Park
Fort Smith
Fort Fitzgerald
Northwest Territories
Saskatchewan
Slave River
Lake Athabasca
Peace River
Fort Chipewyan
Fort Vermillion
British Columbia
Alberta
Saskatchewan
Alberta
Wabasca River
Clearwater River
Fort McMurray
Peace River
Athabasca River
Grande Prairie
Athabasca
Smoky River
Whitecourt
Edson
Hinton
Jasper National Park
Jasper
Dissected - a dissected (or gullied) pattern providing external drainage for an an area.
Hummocky - a very complex sequence of slopes extending from somewhat rounded concavities of various sizes to irregular, conical knolls (or knobs), and short discontinuous ridges.
Knoll and kettle - a very chaotic sequence of knolls and numerous kettles (or sloughs) which occupy 15-20 % of an area and which have have no external drainage.
Level - a flat or very gently sloping, unidirectional surface with a constant slope not broken by marked elevations and depressions.
Rolling - a very regular sequence of moderate slopes extending from rounded and, in some places, confined concave depressions to broad, rounded convexities producing a wavelike pattern of moderate relief.
Ridged - a long, narrow elevation of the surface, usually distinctly crested with steep sides.
Undulating - a very regular sequence of gentle slopes that extends from rounded concavities to broad convexities producing a wavelike pattern of low local relief.
Blanket bog - a bog consisting of extensive peat deposits that occur more or less uniformly over gently sloping hills and valleys; the peat thickness is usually < 2 m.
Horizontal fen - a fen with a very gently sloping, featureless surface; this fen occupies broad, often ill-defined depressions and may interconnect with other fens; peat accumulation is generally uniform.
Peat plateau bog - a bog of perennially frozen peat, rising abruptly about 1 m from surrounding unfrozen fen; surface is realtively flat and even, and commonly covers large areas; the peat was originally deposited in a nonpermafrost environment.
Flat bog - a bog having a flat, featureless surface and occurring in broad, poorly defined depressions; the depth of peat is generally uniform.
Soil Landscapes of Canada
Dominant Mineral
Local Surface Form

FIGURE 2.3

HIGHLANDS

CRETACEOUS
Clearwater, Grand Rapids and Younger Fms: shales, sandstones

LOWLANDS

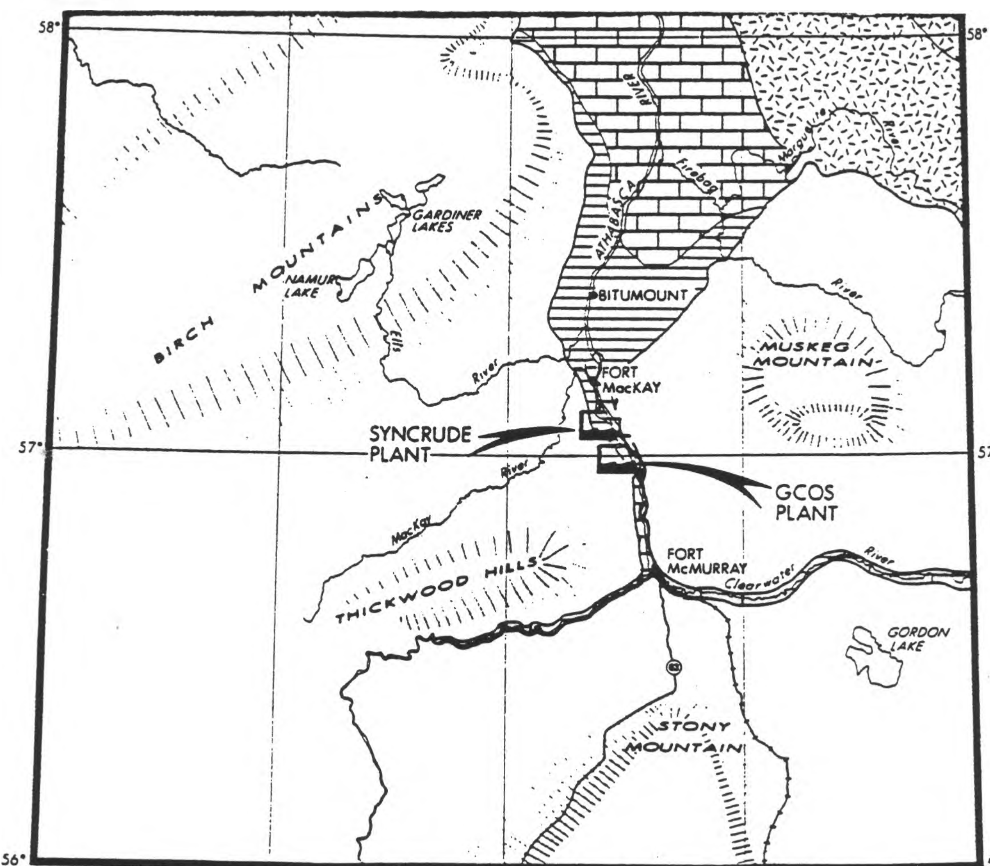
CRETACEOUS
McMurray and Clearwater Fms: oil sands, sandstones, shales

DEVONIAN
Carbonates, evaporites

CANADIAN SHIELD

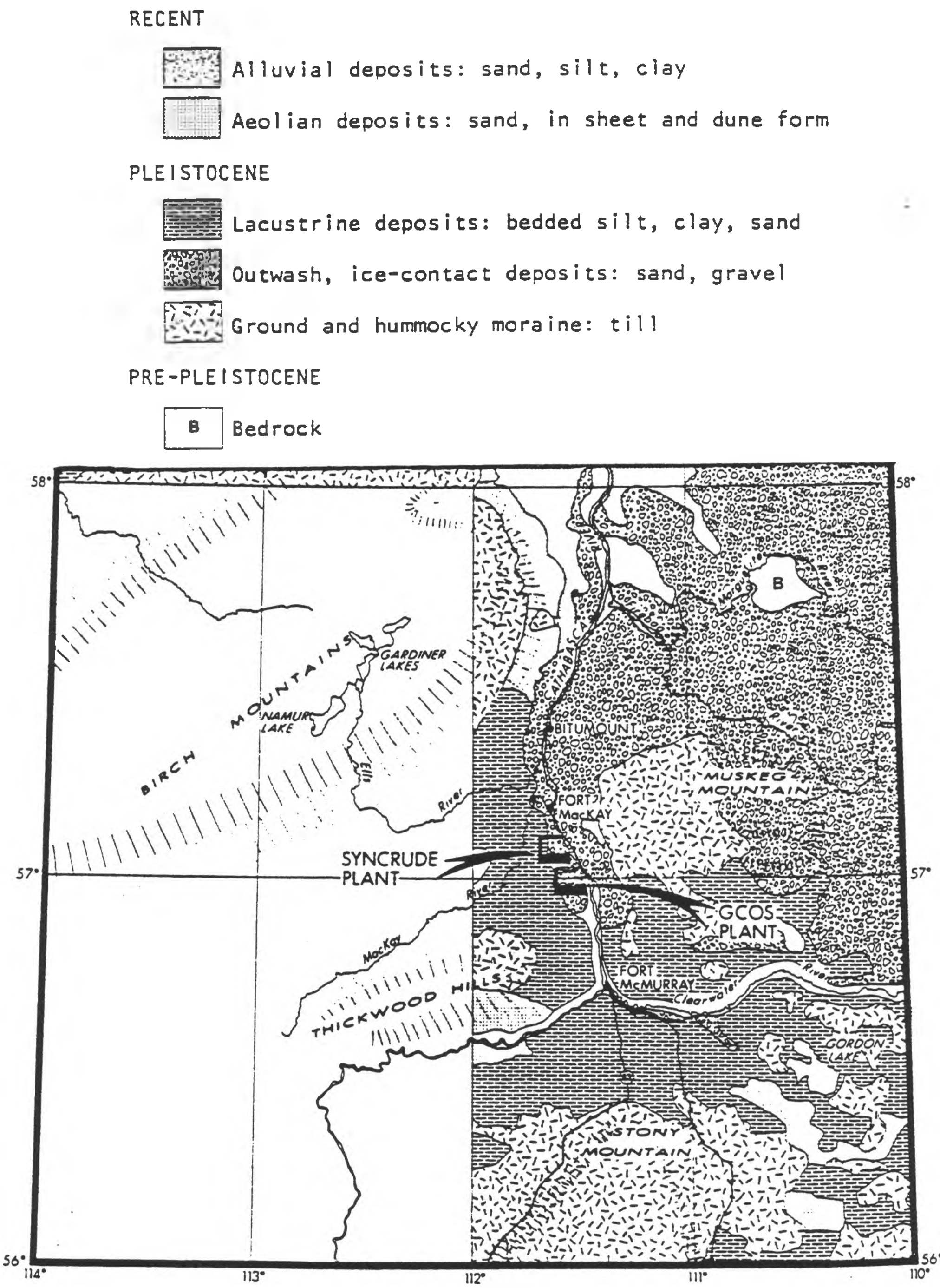
PRECAMBRIAN
Athabasca Fm: quartzite, sandstone

PRECAMBRIAN
Crystalline "Basement" Complex: granitic plutonic rocks



PHYSIOGRAPHY AND GEOLOGY OF LOWER ATHABASCA BASIN
(after Hamilton and Mellon, 1973)

FIGURE 2.4



SURFICIAL DEPOSITS OF LOWER ATHABASCA BASIN
(after Hamilton and Mellon, 1973)

FIGURE 2.5

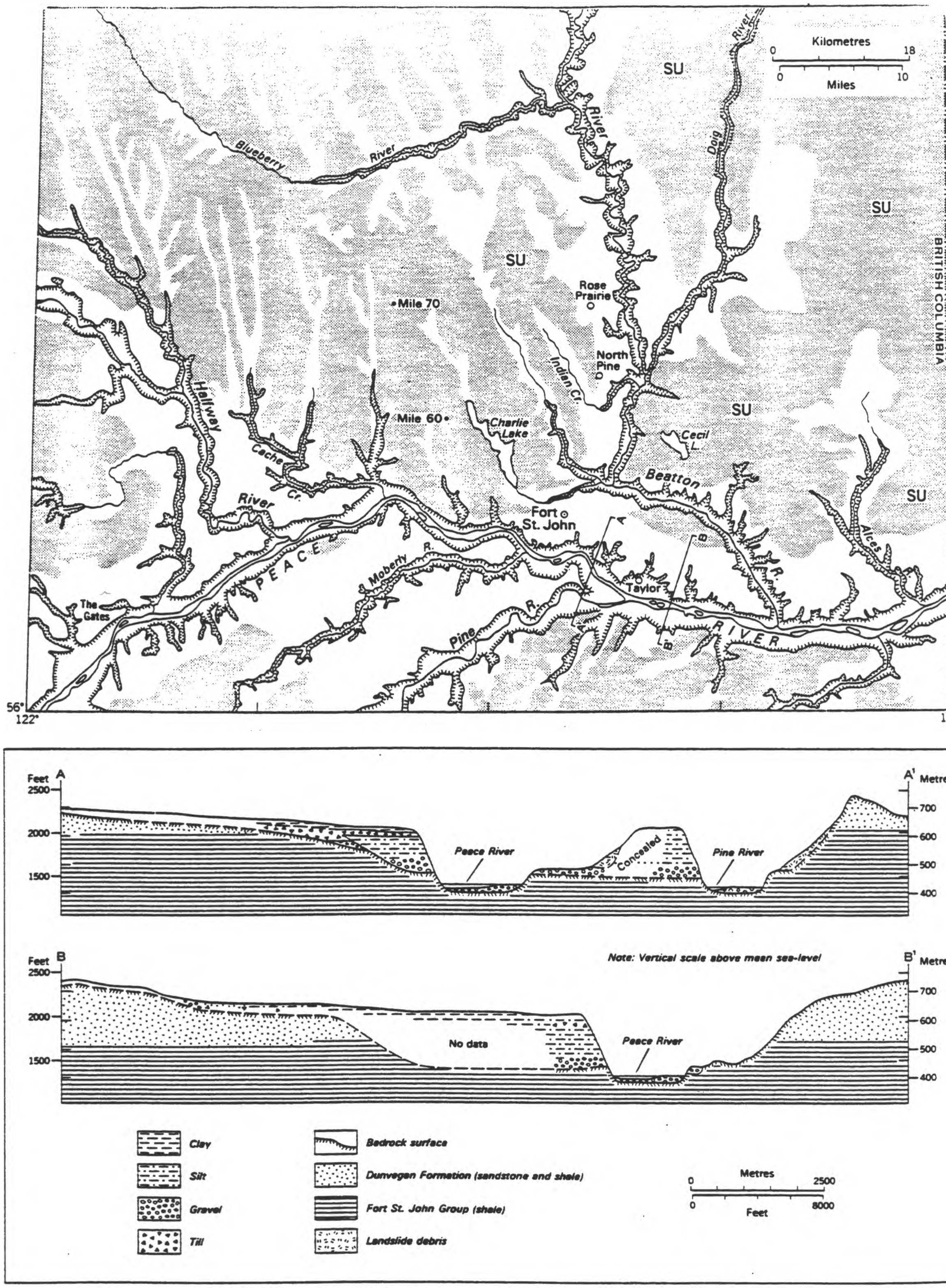


FIGURE 2.6

MAP AND CROSS-SECTIONS OF FORT ST JOHN AREA
(from Mathews, 1978)

