F-1

MACKENZIE RIVER, NWT :

SEDIMENT-RELATED ISSUES AND RECOMMENDATIONS

Prepared by:

M. A. Carson
4533 Rithetwood Drive
Victoria, BC, V8X 4J5

December, 1987

Under contract to:

Sediment Survey Section
Water Resources Branch
Inland Waters Directorate
Environment Canada
Ottawa, Ontario, K1A OH3

Water Planning & Management
Inland Waters Directorate
Environment Canada
P.O. Box 2970
Yellowknife, NWT, X1A 2R2

Supply & Services Canada Contract No.
KE144-7-4155/01-SS

MACKENZIE RIVER, NWT :
SEDIMENT-RELATED ISSUES AND RECOMMENDATIONS

Executive Summary

This planning document describes, in some detail, the major issues related to sediment transport along the Mackenzie River downstream of Great Slave Lake. Eleven major issues are identified. These are:

1. the magnitude, timing and spatial pattern of influx of suspended sediment from the river to the Beaufort Sea: these are key factors controlling the offshore sediment plume (and its relationship to marine productivity), rates of infill of pipeline trenches, seabed stability etc.;

2. inputs of suspended sediment to the Mackenzie Delta as this affects the rate of build-up of the Delta surface - a crucial issue in view of fears of future submergence of the Delta with increasingly rapid rates of local sea level rise and possible permafrost degradation due to global warming;

3. the magnitude, timing and spatial pattern of nutrient supply to the Delta and the Beaufort Sea, bearing in mind that much of the nutrient load is bound to the fine grained suspended load of the river;

4. the transport of contaminants (hydrocarbons, heavy metals etc.) to the Delta and the Beaufort Sea, many of which are also moved primarily in association with the fine grained fraction of the suspended load;

5. identification of the main tributary sources of the suspended load of the Mackenzie, so that the impact of land use changes in these tributaries (e.g. damming of the Liard for hydro power) on the inputs of sediment, nutrients and contaminants at the mouth of the Mackenzie can be assessed in advance of the changes;

6. transport rates of bed material along the channel floor of the Mackenzie, partly to enable calculation of inputs to the Delta (and hence allow assessment of the stability of Delta channels in the years ahead), but more generally to provide a scientific basis for answering more specific issues considered next (7-11) that hinge on the rate of transport of bed material in the channel;

7. shoaling of sediment in key reaches of the Mackenzie bed, as it affects navigation, and the need for channel dredging-especially in relation to the increased traffic in the years ahead associated with oil and gas development;

8. the need to acquire a better understanding of the processes of scour and fill of the bed and banks, under ice and breakup conditions, especially in relation to the stability of pipeline crossings of the mainstem;

9. the need to acquire a better understanding of the role of shoals of sandy bed sediment in localizing ice jams during spring breakup, with the goal of eliminating, reducing or at least predicting, flooding associated with such ice jams;

10. the rapid expansion of the artifical islands at Norman Wells by trapping of sediment, and the implications of this for navigation and ice jams in the local area;

11. the environmental consequences of possible extraction of large quantities of granular material from the bed of the Mackenzie, particularly in connection with pipeline construction along the valley axis.

Recommendations are made for future work needed to supplement existing data in order to address the issues raised above. These recommendations may be summarised as follows:

a. an immediate, in-depth, review of the data for the five main sediment stations on the lower Mackenzie system, to establish whether or not sufficient data exist to develop numerical models for the prediction of suspended sediment loads, broken down by particle size and timing, at these sites from routinely collected hydraulic data such as discharge, water temperature etc.; this will enable decisions to be taken as to whether routine sampling can be terminated at these stations, allowing redeployment of resources elsewhere;

b. a similar analysis of annual loads of bed material sediment in key reaches of the river by analysis of bathymetric charts in areas where repeat surveys have been undertaken by the Canadian Hydrographic Service;

c. following (b), resurveys of key reaches of the river to allow updating of data to the 1980's, and to rectify gaps in the data file;

d. following (a), addition of new sediment stations to the Mackenzie network allowing routine monitoring of suspended material in key reaches: Wrigley, Norman Wells and Fort Good Hope, and at the mouths of the three main Delta channels;

e. following (d), once the sediment regime at these new stations has been established, expansion of the programme at these sites to include nutrients, hydrocarbons and heavy metals;

f. an increase in basic research into ice-jamming in relation to shoaling and into the effects of an ice cover on bed scour.