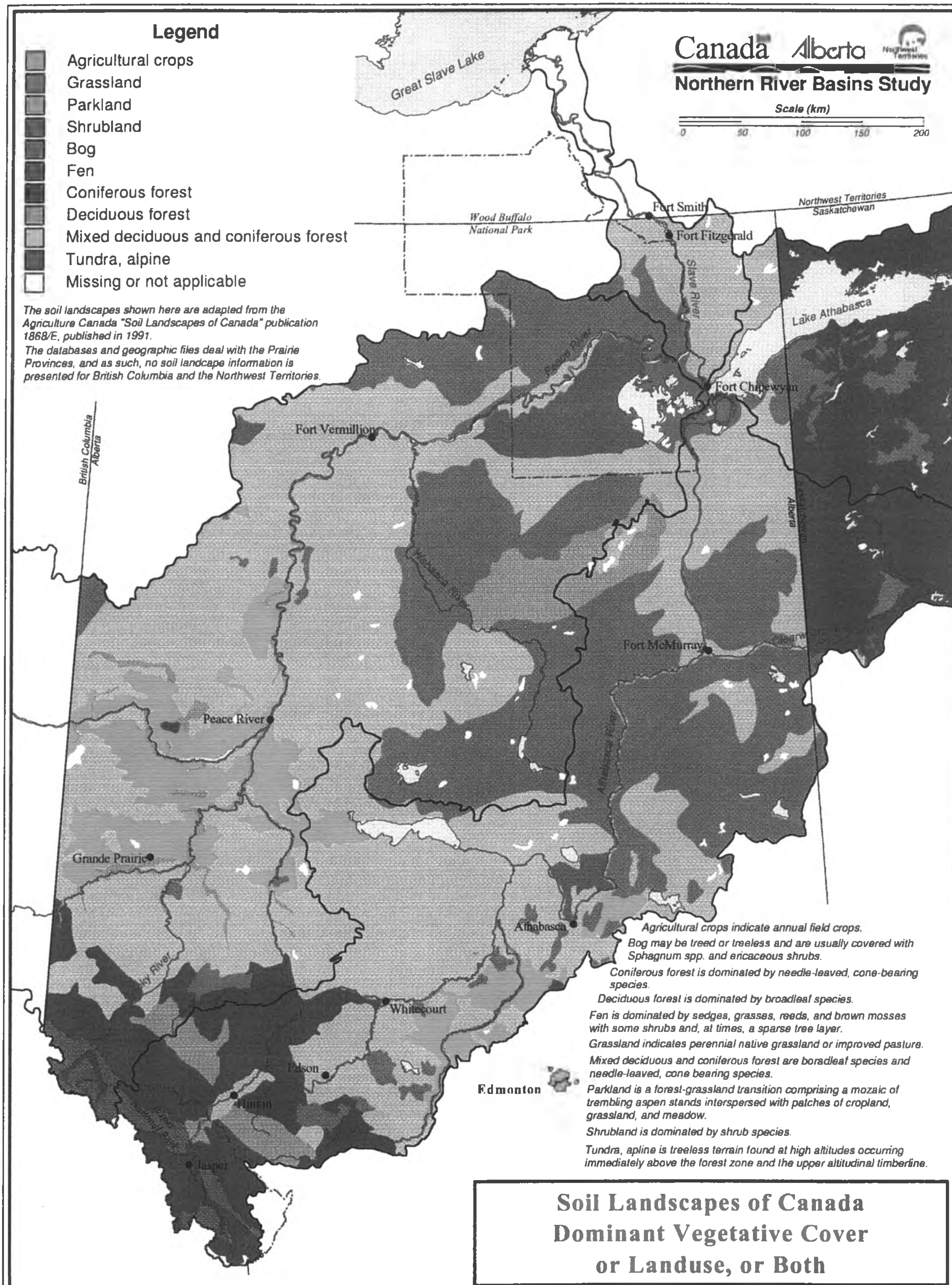
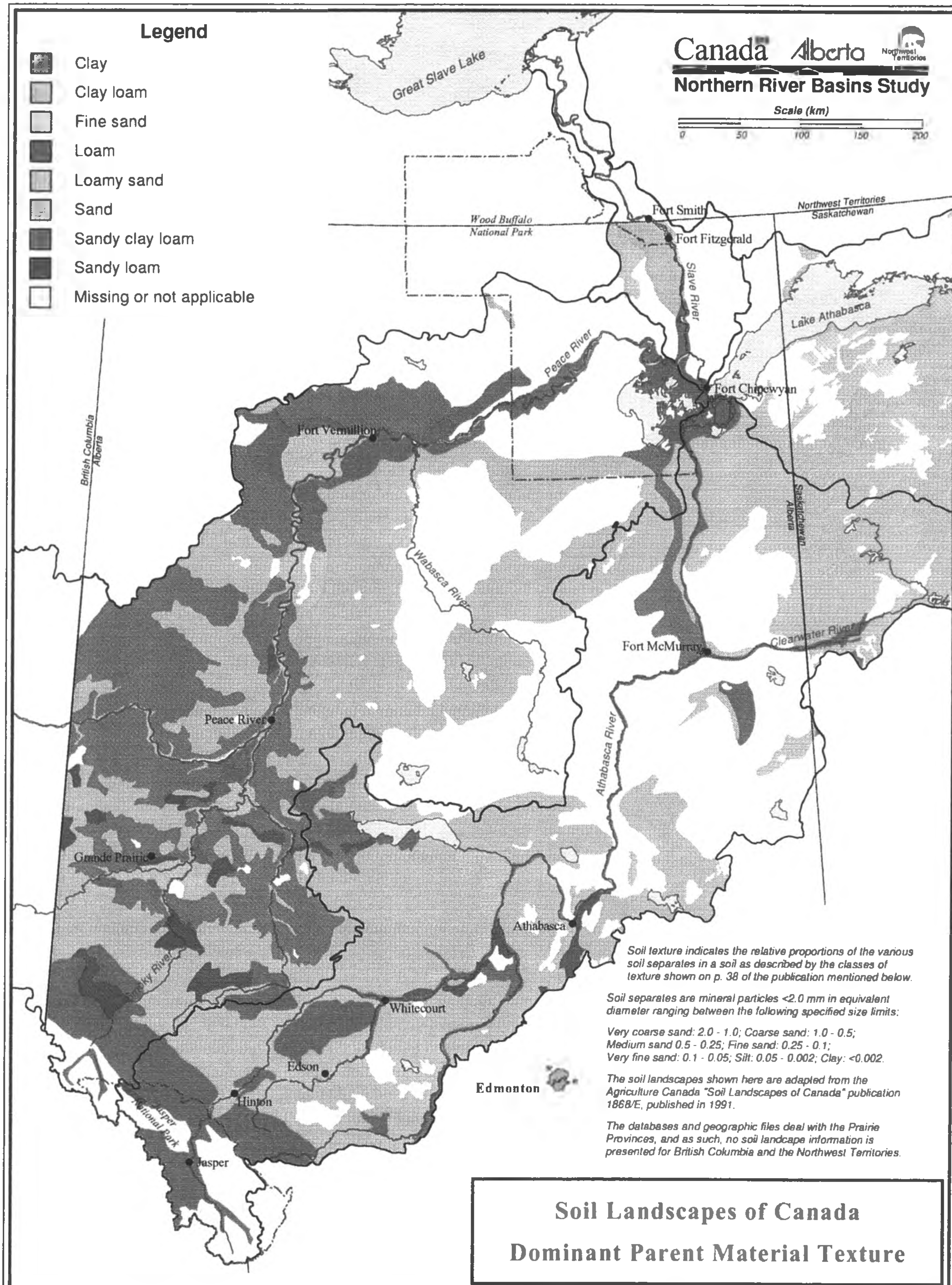

Legend
Agricultural crops
Grassland
Parkland
Shrubland
Bog
Fen
Coniferous forest
Deciduous forest
Mixed deciduous and coniferous forest
Tundra, alpine
Missing or not applicable
The soil landscapes shown here are adapted from the Agriculture Canada "Soil Landscapes of Canada" publication 1868/E, published in 1991.
The databases and geographic files deal with the Prairie Provinces, and as such, no soil landcape information is presented for British Columbia and the Northwest Territories.
Canada Alberta
Northern River Basins Study
Scale (km)
0 50 100 150 200
Great Slave Lake
Wood Buffalo National Park
Fort Smith
Fort Fitzgerald
Northwest Territories
Saskatchewan
Slave River
Lake Athabasca
Peace River
Fort Chipewyan
Fort Vermillion
British Columbia
Alberta
Fort McMurray
Peace River
Athabasca River
Grande Prairie
Athabasca
Whitecourt
Edson
Edmonton
Hinton
Jasper
Agricultural crops indicate annual field crops.
Bog may be treed or treeless and are usually covered with Sphagnum spp. and ericaceous shrubs.
Coniferous forest is dominated by needle-leaved, cone-bearing species.
Deciduous forest is dominated by broadleaf species.
Fen is dominated by sedges, grasses, reeds, and brown mosses with some shrubs and, at times, a sparse tree layer.
Grassland indicates perennial native grassland or improved pasture.
Mixed deciduous and coniferous forest are boradleaf species and needle-leaved, cone bearing species.
Parkland is a forest-grassland transition comprising a mozaic of trembling aspen stands interspersed with patches of cropland, grassland, and meadow.
Shrubland is dominated by shrub species.
Tundra, apline is treeless terrain found at high altitudes occurring immediately above the forest zone and the upper altitudinal timberline.
Soil Landscapes of Canada
Dominant Vegetative Cover
or Landuse, or Both

FIGURE 2.7



Legend
Clay
Clay loam
Fine sand
Loam
Loamy sand
Sand
Sandy clay loam
Sandy loam
Missing or not applicable
Canada
Alberta
Northwest Territories
Northern River Basins Study
Scale (km)
0
50
100
150
200
Great Slave Lake
Wood Buffalo National Park
Fort Smith
Fort Fitzgerald
Northwest Territories
Saskatchewan
Slave River
Lake Athabasca
Peace River
Fort Chipewyan
Fort Vermillion
British Columbia
Alberta
Saskatchewan
Alberta
Wabasca River
Fort McMurray
Clearwater River
Peace River
Athabasca River
Grande Prairie
Athabasca
Smoky River
Whitecourt
Edson
Edmonton
Hinton
Jasper National Park
Jasper
Soil texture indicates the relative proportions of the various soil separates in a soil as described by the classes of texture shown on p. 38 of the publication mentioned below.
Soil separates are mineral particles <2.0 mm in equivalent diameter ranging between the following specified size limits:
Very coarse sand: 2.0 - 1.0; Coarse sand: 1.0 - 0.5; Medium sand 0.5 - 0.25; Fine sand: 0.25 - 0.1; Very fine sand: 0.1 - 0.05; Silt: 0.05 - 0.002; Clay: <0.002.
The soil landscapes shown here are adapted from the Agriculture Canada "Soil Landscapes of Canada" publication 1868/E, published in 1991.
The databases and geographic files deal with the Prairie Provinces, and as such, no soil landcape information is presented for British Columbia and the Northwest Territories.
Soil Landscapes of Canada
Dominant Parent Material Texture

FIGURE 2.8

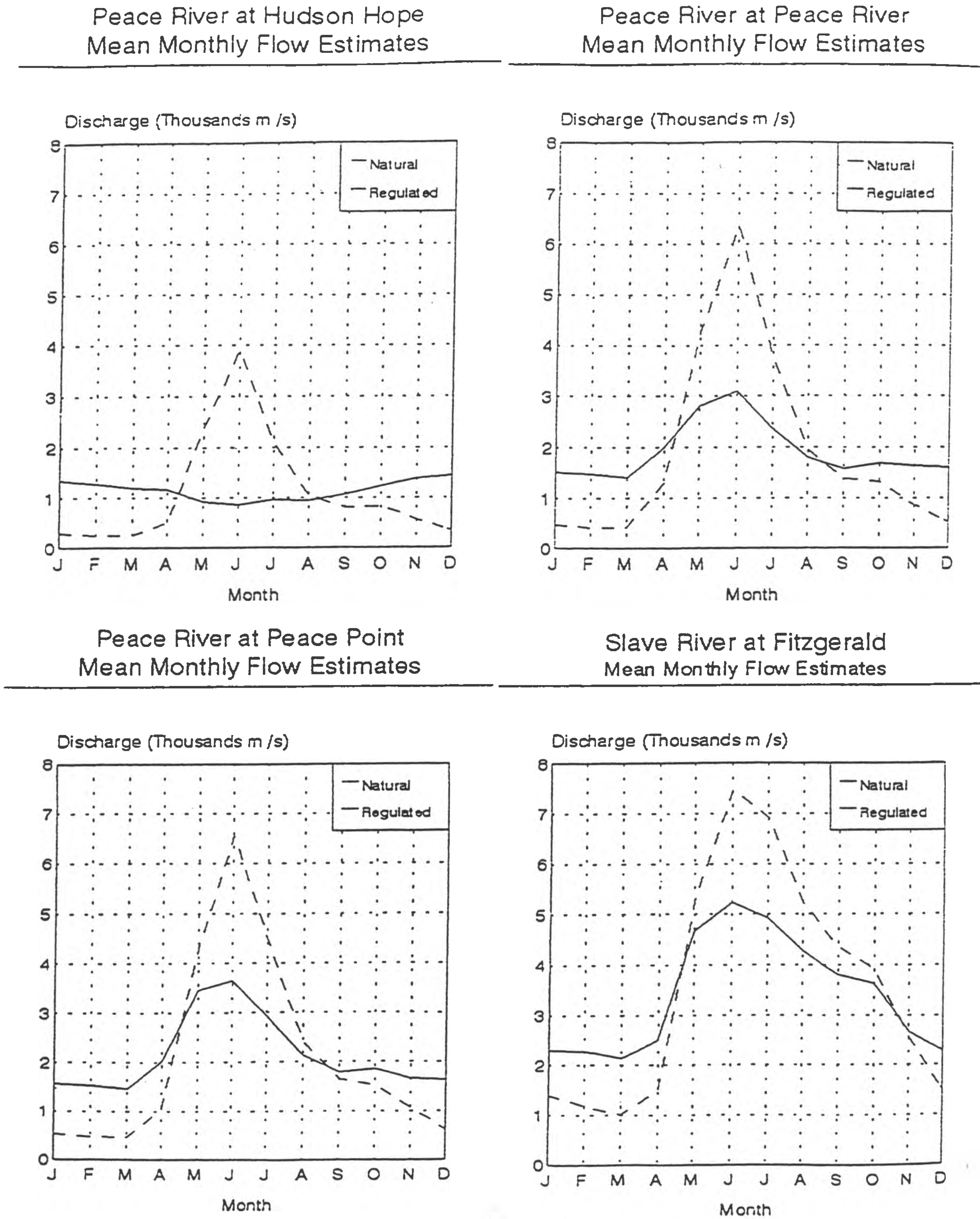


FIGURE 2.9
CHANGES IN FLOW OF PEACE-SLAVE RIVERS DUE TO W.A.C. BENNETT DAM
(after Aitken et al., 1995)

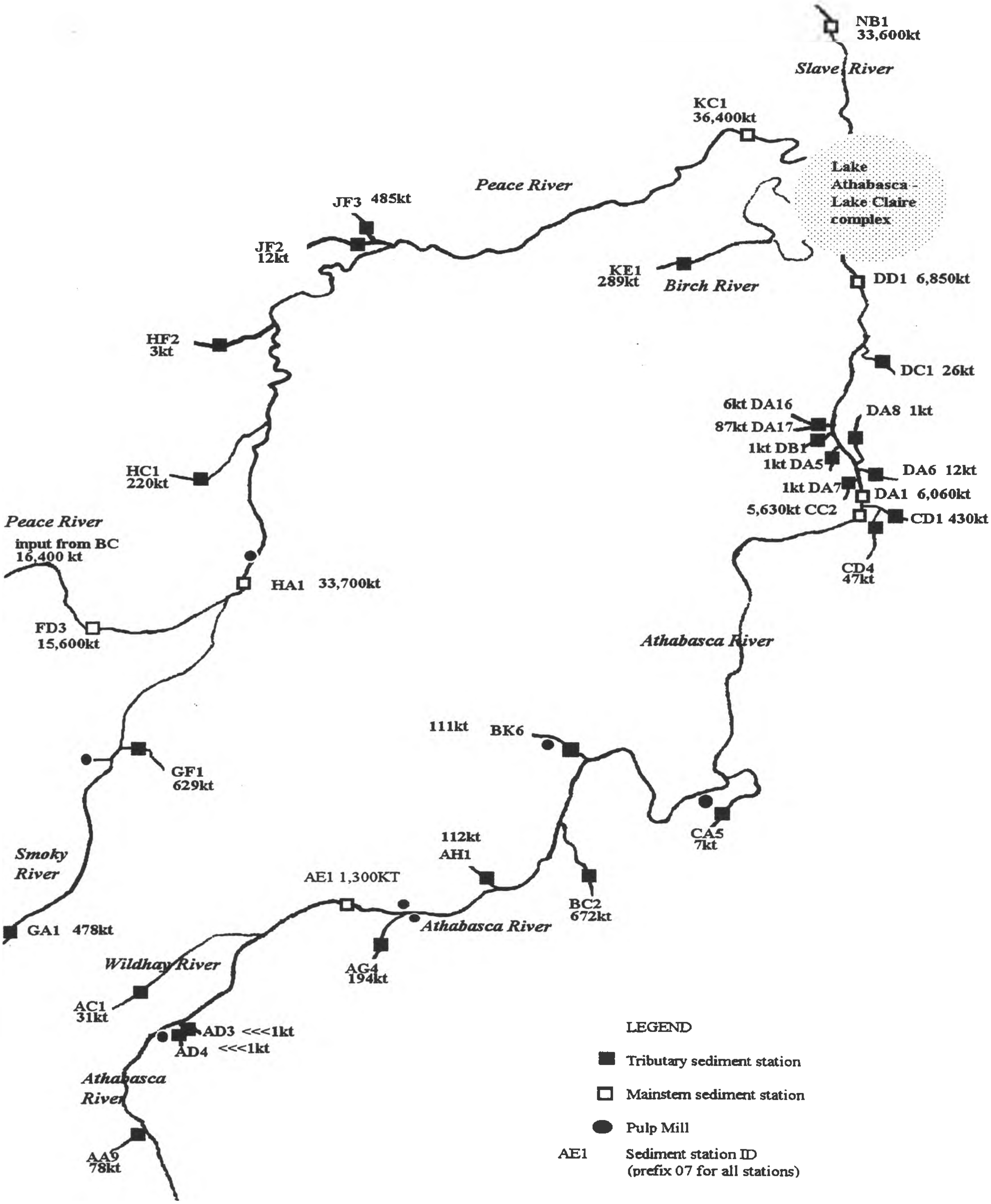
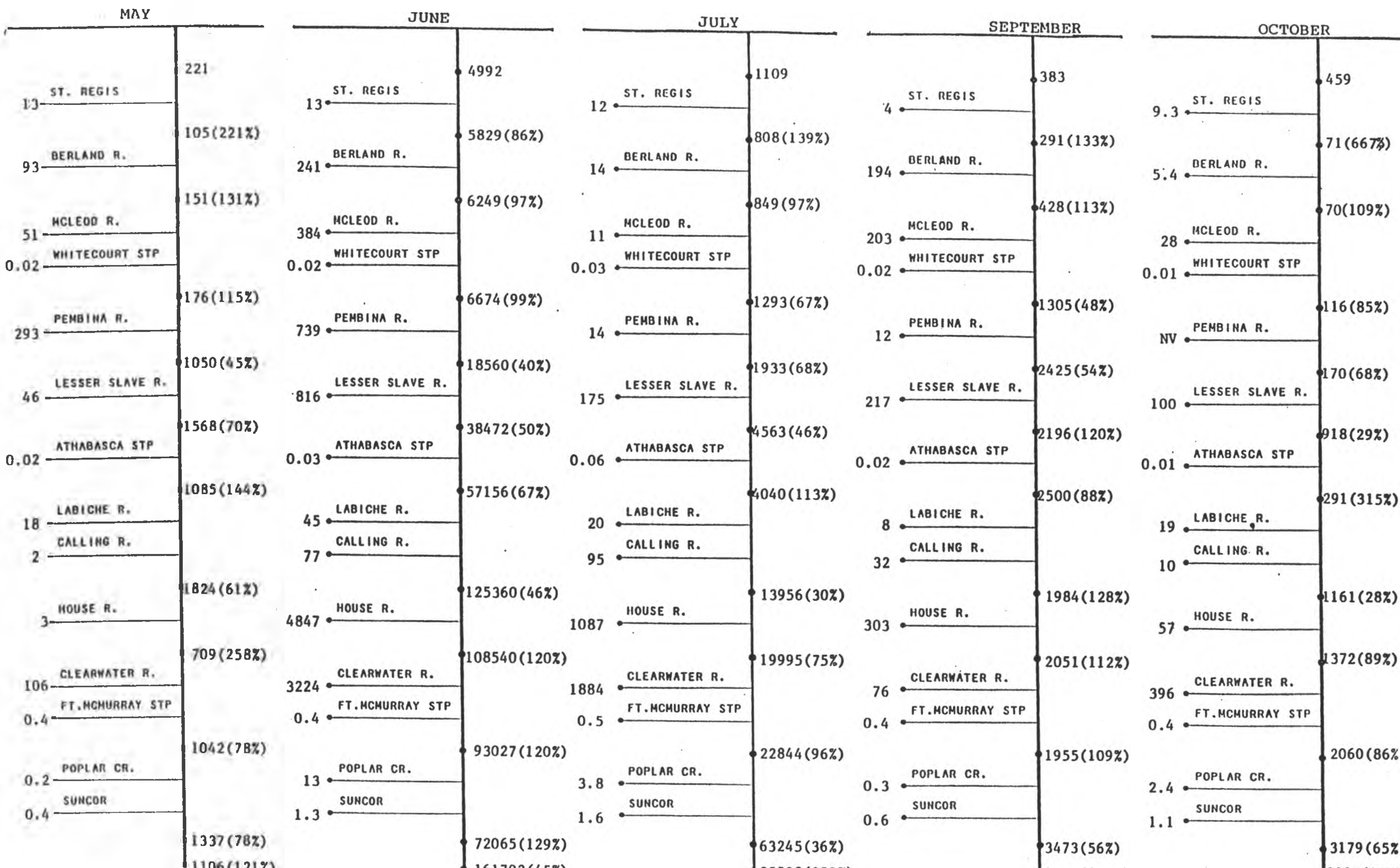


FIGURE 3.1

MEAN ANNUAL SUSPENDED SEDIMENT LOADS OF THE ALBERTA SEDIMENT STATIONS IN THE NRBS AREA (excluding sub-basin tributaries) AND LOCATION OF PULP MILLS

FIGURE 3.2
SEASONAL MASS-BALANCE IN NON-FILTERABLE RESIDUE FOR ATHABASCA RIVER IN 1984 (in tonnes per day)
(after Hamilton et al., 1985)



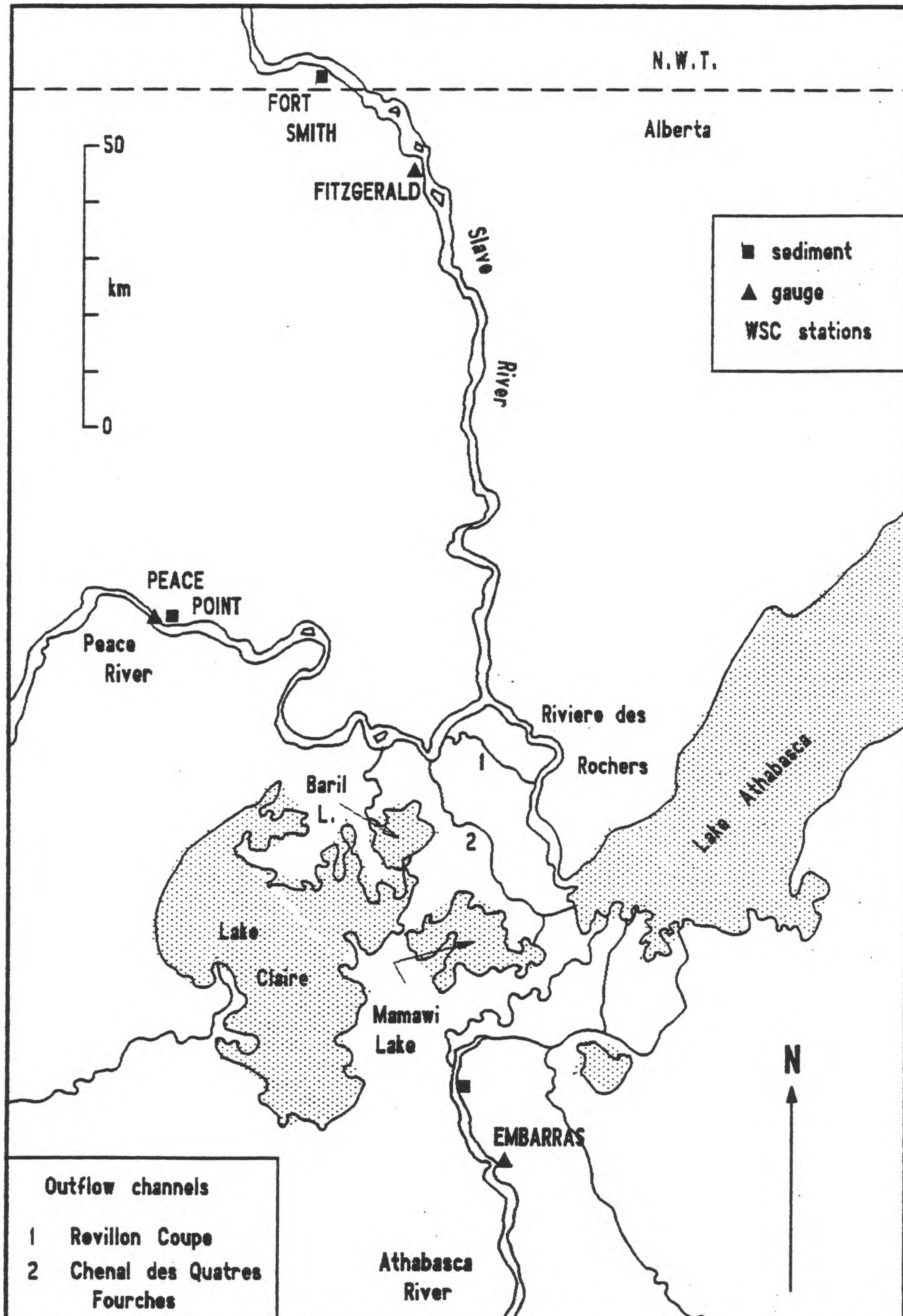


FIGURE 3.3

PEACE-ATHABASCA DELTA REGION:
LOCATION MAP

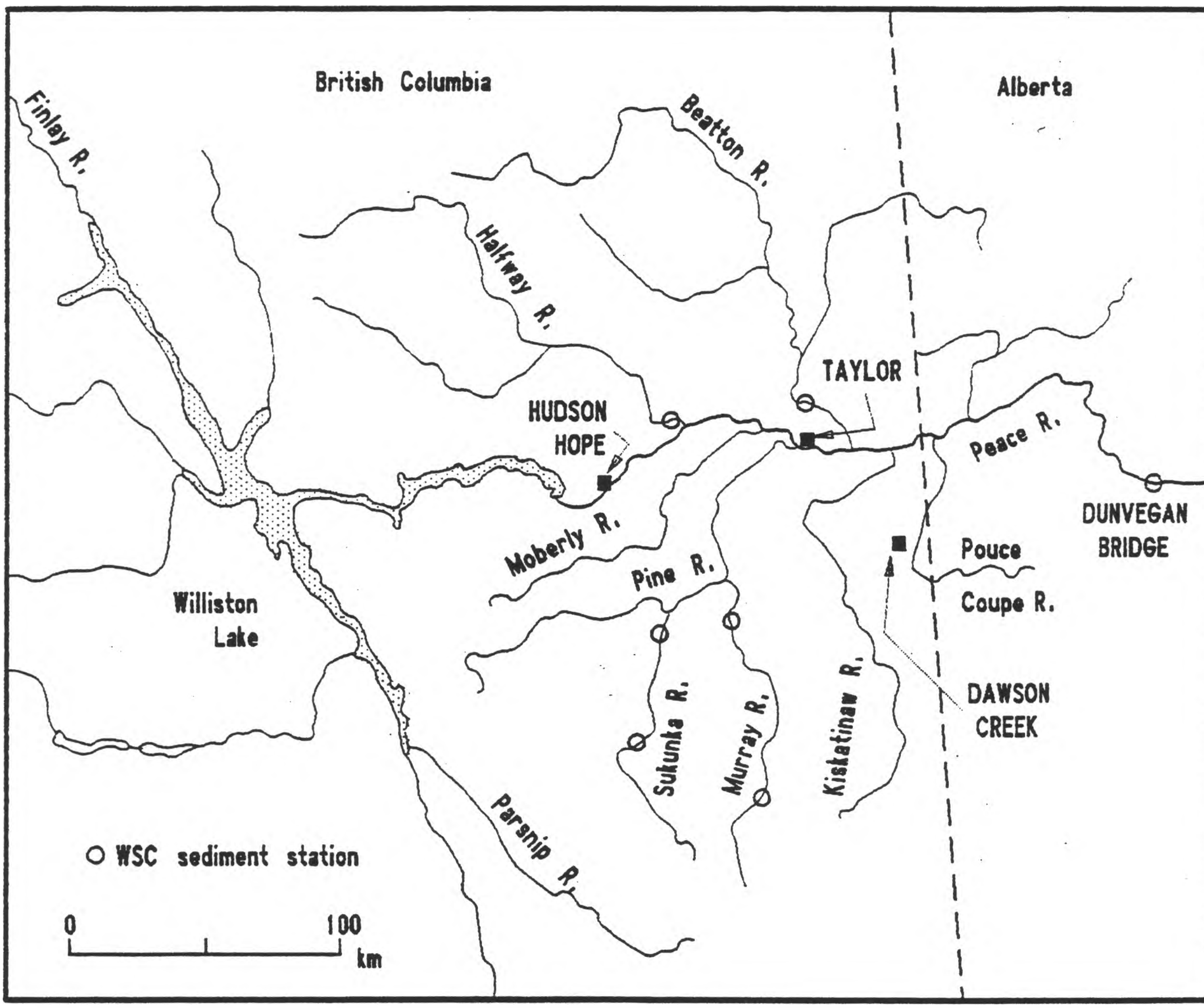
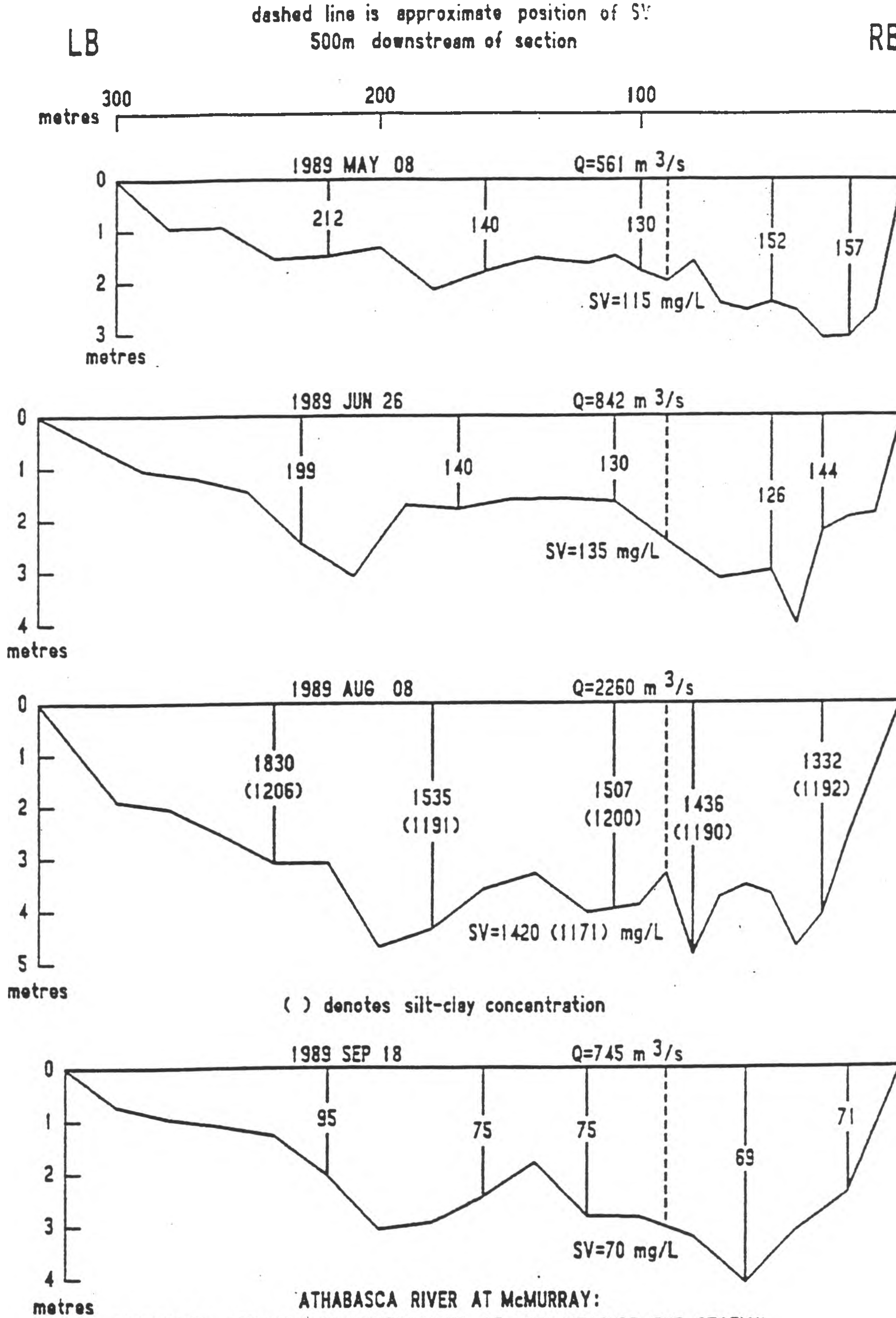