Above all, an agency should be established to ensure full coordination of sediment and water-related issues in the Mackenzie basin downstream of Great Slave Lake.

CONTENTS

Page

INTRODUCTION

This draft planning document has been prepared as part of a broader investigation into problems relating to the source, transfer and fate of sediment along the Mackenzie River, NWT, between Great Slave Lake and Point Separation, scheduled for completion by March 1988.

The present document is a summary of the issues identified in that investigation and the recommendations prompted by the work. The terms of the contract required presentation of this planning document well before completion of the major study. As such, it must be regarded as a draft statement which is liable to possible change in the light of subsequent work in the main investigation.

Preparation of this planning document has been assisted considerably by discussion and correspondence with numerous individuals. Acknowledgements are due, in particular, to Terry Day and Jack Wedel of the Inland Waters Directorate and to:

Applied Ecology Consultants, Vancouver, BC: Stan Hirst
Atlantic Geosciences Centre, Dartmouth, NS: Phil Hill
BC Hydro, Vancouver, BC: Ed MacDonald
Canadian Coast Guard, Vancouver, BC: E.O. Isfeld
Canadian Coast Guard, Victoria, BC: Terry Webber
Canadian Coast Guard, Hay River, NWT: E. Kruggel
Canadian Hydrographic Service, Sidney, BC: Tony O'Connor; Barry Lusk; R.W. Sandilands; Graham Richardson
C.P. Lewis & Associates, Victoria: Peter Lewis
Dept. of Fisheries and Oceans, Winnepeg, Man.: Gregg Brunskill
Gulf Canada Resources Ltd, Calgary: David Townsend
Indian & Northern Affairs, Ottawa: Martin Barnett; Jon Moen; Fred McFarland; David Robinson; Ian Sneddon; David Stone
Inland Waters Directorate, Ottawa: Morley Cashman
Inland Waters Directorate, Yellowknife: Brian Olding, Monika Holenstein
Indian & Northern Affairs, Yellowknife, NWT: J.N. Jasper: David Sherstone
Institute of Ocean Sciences, Sidney, BC: Rob Macdonald; Ed Carmack; Mark Yunker
M. J. Miles & Associates, Victoria, BC: Mike Miles
National Hydrology Research Institute, Saskatoon, Sask.: Terry Prowse; Phillip Marsh; John Tisdale
Northern Transportation Company Ltd, Edmonton: Asbjorn Woldmo
NWT Public Works & Highways, Yellowknife: D.A. Buchan
NWT Renewable Resources, Yellowknife: Lorne James
Polar Gas, Toronto: O. M. Kaustinen
Public Works Canada, Edmonton, Alta.: R.C. Smith

PART I: ISSUES

Examination of the literature, together with contact with various individuals and agencies, indicates several sediment-related issues, which are itemized below. As might be expected, there is often a fair degree of interaction among these topics, and they should not, therefore, be considered completely in isolation.

1. Input of suspended sediment to the Beaufort Sea.

This topic is of interest to numerous agencies for different reasons, not only in terms of the mass of wash load, but also the chemistry of material that is adsorbed on it. The latter is treated below as separate issues. Strictly speaking, the sedimentary environments of the Delta and inputs to the Beaufort Sea fall beyond the geographic terms of reference of this contract. They have already been treated by Lewis (1987, in prep.). Nonetheless it is worth highlighting work in the Beaufort Sea as it relates to sediment transport by the Mackenzie River.