FIGURE 3.4

PEACE RIVER DRAINAGE NETWORK UPSTREAM OF DUNVEGAN BRIDGE



ATHABASCA RIVER AT McMURRAY:
SUSPENDED SEDIMENT CONCENTRATIONS AT 1989 MEASUREMENT SECTION

FIGURE 3.5

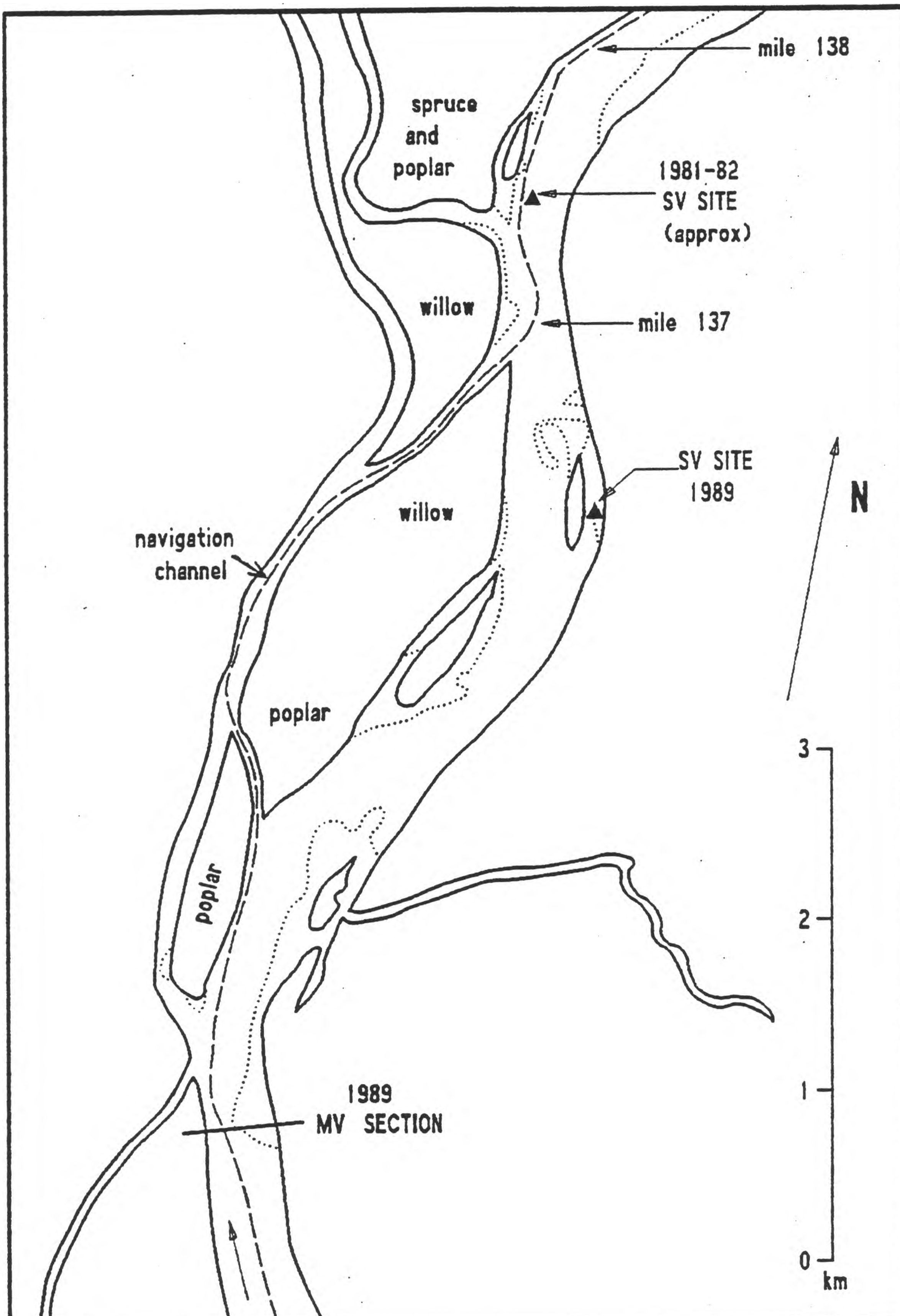
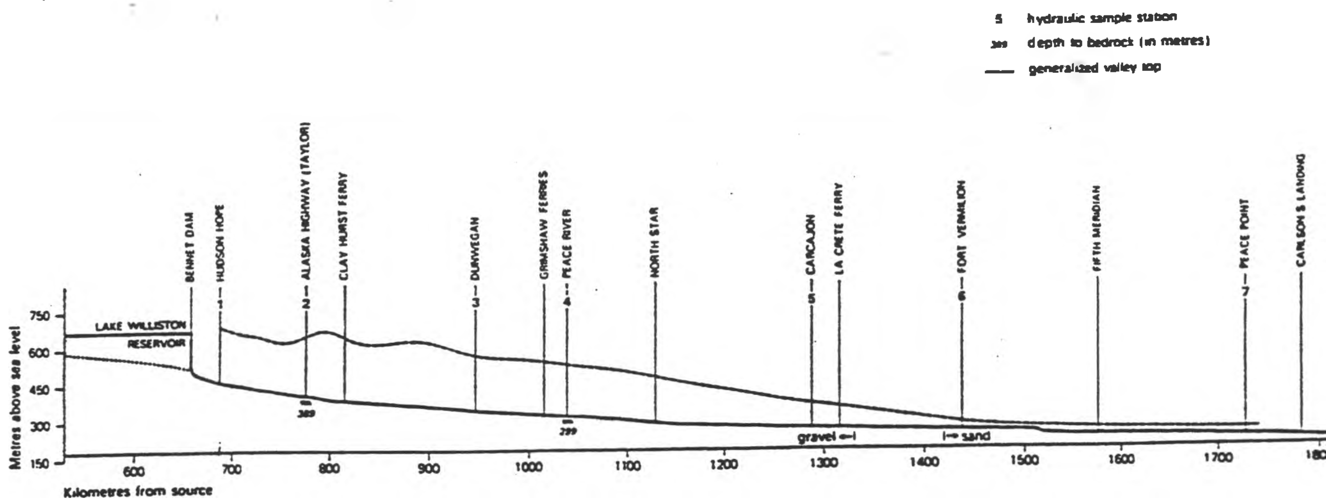


FIGURE 3.6

**LOCATIONS OF EMBARRAS SAMPLING SITES
BASED ON 1973 HYDROGRAPHIC CHART**

Longitudinal profile of the Peace River



Longitudinal profile of the Athabasca River

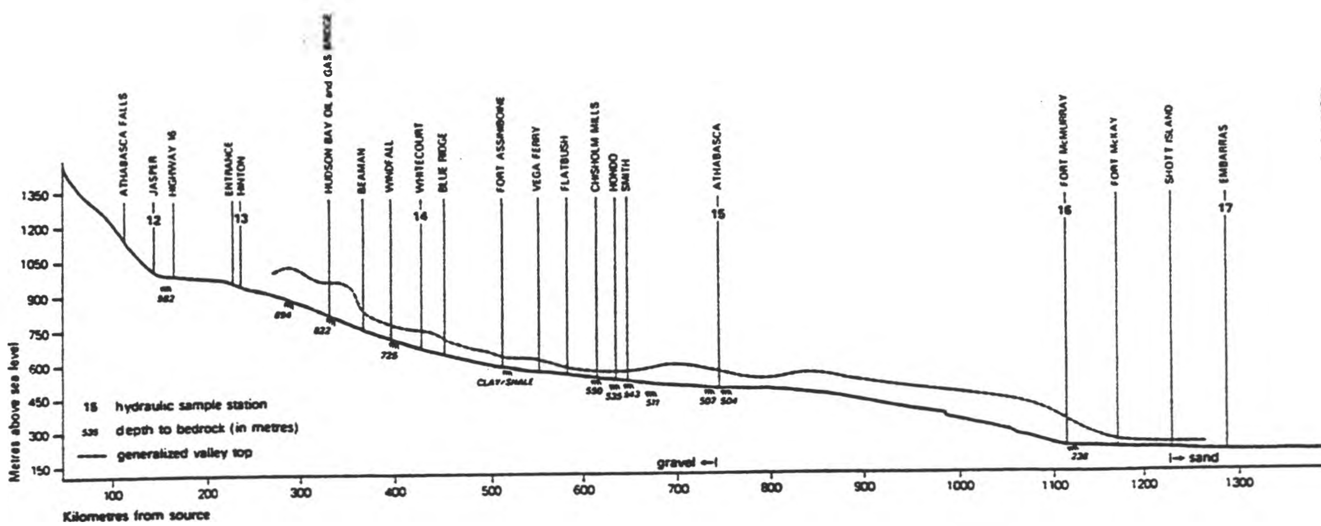
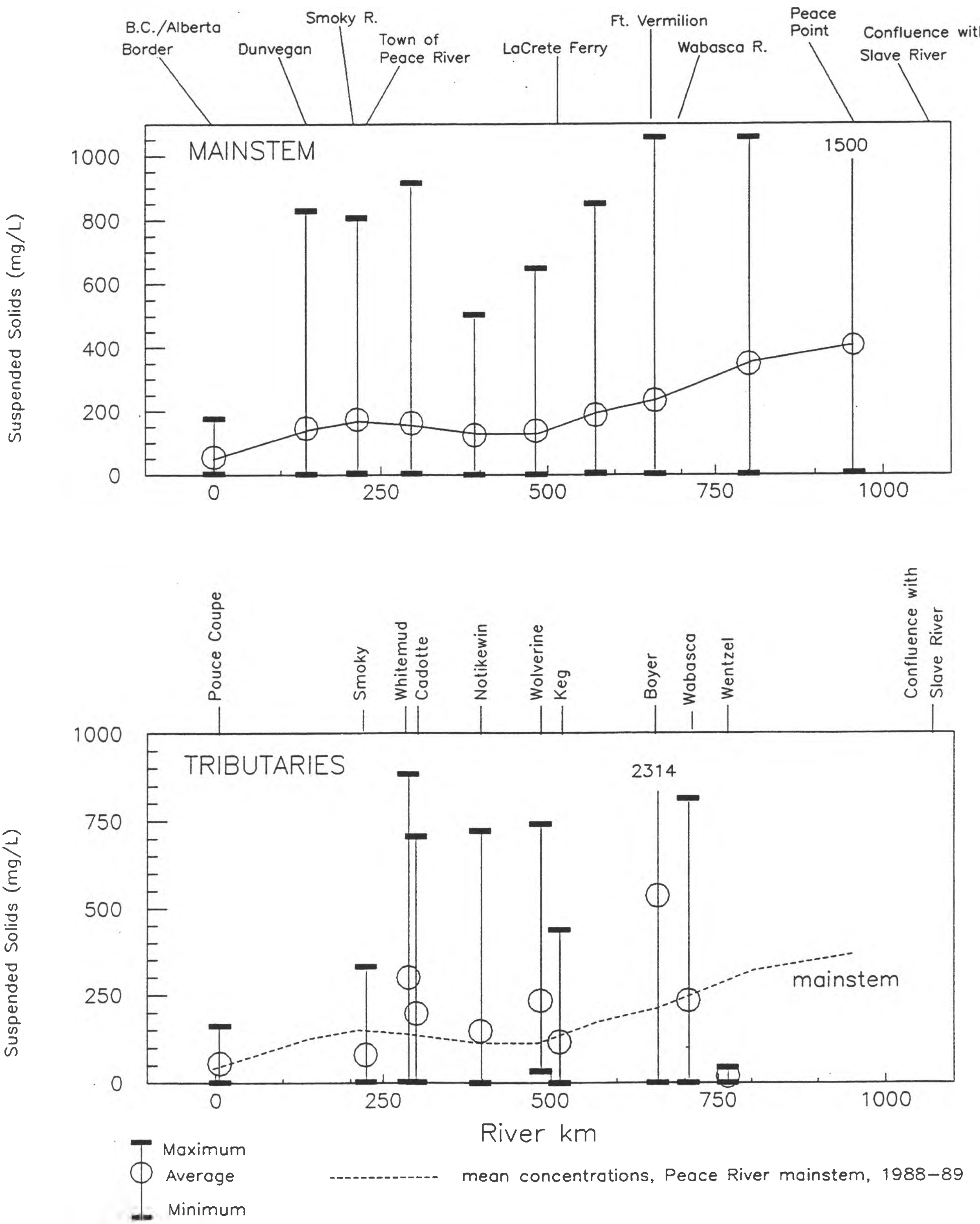


FIGURE 5.1

Long profiles of Athabasca and Peace Rivers (from Shaw and Kellerhals, 1982).



Suspended solids concentrations in the Peace River system, 1988–89.

FIGURE 5.2
(from Shaw et al., 1990)

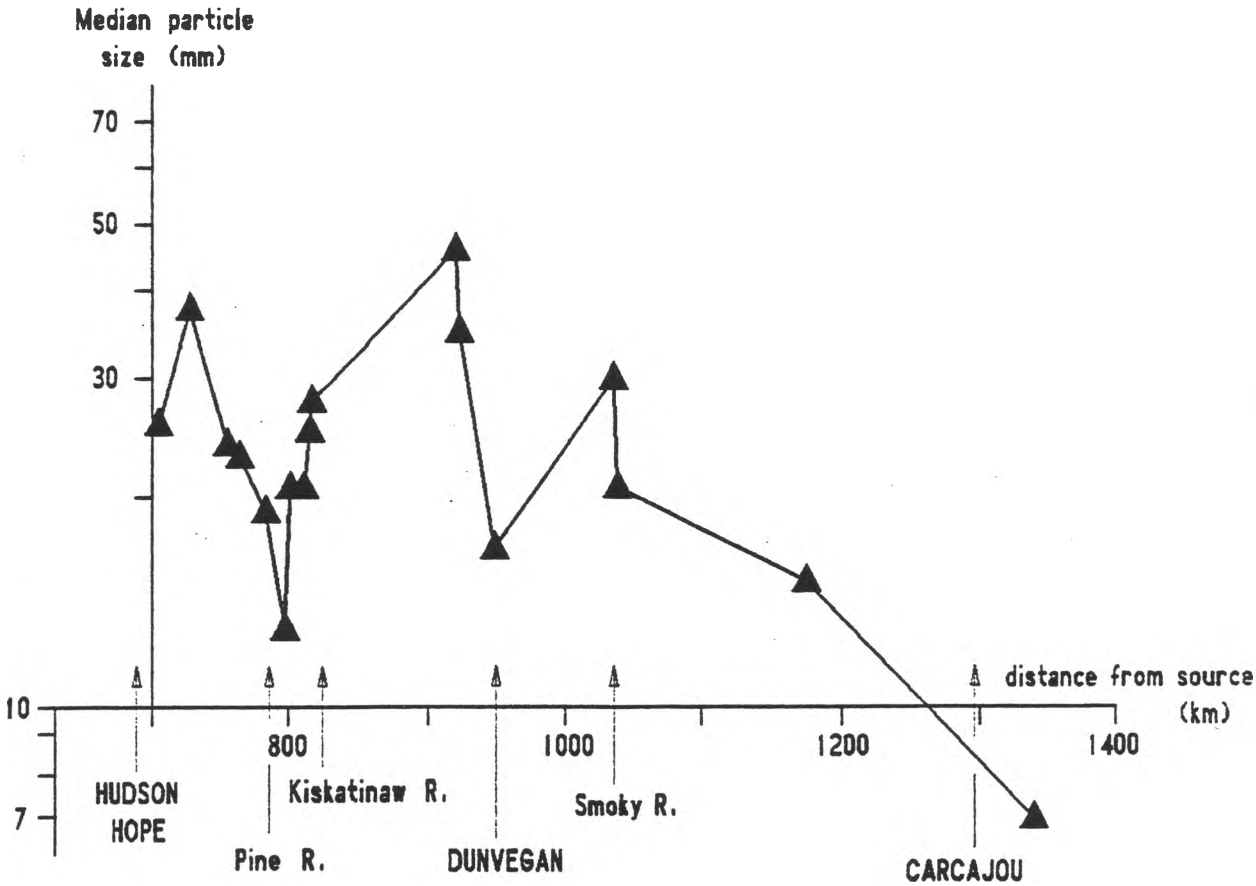


FIGURE 5.3

CHANGE IN BED MATERIAL SIZE ALONG PEACE RIVER BETWEEN HUDSON HOPE AND CARCAJOU

(after Shaw and Kellerhals, 1982)

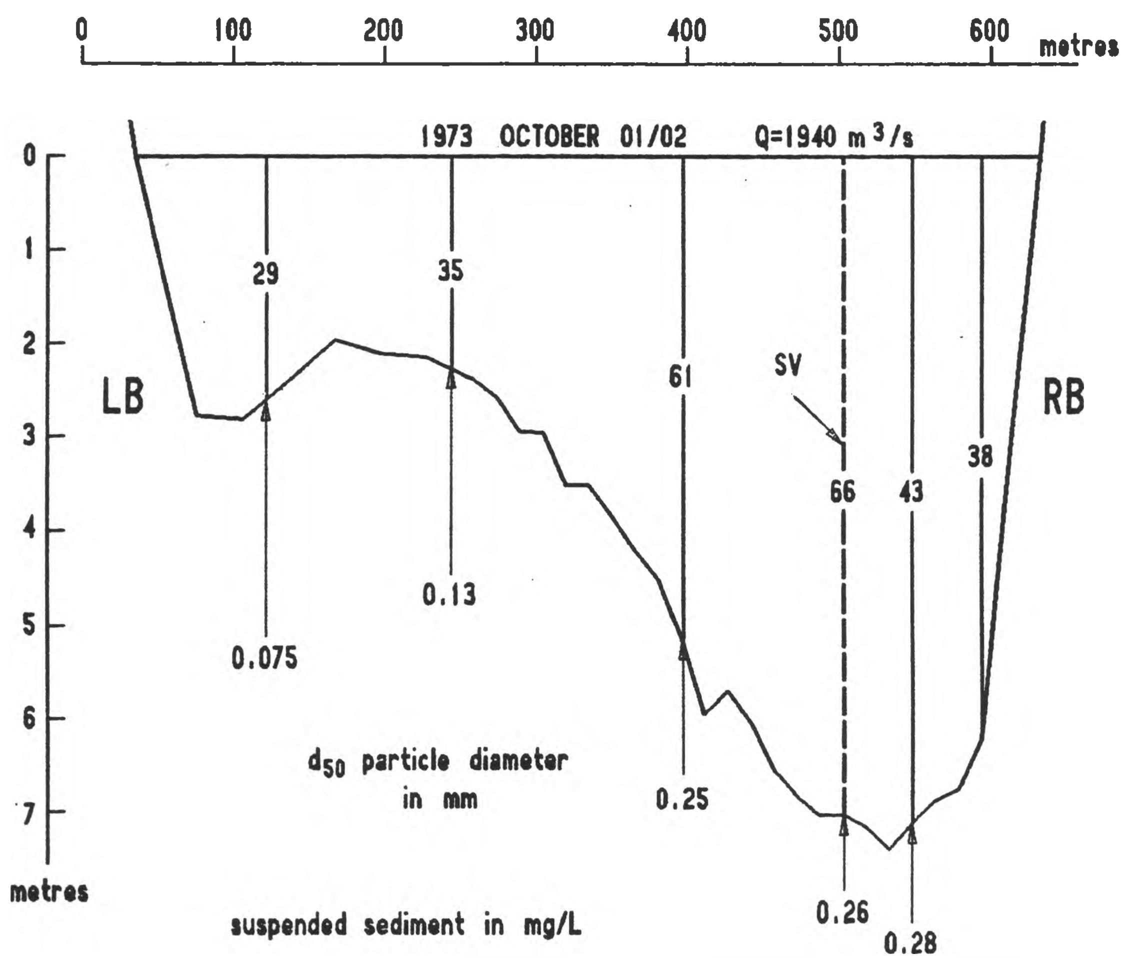


FIGURE 5.4

PEACE RIVER AT PEACE POINT: CROSS-SECTIONAL DISTRIBUTION OF SUSPENDED SEDIMENT AND BED MATERIAL SIZE

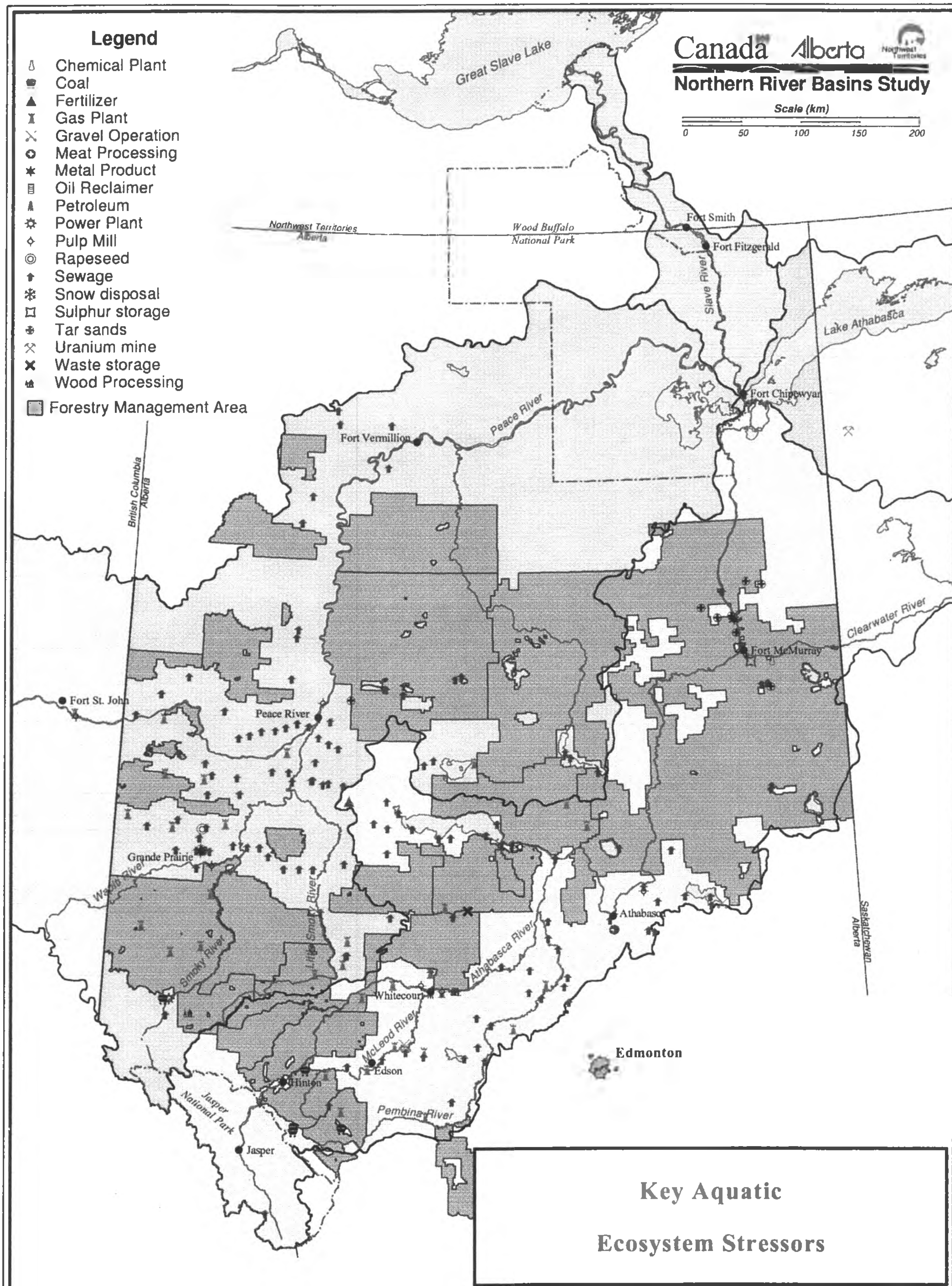
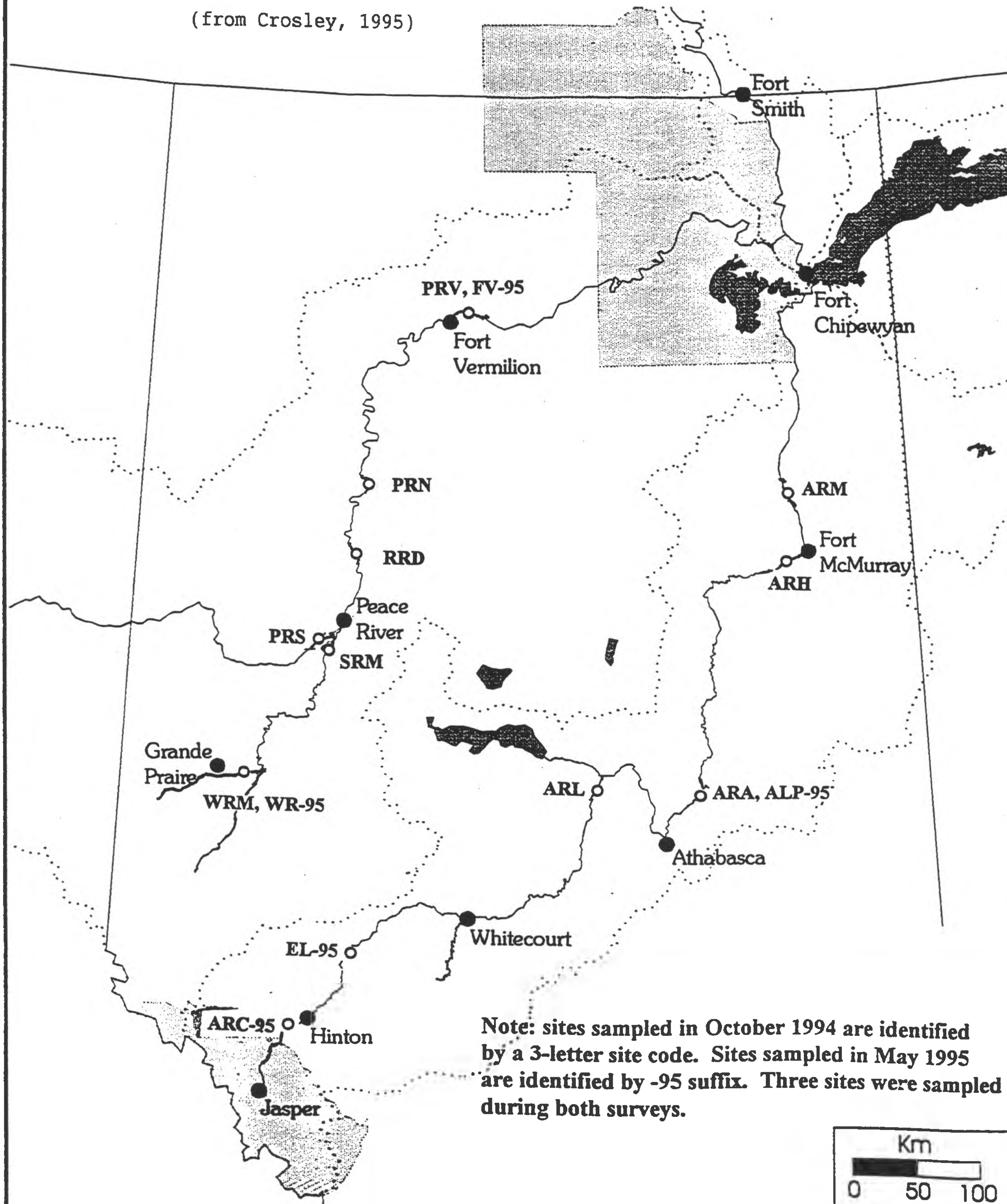

Legend
Chemical Plant
Coal
Fertilizer
Gas Plant
Gravel Operation
Meat Processing
Metal Product
Oil Reclaimer
Petroleum
Power Plant
Pulp Mill
Rapeseed
Sewage
Snow disposal
Sulphur storage
Tar sands
Uranium mine
Waste storage
Wood Processing
Forestry Management Area
Canada
Alberta
Northern River Basins Study
Scale (km)
0 50 100 150 200
Great Slave Lake
Northwest Territories
Alberta
Wood Buffalo National Park
Fort Smith
Fort Fitzgerald
Slave River
Lake Athabasca
Fort Chipewyan
Peace River
Fort Vermillion
British Columbia
Alberta
Clearwater River
Fort McMurray
Fort St. John
Peace River
Grande Prairie
Wapiti River
Smoky River
Little Smoky River
Athabasca River
Athabasca
Saskatchewan
Alberta
Whitecourt
McLeod River
Edson
Edmonton
Hinton
Jasper National Park
Jasper
Pembina River
Key Aquatic
Ecosystem Stressors

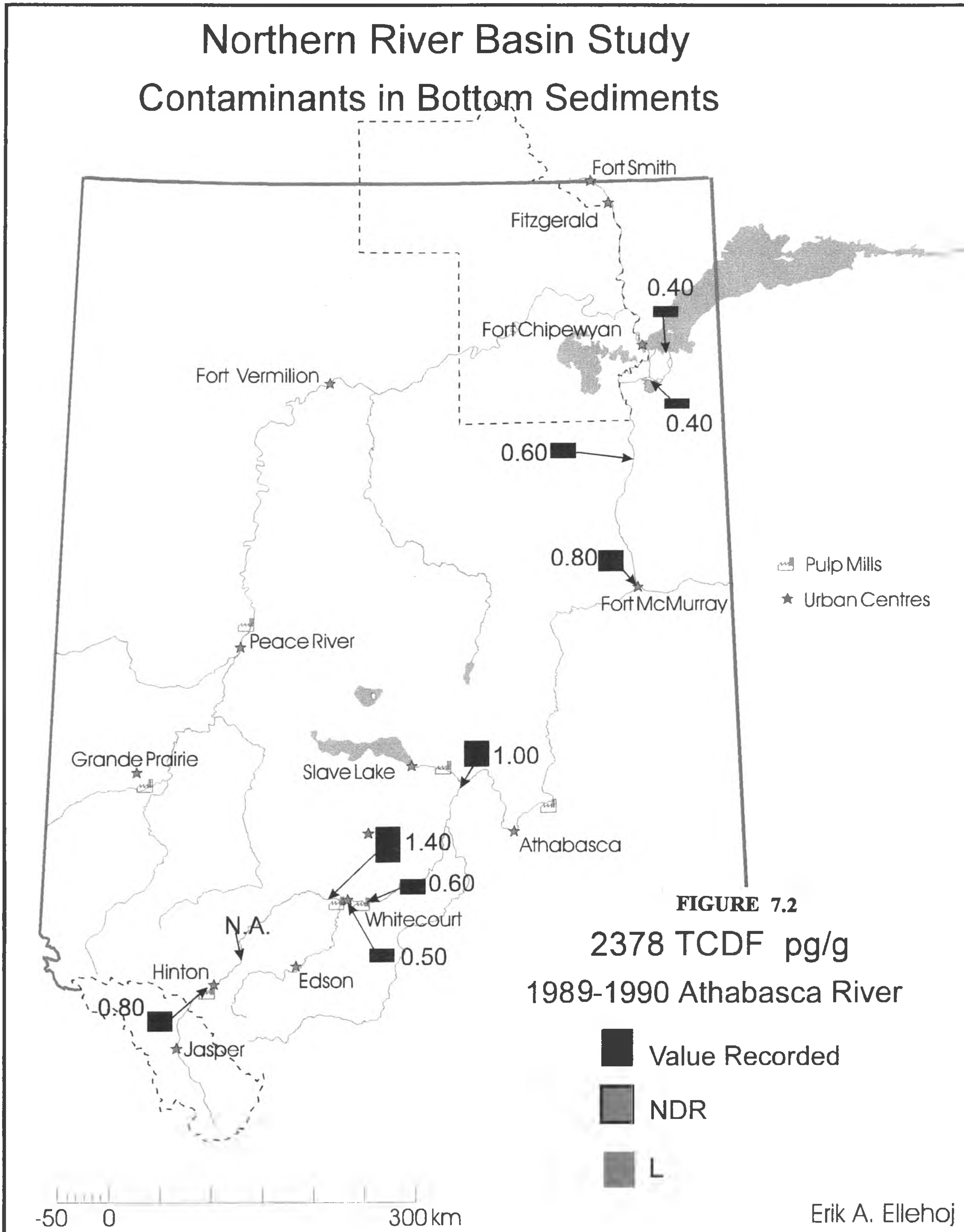
FIGURE 6.1

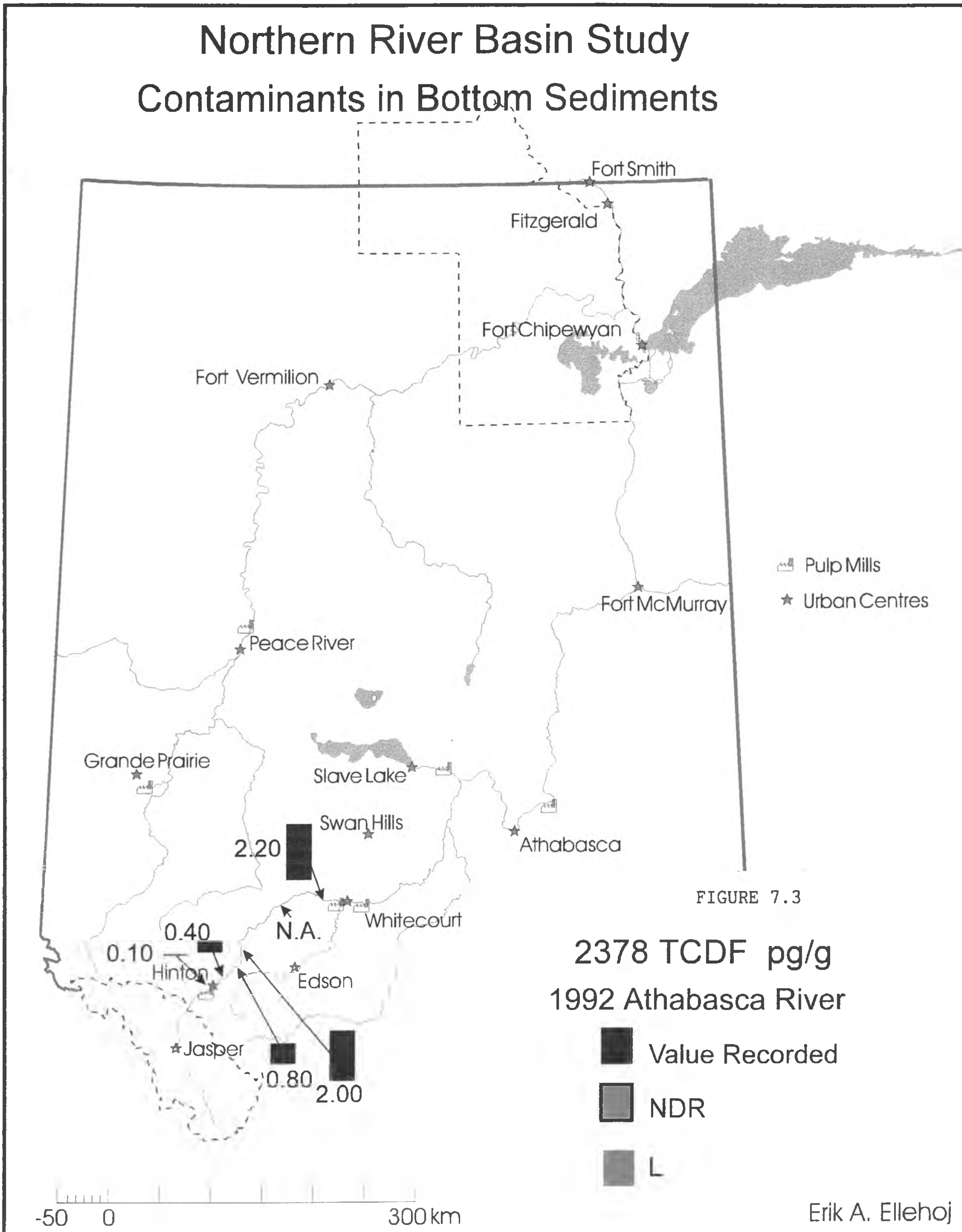
Bottom Sediment Sampling Locations, October 1994 and May 1995

FIGURE 7.1

(from Crosley, 1995)