The Atlantic Geoscience Centre of the Geological Survey of Canada is engaged in a sediment budget for the Beaufort Sea shelf in which the annual input of suspended material by the Mackenzie, at its mouths, is a key component. That study also requires a clear indication of the spatial character of the input, among the different distributary channels, preferably broken down by particle size and by timing.

The Institute of Ocean Sciences of the Department of Fisheries and Oceans (DFO) is involved in two Beaufort Sea projects that are related to the flux of suspended sediment from the Mackenzie. One is concerned with the input of hydrocarbons; the other deals with the input of nutrients as this relates to primary productivity in the shelf area. Both hydrocarbons and nutrients are moved down the Mackenzie and into the sea primarily through adsorption to fine sediment in suspension. These two topics are dealt with separately below.

More generally, the Institute is interested in the magnitude, timing, spatial pattern and grain size breakdown of suspended sediment itself introduced to the Beaufort Sea by the Mackenzie. The plume of suspended sediment, for example, affects primary productivity through its control on light transmission into sea water. In terms of offshore oil development, the affinity of fine sediment for hydrocarbons suggests that Mackenzie wash load may play a major role in transporting the products of oil spillage in the shelf i.e. Mackenzie wash load may act as a partial natural cleanser in relation to chronic offshore oil spills.

Personnel at both of these centres also emphasize one further point: the sediment input of the Mackenzie-Peel rivers will always be of major concern to studies of the estuarine area, and it is essential that a long-term record be built up, not merely to establish accurate long-term averages, but also for monitoring annual variances, cycles and long-term trends.

2. Input of suspended sediment to the Mackenzie Delta.

A substantial portion of the sediment input to the delta originates from the Peel River. Again, while this is beyond the original terms of reference, it will be treated in this study, for the sake of completeness.

A second Atlantic Geoscience Centre project relates to annual accumulation of sediment on the Delta and particularly its spatial pattern. The Delta is at present in a very delicate state of balance in terms of the aerial extent that is not submerged. This balance is controlled by the pattern of sediment input, the direction and rates of sea-level change, the pattern of coastal erosion, and rates of permafrost aggradation or degradation in the Delta. Expectations of continued local sea-level increase in the next century lead to expectations of shrinkage in delta area. The pattern of this change will depend not only on present delta topography, but also the pattern of present rates of aggradation on the subaerial and submerged parts of the delta. At present there is a wide range of opinion as to the proportion of the Mackenzie-Peel sediment that is trapped on the Delta and the proportion that actually reaches the sea.

The spatial pattern of sediment accumulation on the Delta has also been of major interest to British Columbia Hydro and Power Authority, arising from possible effects on delta environments of hydroelectric development on the Liard River. The topic is discussed by Lewis (1987, in prep.).

3. <u>Transport of nutrients adsorbed to wash load down the Mackenzie and into the Delta and Beaufort Sea</u>.

Nutrient movement in the Mackenzie is related to sediment transport because most of it takes place adsorbed to fine sediment. Nutrient availability is not an "issue" as such, at present, but information regarding the amounts, type and timing of nutrient supply by the Mackenzie is crucial to understanding the pattern of primary productivity in the Beaufort Sea, and how it might be disturbed by offshore oil exploration. It is therefore a definite topic of interest to the Institute of Ocean Sciences. To a lesser extent, the input of sediment-bound nutrients to delta ecosystems has been of interest to BC Hydro in connection with proposals to dam the Liard River for hydro-electric power.

4. <u>Transport of contaminants adsorbed to wash load down the Mackenzie and into the Delta and Beaufort Sea</u>.

This general topic is also of interest to the Institute of Ocean Sciences as it affects the Beaufort Sea, as well as to many other agencies concerned with aquatic life in the Mackenzie Delta and the river itself.

The major contaminant of interest, but not the only one, is hydrocarbon material. The Institute of Ocean Sciences is studying present day movement of hydrocarbons into and through the shelf area in the belief that, by understanding these processes, it will be better able to predict the fate of spilled hydrocarbon material following oil development on the shelf. The magnitude, routing and timing of Mackenzie inputs of hydrocarbons are therefore necessary information for their work. The Water Quality Branch of the Inland Waters Directorate (Environment Canada) and the Northern Environment Directorate of Indian & Northern Affairs Canada (INAC) also want to know more about background levels of hydrocarbons in the river and the Beaufort Sea. Both agencies are also interested in the input of adsorbed metals from the Mackenzie River.

Movement of hydrocarbons within the mainstem Mackenzie is also an issue to the extent that it may be related to impaired fish quality as reported by local fisheries on the lower river. Preliminary results from DFO research at Fort Good Hope are reported to indicate substantially greater hydrocarbon concentration in winter under an ice cover that inhibits evaporation of the more volatile fractions. If this also applies to hydrocarbons adsorbed to the wash load, it may indicate that a reconsideration of winter sampling of suspended sediment is warranted, even though <u>sediment</u> loads are minimal at this time of the year.

In the longer term, it seems advisable to establish current background levels of hydrocarbons in the river, and to identify their sources, in order that the magnitude of pollution associated with natural seepages at Norman Wells and future inland oil development can be established unequivocally.

Staff at INAC have also raised questions concerning contaminants adsorbed to sediment entering the mainstem from Great Slave Lake and further upstream.

5. Sources of wash load in the Mackenzie Basin.

The importance of wash load inputs to the delta at Point Separation, and beyond to the sea, has already been noted. Short term prediction of inputs may be possible solely on the basis of statistical relationships between concentration and water discharge, time of year, temperature etc. at stations near the input sites on the Mackenzie, Arctic Red and Peel Rivers. Such relationships are unlikely to remain stable over a long period of time because of changes in supply rates from the source areas due to changes in environmental conditions. For this reason, and in order to assess the impact of changes in the source areas, it is desirable to have a clear picture of the proportion of the downstream wash load originating in different subbasins.

One obvious example of this is the need to be able to accurately predict the reduction in wash load input to the Delta that would result from damming of the Liard. A less obvious point would be the magnitude of wash load increase in the event of permafrost degradation (due to CO_2 warming of the atmosphere) and the resultant increase in bank slumping along the Mackenzie main stem. Another is the impact of forest fires on thaw of ground ice and increased delivery of fine sediment to rivers from gullying and bank collapse. A further one is the recently announced proposal for increased logging in the Liard basin.

Moreover, in any attempt to understand changes in concentration of adsorbed materials, whether over time or spatially, a breakdown of the total into its component supply areas is needed.

6. Transportation of bed material along the Mackenzie River.

Most discussion of sediment input to the Delta has concerned suspended sediment which is assumed to be largely wash load. The fate of bed material brought in by the Mackenzie at Point Separation seems to have been largely ignored. Yet in terms of shoreline stability along the Delta margins and in terms of depth of flow along distributary channels, the magnitude and spatial pattern of sand movement through the delta need to be known.

Work at the National Hydrology Research Institute (Lapointe, 1984, 1986) has already identified several such issues here. One concerns the existence of deep "scour" holes maintained by the failure of sediment to accumulate on the bed at such sites. Another concerns the abandonment of distributary channels by shoaling of bed sediment at the site of bifurcation from the main channel. The entry area to the East Channel is heavily shoaled, raising the question of the future of this distributary. Interestingly, the Northern Transportation Company Limited has recently designated Kitti Channel at the East Channel entrance to Kittigazuit Bay (km 1715-1722) as the thirteenth in a list of 26 priority dredging sites on the Mackenzie River.

More generally, the question must be asked: How quickly are the distributary mouths, e.g. Shallow Bay, Kittigazuit Bay, being infilled? Most data on sedimentation have been offshore beyond the 10 m bathymetric contour. Very little seems to be known about how much sand moves downstream past Point Separation and how much reaches the distributary mouths.

In addition to bed material inputs to the Mackenzie Delta, the sources of this sediment load also need to be determined.