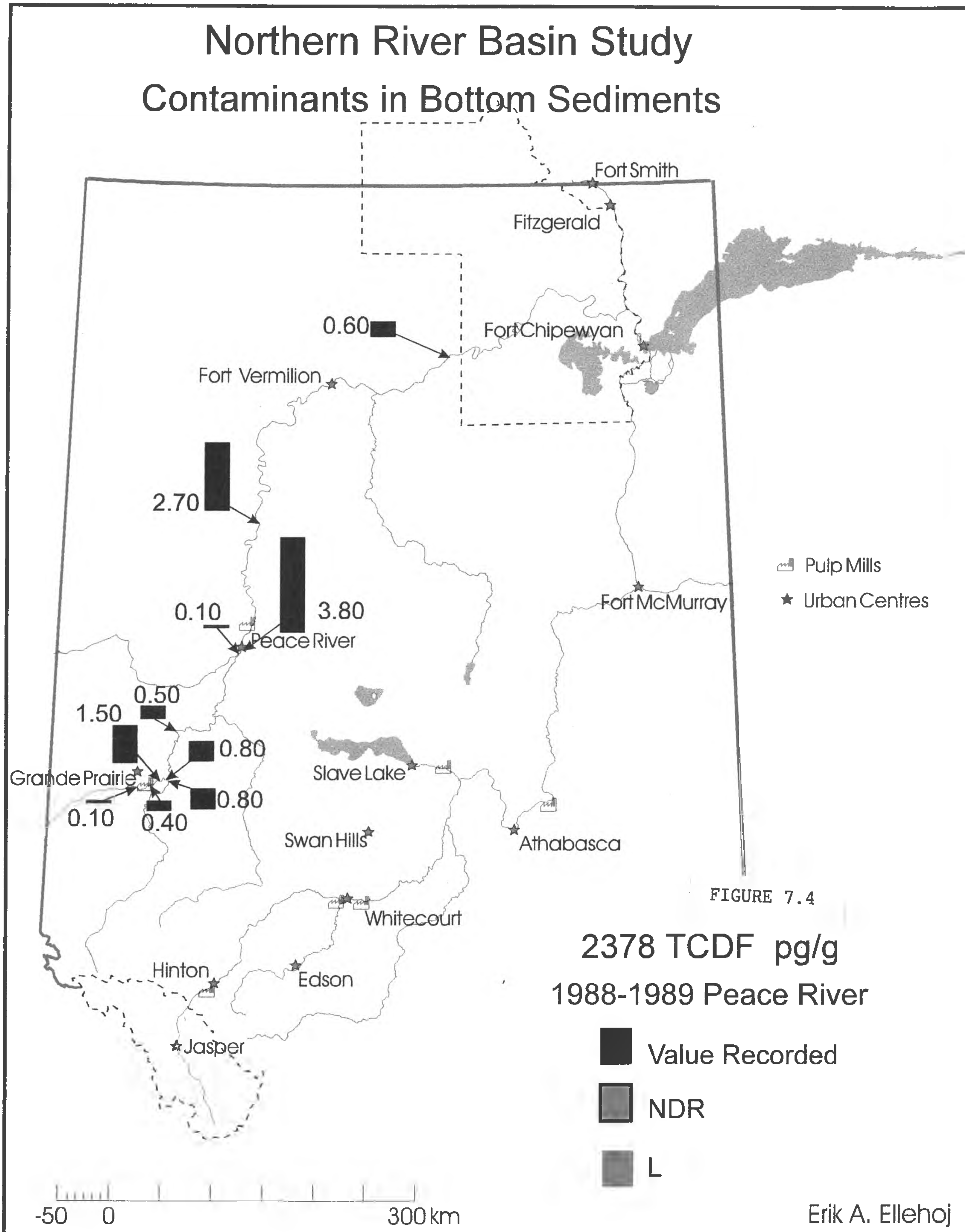



Northern River Basin Study
Contaminants in Bottom Sediments
Fort Smith
Fitzgerald
0.40
Fort Chipewyan
Fort Vermilion
0.40
0.60
0.80
Pulp Mills
Urban Centres
Fort McMurray
Peace River
Grande Prairie
Slave Lake
1.00
Athabasca
1.40
0.60
Whitecourt
N.A.
0.50
Hinton
Edson
0.80
Jasper
FIGURE 7.2
2378 TCDF pg/g
1989-1990 Athabasca River
Value Recorded
NDR
L
-50 0 300 km
Erik A. Ellehoj



Northern River Basin Study
Contaminants in Bottom Sediments
Fort Smith
Fitzgerald
Fort Chipewyan
Fort Vermilion
Pulp Mills
Urban Centres
Fort McMurray
Peace River
Grande Prairie
Slave Lake
Swan Hills
Athabasca
2.20
N.A.
Whitecourt
0.40
0.10
Hinton
Edson
Jasper
0.80
2.00
2378 TCDF pg/g
1992 Athabasca River
Value Recorded
NDR
L
-50 0 300 km
Erik A. Ellehoj

FIGURE 7.3



Northern River Basin Study
Contaminants in Bottom Sediments
Fort Smith
Fitzgerald
0.60
Fort Chipewyan
Fort Vermilion
2.70
0.10
3.80
Peace River
Pulp Mills
Urban Centres
Fort McMurray
0.50
1.50
0.80
Grande Prairie
0.10
0.40
0.80
Slave Lake
Swan Hills
Athabasca
Whitecourt
Hinton
Edson
Jasper
2378 TCDF pg/g
1988-1989 Peace River
Value Recorded
NDR
L
-50 0 300 km
Erik A. Ellehoj

FIGURE 7.4

APPENDIX A: DEPOSITION AND RE-SUSPENSION OF FINE GRAINED SEDIMENTS.

Report by Trillium Engineering and Hydrographics Inc.

Trillium
Engineering and
Hydrographics Inc.

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Edmonton, Alberta
Canada T6E 4T3
Phone: (403) 496-7671
Fax: (403) 463-7185

November 13, 1995

Dr. Henry Hudson
A/Head, Ecosystem Processes
Environment Conservation Branch
Prairie and Northern Region
Environment Canada
500 - 269 Main Street
Winnipeg, Manitoba, R3C 1B2

RE: Deposition and Re-suspension of fine grained sediments.

Dear Dr. Hudson:

As discussed, we have attempted to answer your questions regarding the deposition and re-suspension of fine grained sediments in the Peace-Athabasca River System with the following analysis.

Background

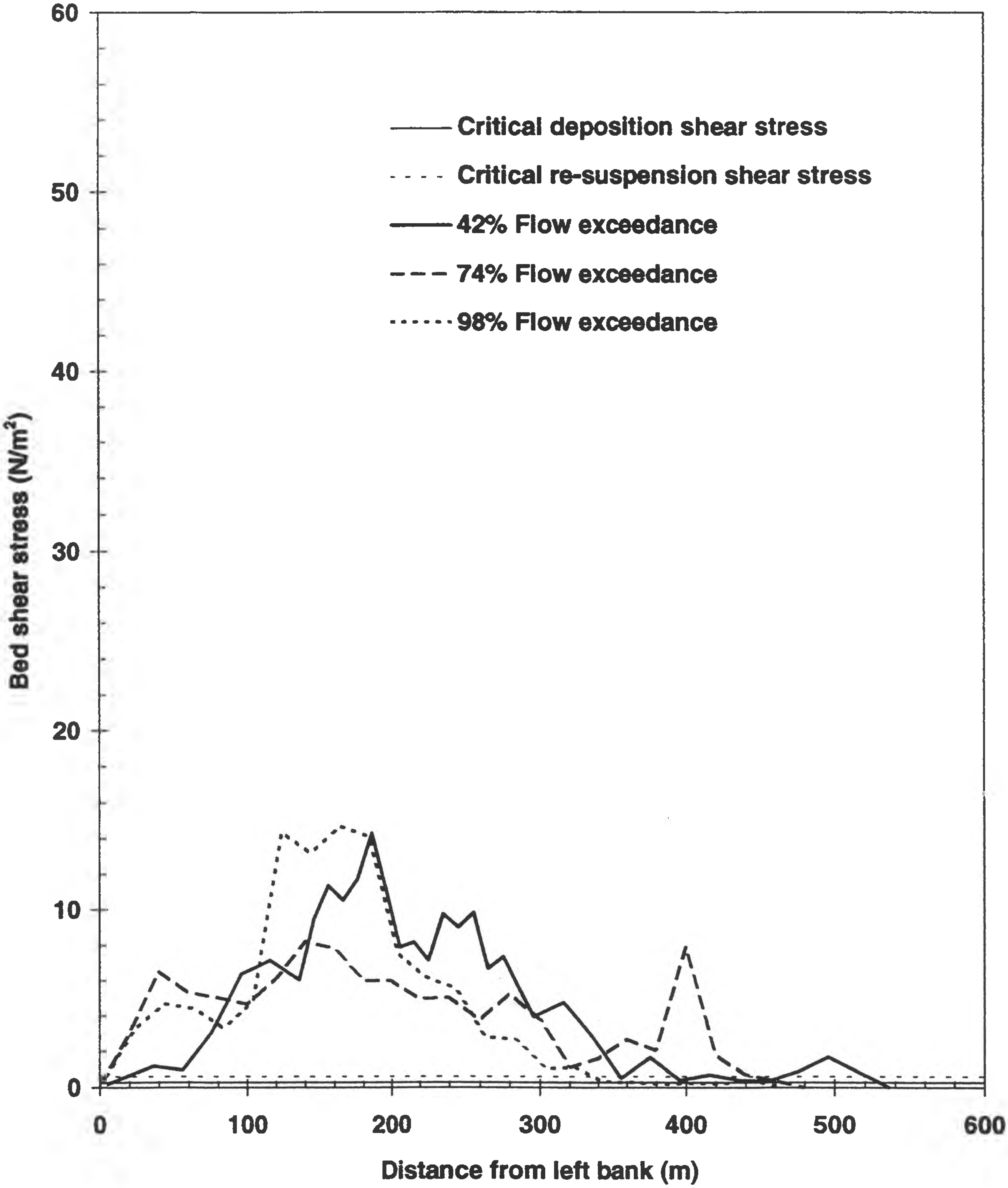
This background material is a summary of some of the information that you provided to us and is included herein for completeness. Krishnappan and Engel (1994) and Lau and Krishnappan (1994) showed that the deposition of fine grained material was related to the bed shear stress. In laboratory studies the critical shear stress below which settlement occurred was found to be 0.056 N/m^2. Due to scale effects which were not explained in your summary, the critical shear stress in a large natural river would be five times larger, or 0.28 N/m^2. The critical shear stress required before re-suspension began was found to be 0.12 N/m^2 in the laboratory and 0.60 N/m^2 in a large natural river.

These critical shear stress values can be used to determine the extent of the deposition and re-suspension zones in a river over a range of flows. However, some knowledge of the spatial and temporal variation of the bed shear stress in the river is required for this analysis. An approximation of the extent of these zones can be obtained by calculating shear stress from depth and velocity measurements recorded at discharge gauging stations. This technique provides data for a range of discharges but only at one cross-section location. The significant channel variability in the longitudinal direction is not captured by this approach.

Site selection

Two discharge gauging sites were selected for this analysis: the Athabasca River at Hinton and the Peace River at Peace River. The Athabasca River at Hinton has been monitored since 1955

Figure 6 Peace River at Peace River - ice cover



while the Peace River at Peace River has been monitored since 1957. Additional sites such as the Athabasca River at Athabasca or the Peace River at Peace Point would also be appropriate for the analysis.

The Hinton gauge data is assumed to be representative of the upper portions of the Athabasca River and is just below a pulp mill which discharges fine grained materials into the river. This river is unregulated so the winter discharges under the ice cover are quite low.

The Peace River site is assumed to represent the middle portions of the Peace River where the Daishowa mill is located. This river has been regulated since 1967 therefore the winter discharges are much higher than they would be under natural conditions. These higher discharges tend to produce a thicker, rougher ice cover as well.

Flow Duration Curves

Daily mean discharges reported by Environment Canada were used to develop flow duration curves for the two gauge sites selected. These curves show the percentage time for which a given discharge is exceeded. The annual, summer, and winter flow duration curves for both sites are shown in Appendix A.

Data from 1961 to 1992 were used to develop the curves at Hinton. The annual curve is shown in Figure 1. The minimum daily mean discharge during this period was 10.8 m^3/s; the median value, 74.5 m^3/s and the maximum value, 1,201 m^3/s. Typical winter flows are between 25 and 40 m^3/s.

Only data from the regulated flow regime from 1971 to 1991 was used to develop the flow duration curves at Peace River. The annual curve is shown in Figures 2. The minimum daily mean discharge during this period was 500 m^3/s; the median value, 1,710 m^3/s and the maximum value, 16,501 m^3/s. Typical winter flows are between 1000 and 2000 m^3/s.

The flow duration data was used to select metering notes for analysis for a range of flow exceedance values during open water and ice covered flow conditions. A list of the selected meter notes is given in Table 1.

Shear Stress Calculations

Local bed shear stress, τ_o is a function of the local flow depth, h and the local energy slope, S. That is

$$\tau_o = \sqrt{\gamma h S} \qquad [1]$$

where γ = 9,806 N/m^3, the unit weight of water. Local depth can be obtained directly from the metering notes but the local energy slope must be determined indirectly from the local velocity

Table 1 Summary of discharge metering notes selected for analysis.

Location	Conditions	Date	Discharge (m^3/s)	Annual Exceedance (%)
Hinton	open water	June 10, 1971	825	1
		July 25, 1991	536	6
		Sept. 12, 1985	178	35
		Mar. 17, 1992	46.8	61
Hinton	ice cover	Dec. 04, 1973	58	53
		Mar. 27, 1973	37.1	74
		Jan. 10, 1973	31.7	85
Peace River	open water	May 29, 1962	6880	1
		May 12, 1982	3130	9
		May 21, 1975	2030	29
		Sept. 23, 1988	1580	60
		Sept. 05, 1975	980	92
Peace River	ice cover	Jan. 08, 1986	1820	42
		Jan. 17, 1980	1360	74
		Jan. 21, 1983	708	98

measurements.

The velocity, **v** is related to the friction factor, **f** as follows

$$v = \sqrt{\frac{8ghS}{f}} \qquad [2]$$

where g = 9.806 m/s^2, the acceleration due to gravity. In turn, **f** is related to the bed roughness height, k_s. The actual form of this relationship is logarithmic but a close approximation is given by

$$f = 0.113\left(\frac{k_s}{h}\right)^{1/3} \qquad [3]$$

The above Equations are summarized by Henderson (1966).

Equations [1] to [3] can be combined to produce the following relationship between local shear stress, velocity, and flow depth

$$\tau_o = 0.0141\,\rho v^2\left(\frac{k_s}{h}\right)^{1/3} \qquad [4]$$

The roughness height was assumed to be constant across the section and therefore was calculated by substituting the mean channel characteristics into Equation [4] for each discharge. This mean roughness height was then input into Equation [4] along with the local values of depth and velocity to determine the local shear stress values. These calculated shear stresses are presented in Figures 3-6 relative to their distance from the left bank of the channels. Calculations for ice-covered conditions were done using the hydraulic radius rather than the flow depth. The hydraulic radius can be approximated as about one-half of the flow depth in most natural channels for the range of winter flow depths and ice conditions experienced at both these sites.

Deposition and Re-suspension Zones

The deposition zone for each of the data sets presented in Figures 3-6 was defined as the percentage of the top width in which the bed shear stress was less than the critical shear stress for deposition of 0.28 N/m^2. The re-suspension zone for each of the data sets was defined as the percentage of the top width in which the bed shear stress was greater than the critical shear stress for re-suspension of 0.60 N/m^2. These percentages are listed in Table 2 and are plotted in Figures 1 and 2 relative to the flow durations for the measurements.

The bed shear stress distributions in Figures 3-6 indicate that deposition would typically occur in a small zone near each of the banks. However, one set of measurements at Hinton under an ice cover indicated a zone of zero shear stress in the centre of the channel. This was caused by the presence of slush ice over the whole depth. Some water would be present in this slush so this may be a deposition zone. This portion is included in the total deposition zone for this site.

Some trends are evident when the sizes of the deposition and re-suspension zones are compared with the flow duration. The size of the deposition zones was found to be greater for the winter discharges. The presence of an ice cover increases the channel variability and thus there should

Table 2 Summary of deposition and re-suspension zones.

Location	Conditions	Annual Exceedance (%)	Winter[1] Exceedance (%)	Deposition zone (% width)	Re-suspension zone (% width)
Hinton	open water	1	-	29.7	70.0
		6	-	0.8	98.4
		35	-	3.4	93.0
		61	-	1.2	97.4
Hinton	ice cover	53	1	39.1	57.1
		74	24	10.3	87.2
		85	53	23.2	62.7
Peace River	open water	1	-	0.0	100.0
		9	-	0.1	99.7
		29	-	1.6	92.8
		60	-	0.6	98.7
		92	-	0.5	99.0
Peace River	ice cover	42	16	2.8	82.0
		74	56	3.7	92.1
		98	95	21.1	71.5

[1] Based on flow duration for January to March.

be more area of low bed shear stress. The data at Hinton also indicates that an increase in the size of the deposition zone also occurs at high flows. This is likely due to over-bank flow. Thus the actual size of this zone is increased as well because the channel is much wider. At Peace River, only the low flow, ice covered conditions had large deposition zones.