Even more important in the context of the bed material load than for the wash load, there is the question of how uniform are transport rates along the course of the river. Are there distinct areas of degradation and aggradation? Do tributary loads have well-defined local sinks near the confluence with the main stem, or do they become incorporated in the general load of the Mackenzie? These are general scientific questions that need to be answered in order to understand the overall behaviour of the Mackenzie River. The topic also provides a necessary framework for answering more immediate specific questions related to bed material transport noted next.

7. <u>Navigation problems on the Mackenzie and the feasibility of dredging at problem sites</u>.

Certain sites on the Mackenzie already present problems to barge traffic and limit the annual freight volume. Though traffic is estimated to decrease to 1990 due to a decrease in oil exploration work in the Delta and Beaufort Sea areas, an increase of more than 50% is expected by 1994 due to start of construction associated with oil development, and almost 300% by 1998 at the time of natural gas related construction. After these peaks, traffic is expected to drop back to levels that are still 50% higher than today (Acres, 1987).

Most of the problem areas on the Mackenzie are not related to bed material accumulation; they are generally in "rapids" areas, primarily upstream of Fort Simpson. There are, however, exceptions to this statement. Dredges operated by Public Works Canada have removed, on average, slightly more than 40,000 cubic metres of bed sediment per year over the last 23 years during routine maintenance dredging of some problem sites. The estimated cost of maintenance dredging in the years ahead is in the region of $1 million to $4 million, but is uncertain due to the difficulty of predicting rates of infill. Acres (1987), at the conclusion of their report, emphasized that "as information on existing bed loads is virtually non-existent, a survey should be undertaken to provide a basis for determining potential infill rates at the twenty-six priority dredging sites".

Equally important is the need to have some understanding of the sediment transporting processes at local problem areas where sand shoaling is severe or where rapid change in the navigation channel is likely. From a different standpoint, the effect on fish of increased wash load concentrations, and associated contaminants, that would temporarily result from such dredging has been raised as an issue by Indian and Northern Affairs.

8. Magnitude of scour and fill in the sand bed reaches.

This looms as a rather significant concern at specific sites that may be proposed for pipeline crossings. Church (1971), in a report for Mackenzie Valley Pipe Line Research Ltd emphasized the need for observations on seasonal scour and fill, and, in particular, the possibility of increased bed scour under winter ice at times of increased discharge.

9. Shoaling as a control on the location of ice jamming.

Work by NHRI has recently indicated a possible relationship between sites of shoals and locations of the river particularly liable to ice jams during spring breakup. Mackay and Mackay (1973) presented data that implied a similar relationship. Ice jams constitute an issue of some importance on the river. Severe flooding at Fort Simpson in 1963 and 1972, and at Fort Norman in 1964 and 1972, resulted from ice jams. A better understanding of the role played by shoals in this process may not be sufficient to prevent ice jams, but would lead to improved prediction of such events.

10. Enlargement of artificial islands at Norman Wells.

Several scientists at Indian and Northern Affairs Canada commented upon this as a possible, though somewhat poorly defined, environmental concern. It would certainly seem that some assessment of what is going on would be in order, not only in relation to #7 and #9 above, but in the more general context of understanding bed load movement processes in this part of the Mackenzie. Islands play a major role in bed material transport, often trapping sand at the upstream end and sometimes losing it at the downstream end. Any island which is protected from bank scour may thus be anticipated to enlarge and become a trap for bed sediment (as well as suspended sediment) from upstream.

11. Exploitation of sand and gravel resources.

Indian and Northern Affairs in Ottawa raised this issue in terms of potential environmental consequences. Whether or not it is serious will depend upon volumes involved, rates of extraction and sites.

Granular borrow material will be needed in large amounts along the Mackenzie corridor. EBA (1980), for example, calculated that 11.1 million cubic metres would be needed just for the Canadian Arctic Gas Pipeline Limited proposal between Jean Marie River (km 270) and Thunder River (km 1300). This is almost twenty times the annual bed material yield of the Mackenzie at Norman Wells computed by Church et al. (1986) for 1950-1971, although the EBA figure may be an overestimate based on current technology.