Limitations of One-Dimensional Approach

There are some significant limitations to the one-dimensional approach described above. Many locations used for discharge metering are selected at a bridge site for easy access. The bridge sites tend to have constricted sections due to the road embankments. This tends to produce a deeper narrower channel than would occur in other parts of the river. At Peace River, this effect is exacerbated. All the summer discharge measurements have been made at a location where the channel is very deep due to a geomorphic anomaly.

Locations used for discharge metering also tend to be straighter and more uniform that the typical channel so that the gauge rating curves are well behaved. This makes it difficult to extrapolate the data with any confidence because important flow features such as deep pools and back eddies are not represented.

Alternative Approaches

There are some alternative approaches to this problem which would provide a more complete description of the deposition and re-suspension zones but they will take more time and effort to evaluate. Two possible approaches are: using at two-dimensional flow model to evaluate shear stress and using tracer dye measurements to provide an index of the low velocity channel volume.

Two-dimensional flow models are available which can accurately predict local depths, velocities and bed shear stresses, however, the models require considerable detail in bed topography data. It may be feasible to model a short typical reach of river which includes the various flow features and then extrapolate the results to the general river. This would require field measurements of channel topography as well as numerical modelling of the various flows.

Tracer dye measurements may be used as a method of integrating the deposition zone over a larger distance. Our experience with tracer dye tests has indicated to us that the travel time of a dye cloud is typically faster than that predicted from the mean channel hydraulic analysis and that the difference is a function of the volume of channel storage in a river reach. That is, reaches with more channel areas which do not contribute to the main channel flow tend to have higher dye cloud velocities relative to the hydraulic mean velocity calculated from cross-section data. Since this non-contributing area has a low net velocity, much of the area would have low bed shear stress as well. This approach would provide an index for deposition but the actual amount of deposition could not be evaluated unless another technique was used to quantify the actual flow characteristics in the channel relative to this index.

In the Peace River near Peace River, a tracer dye test under the ice cover indicated that the dye cloud velocity was about 40% faster than the hydraulic mean velocity (Van Der Vinne, Neill, and Andres, 1995). This indicates that approximately 30% of the flow width was not contributing to the discharge of 1740 m^3/s (exceeded about 47.5% of the time). Thus, one could say that deposition may occur over 30% of the channel width. The corresponding deposition zone suggested from the metering data at this discharge is only about 3% of the width.

In the Athabasca River at Hinton, however, there was very little difference between the tracer dye velocity and the hydraulic mean velocity (Andres, Van Der Vinne and Trevor, 1989) at a discharge of 31.3 m^3/s (exceeded about 86% of the time). This indicates very little deposition would occur during the winter flow period. On the other hand, the metering data suggests that about 23% of the width can be classified as a deposition area.

The tracer dye data suggests a different deposition area than the discharge metering data at both evaluation sites. This is because the discharge metering sections are not representative, and perhaps the tracer dye data does not accurately reflect the deposition mechanisms of fine grained material.

Summary

Two discharge gauging sites were selected for this analysis: the Athabasca River at Hinton and the Peace River at Peace River. The critical shear stress for the deposition of the particulate in the effluent is 0.28 N/m^2 in a large natural river. The critical shear stress for the re-suspension of that matter is 0.60 N/m^2 in a large natural river. Flow duration curves were used to select metering notes for analysis for a range of flow exceedance value during open water and ice covered flow conditions.

A relationship was developed between bed shear stress, velocity, and flow depth. This relationship was used to calculate local bed shear stress values from measured depths and velocities. Deposition and re-suspension zones were defined as the percentage of the top width in which the bed shear stress was less than or greater than the critical shear stress values.

The bed shear stress distributions indicate that deposition would typically occur in a small zone near each of the banks. The size of the deposition zones was found to be greater for the winter discharges. The data at Hinton also indicates that an increase in the size of the deposition zone also occurs at high flows possibly due to over-bank flow. This does not occur at Peace River.

A limitation to the one-dimensional approach is that many locations used for discharge metering are not representative of important flow features such as deep pools and back eddies. Two possible alternative approaches are: using at two-dimensional flow model to evaluate shear stress and using tracer dye measurements to provide an index of the low velocity channel volume. Two-dimensional flow models are available which can accurately predict local depths, velocities and bed shear stresses, however, the models require considerable detail in bed topography data so they are only practical for short reaches.

Tracer dye measurements may be used as a method of integrating the deposition zone over a larger distance. The velocity of a dye cloud is typically faster than that predicted from the mean channel hydraulic analysis. This difference is a function of the volume of channel storage in a river reach which may also be an index of the deposition area. However, the tracer dye data seems to indicate different amounts of deposition zone than the discharge metering data at both evaluation sites. Thus, the discharge metering sections probably are not representative of the reach or the tracer dye data is not related to deposition of fine grained material.

Yours sincerely,

D. D. Andres, P. Eng.

P.G. Van Der Vinne, P. Eng.

References

Andres, D.D, Van Der Vinne, G. and Trevor, B., 1989. Low flow winter travel time characteristics of the Athabasca River, Hinton to Athabasca. Report No. SWE-89/06, Resource Technologies Department, Alberta Research Council.

Henderson, F.M., 1966. Open channel flow. Macmillian Publishing Co. Inc., New York.

Van Der Vinne, G. Neill, C. and Andres, D.D., 1995. Hydraulic characterization of flows under an ice cover. Proceedings of the Eighth Workshop on the Hydraulics of Ice Covered Rivers, Kamloops, B.C. (in prep.).

Figure 1 Athabasca River at Hinton

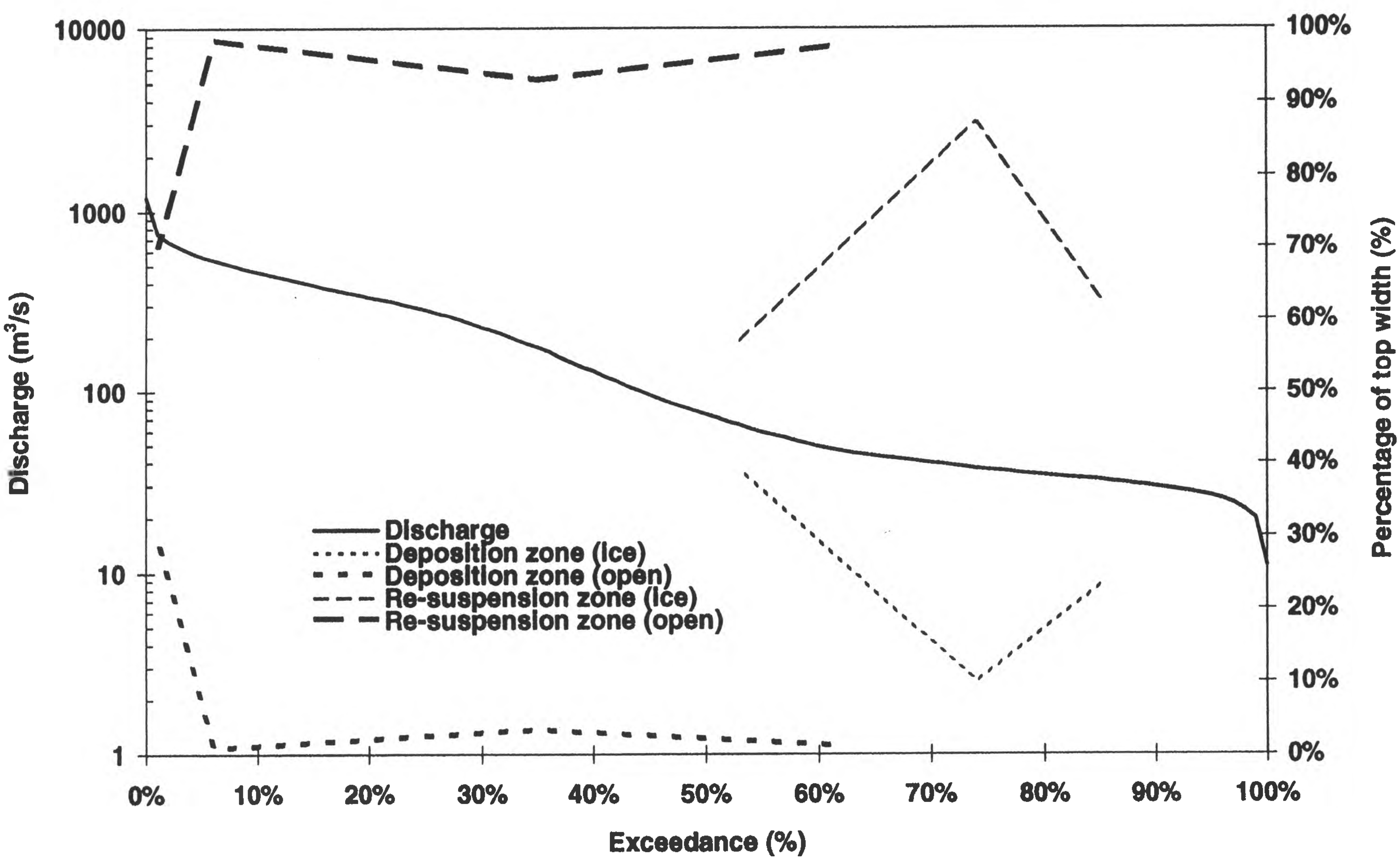


Figure 2 Peace River at Peace River

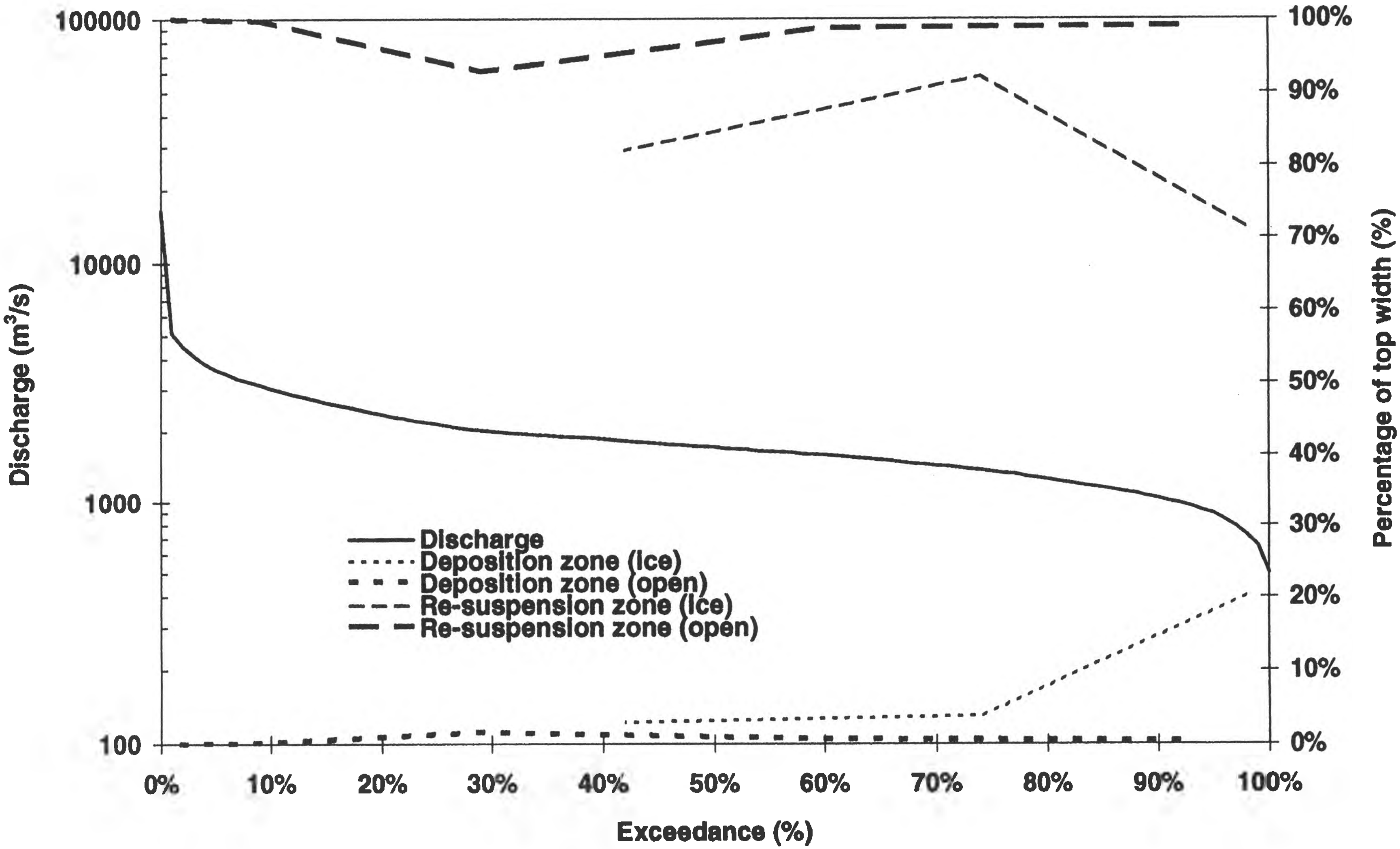


Figure 3 Athabasca River at Hinton - open water

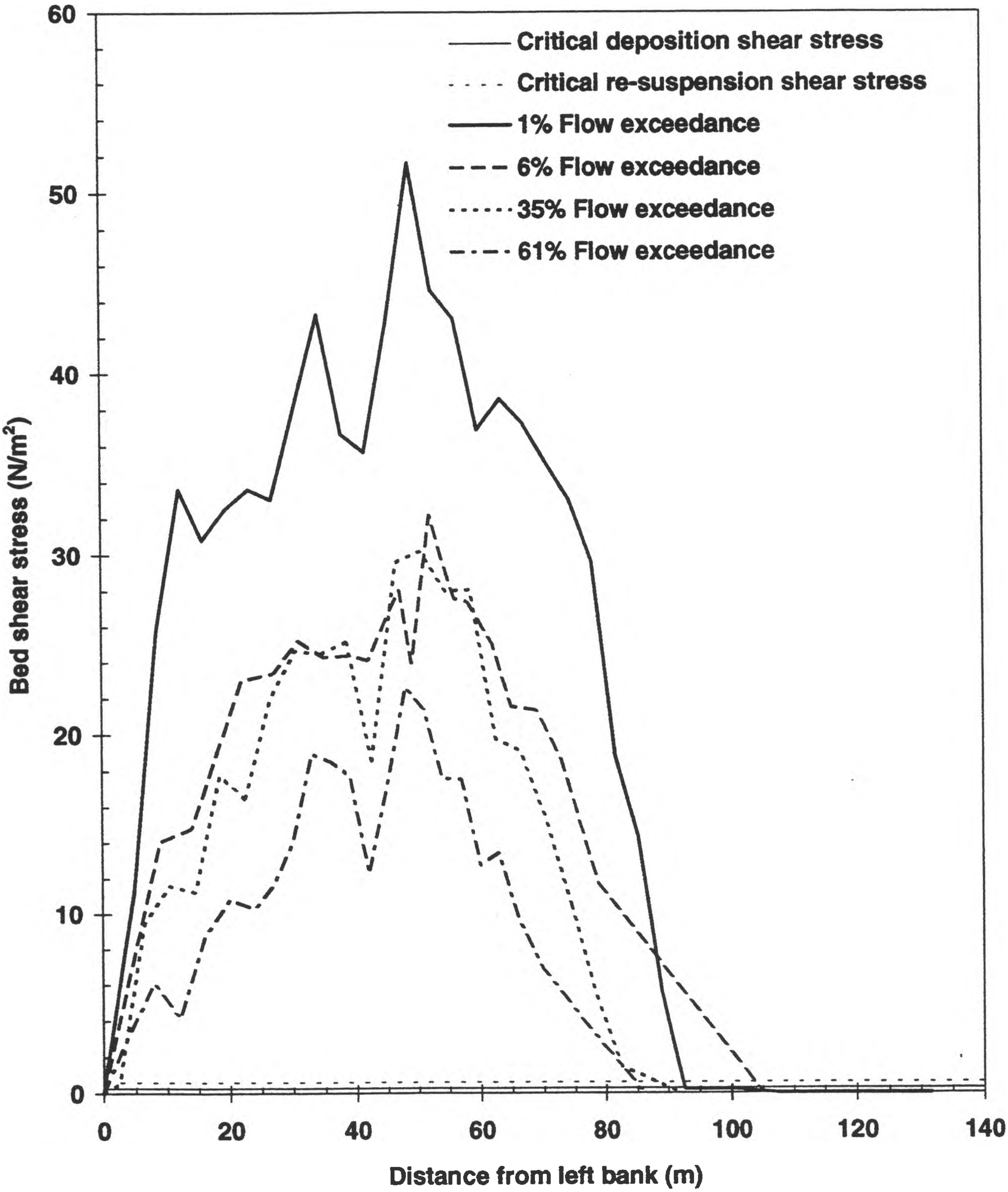


Figure 4 Athabasca River at Hinton - ice cover

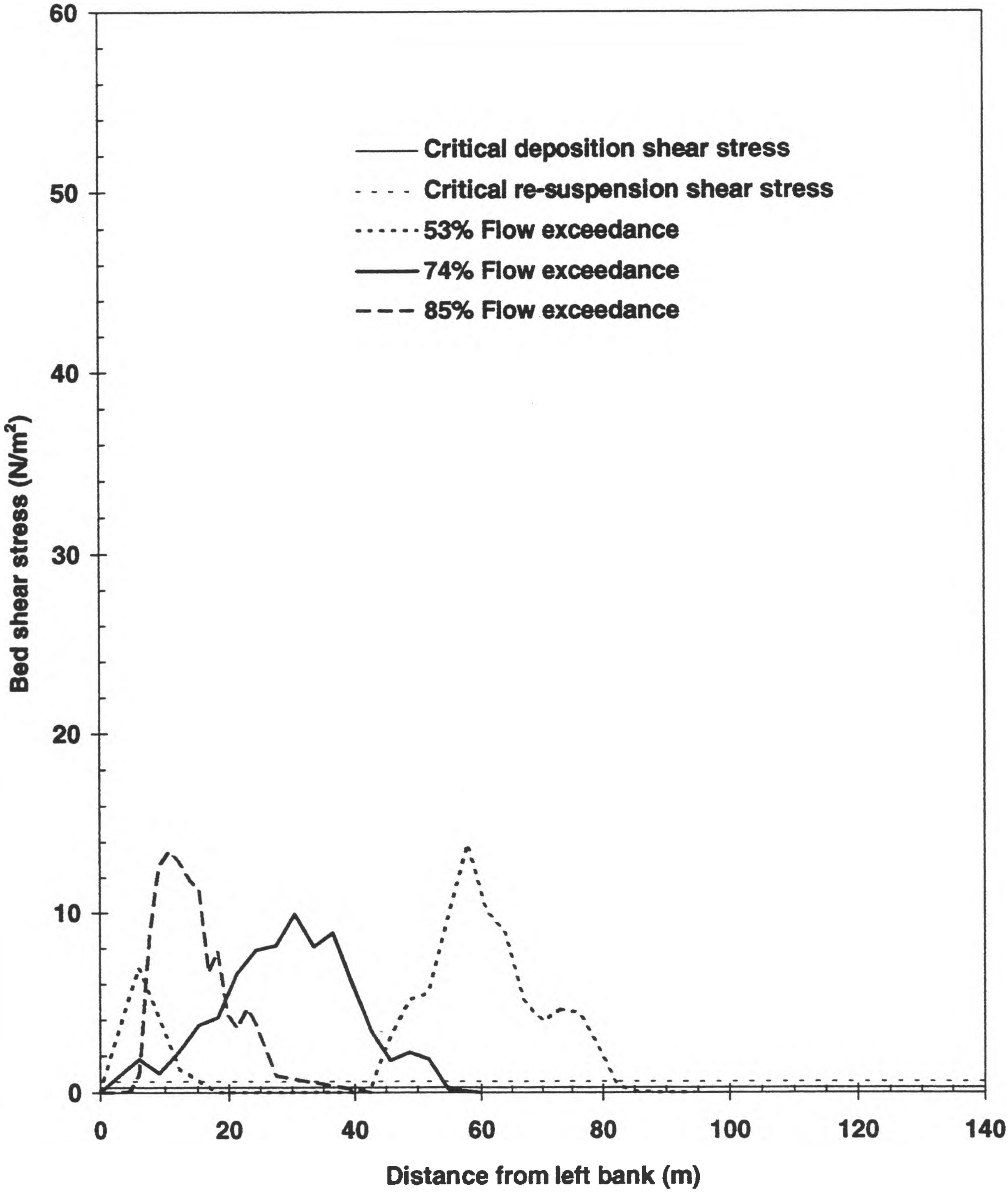
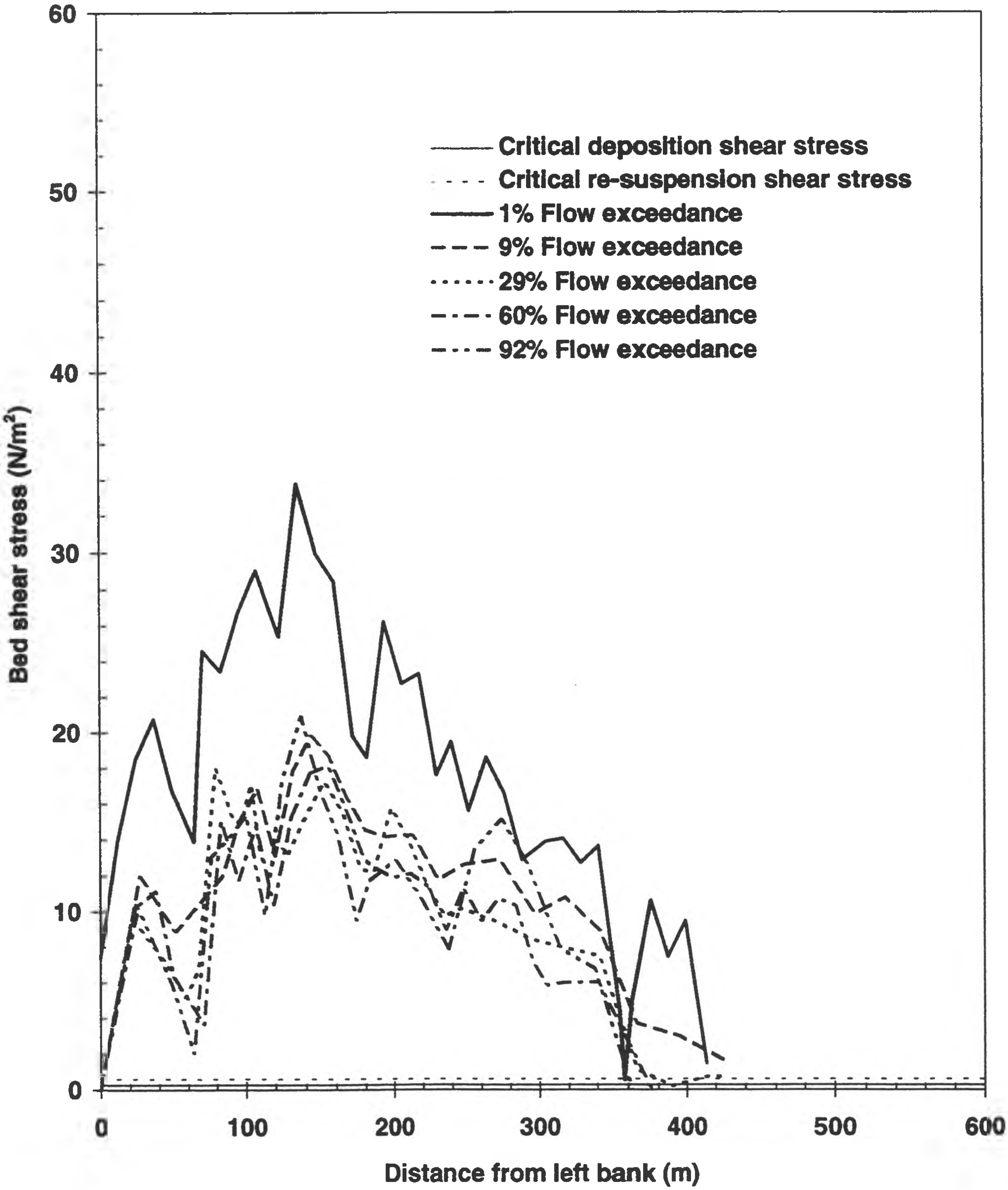


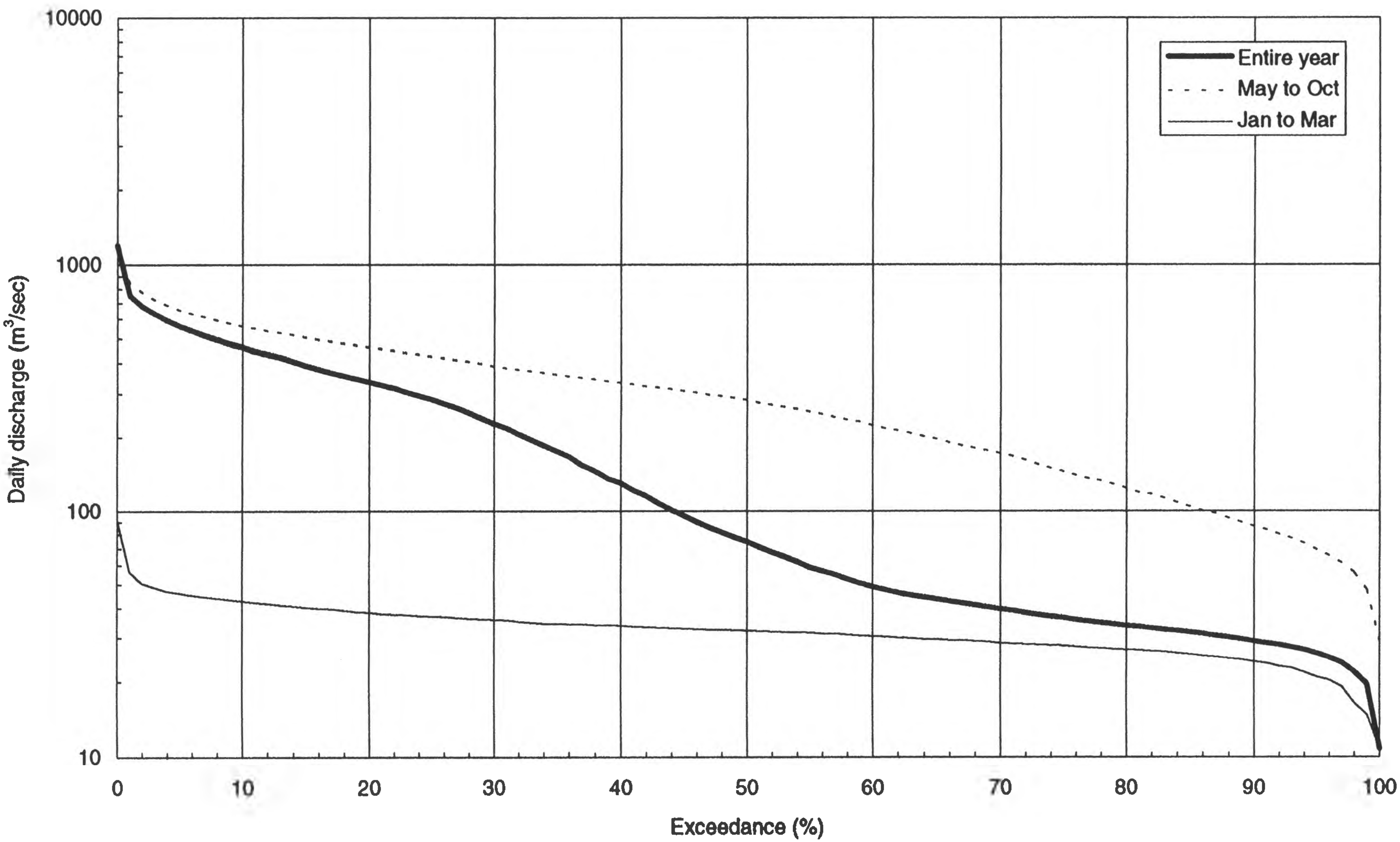
Figure 5 Peace River at Peace River - open water

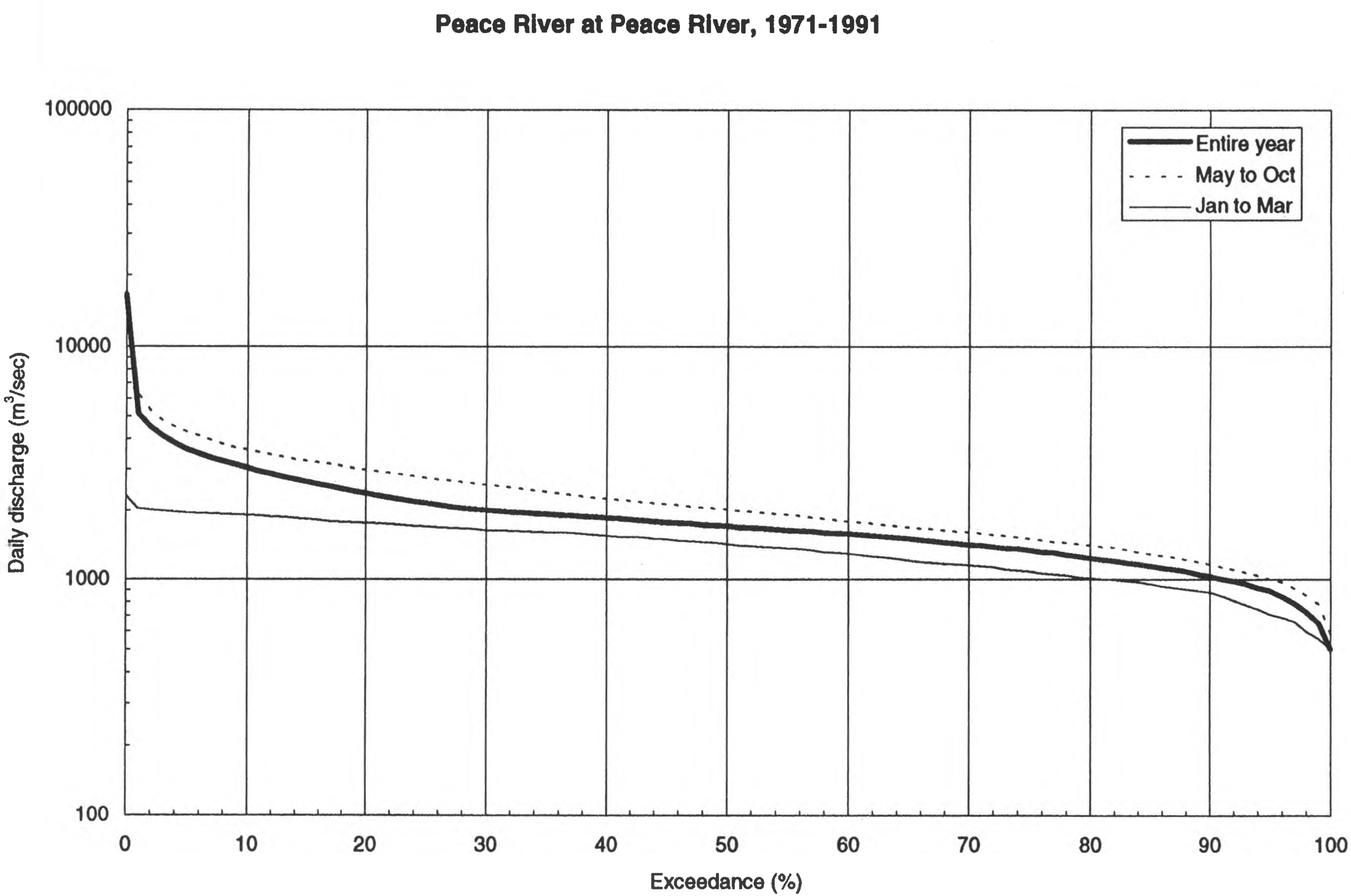


Appendix 1

Annual, summer, and winter flow duration curves

Athabasca River at Hinton, 1961-1992





Peace River at Peace River, 1971-1991
Entire year
May to Oct
Jan to Mar
100000
10000
1000
100
Daily discharge (m3/sec)
0
10
20
30
40
50
60
70
80
90
100
Exceedance (%)

APPENDIX B: TERMS OF REFERENCE

NORTHERN RIVER BASINS STUDY

TERMS OF REFERENCE

Project 5315-E1: Sediment Dynamics and Implications for Sediment-Associated Contaminants in the Peace, Athabasca and Slave River Basins

I. <u>OBJECTIVES</u>

Provision of expert advice and analysis on sediment-associated contaminant dynamics in support of the Northern River Basins Study project on "Sediment Dynamics - Contaminant Implications in the Peace, Athabasca and Slave River System". The consultant is expected to provide written and verbal information and advice, as directed by the Scientific Authority, to the Scientific Authority regarding:

a) sediment budgets of full time sediment stations in the Peace, Athabasca and Slave River system;

b) error analysis in sediment load estimates;

c) sediment sources in the Peace, Athabasca and Slave River system; and

d) implications for monitoring and assessment of pulp mill and hydrocarbon developments on sediment quality in the Peace, Athabasca and Slave River system, implications of pulp mill effluents on sediment quality and monitoring and assessment needs.

II. <u>DELIVERY DATES</u>

Starting Date: September 15, 1995.
Finishing Date: December 15, 1995.

III. <u>SCIENTIFIC AUTHORITY</u>

The Scientific Authority for this project is:

Dr. Henry R. Hudson
Ecological Research Division
Environment Canada
Prairie and Northern Region
Room 300 Park Plaza
2365 Albert Street
Regina, Saskatchewan S4P 4K1

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