A report by EBA (1987) indicates that about two-thirds of the Mackenzie Valley lacks suitable granular material for construction purposes within 15 km of the riverbank. This is particularly true of the first 500 km to about McGern Island. It is also reported for km 750-875 (Keele River almost as far as

Norman Wells), km 1000-1100 (Axel Island to Fort Good Hope) and km 1325-1475 (upriver of Barrel Crossing to Point Separation).

The same report indicates a high potential for granular borrow material from 22% of the Mackenzie river bed, based on a rating system in which channel braiding, steep river gradients and proximity of gravel-bed tributaries were seen as indicators of suitable granular alluvium. Costs of utilizing this material indicated that river operations would be more economical than land exploitation where hauls of greater than 7 km were involved. EBA (1987) also review the environmental implications of such extraction.

It is worth emphasising that the notion of utilizing Mackenzie riverbed sediment as a source of borrow material was bolstered by the success of Esso Resources Canada Ltd in dredging bed sediment at Norman Wells for the construction of artificial islands. EBA (1987) notes that, while preliminary sampling had suggested that the river bed there was silty sand, most of the dredged fill, in fact, turned out to be sandy gravel.

PART II : RECOMMENDATIONS

Recommendations for future work should only be provided after a careful statement of the issues and a review of available information that pertains to these issues. A literature review will be provided in the final report dealing with this project. A summary of the major issues has been provided in Part I, but in some cases additional discussion is needed here to establish the proper perspective for planning purposes. Readers who simply wish to peruse the recommendations will find these highlighted in boxes. A summary of the recommendations is provided at the end of Part II.

SUSPENDED SEDIMENT

1. SUSPENDED SEDIMENT INPUT TO THE BEAUFORT SEA

Comprehensive recommendations for addressing this topic fall beyond the mandate of this document. To some extent, the issues have been examined by Lewis (1987) in a related planning document concerning the Mackenzie Delta. He emphasizes the following points, most of which include suspended sediment, that need further research:

a. examination of the Delta stratigraphy through a programme of borehole coring;
b. assessment of the controls on the character, amount, timing and spatial variation of sediment transport in the Delta distributaries;
c. evaluation of the factors controlling channel mouth, and inter-channel, delta front sedimentary environments;
d. examination of the scale and pattern of instability of the Delta distributary channels;
e. determination of the character, amount, distribution and timing of annual sediment deposition on the Delta surface.

The specific task of determining the amount, type, distribution and timing of suspended sediment fluxes to the Beaufort Sea (the term is used here to include the estuarine area) is closely identified with that of (b) above. The comments below are intended to supplement those of Lewis (1987).

The complexity of the distributary network renders monitoring of the suspended sediment flux to the Beaufort Sea a formidable logistical operation. Nonetheless, it is simplified by the dominance of three major channels.

Recommendation 1. Suspended sediment sampling be undertaken, over a period of at least three years, at strategic points on Reindeer Channel, East Channel and Middle Channel for the purpose of determining the combined suspended sediment input to the Beaufort Sea, together with its change through the ice-free season, and the variation in load and particle size during the year between the distributaries.

Assessment of results would be required after about three years in order to determine the stability of this partition among the three distributaries as well as the percentage of the sediment inflow to the Delta that actually reaches the Sea. Depending on the results, and on the hydrological character of the three years, a longer programme may be needed.

Suitable sites would be those used by Davies (1975): No. 15 downstream from the entrance of Reindeer Channel; No. 17 on East Channel downstream from Neklek Channel; and a new site on Middle Channel upstream of No. 20, prior to the loss of flows down the unnamed channels gauged by Davies at No. 18 and 19. This new site could be at Station 106 marked on the Hydrology Information Series 1:250,000 Sheet 107C (Inland Waters Directorate, 1985).

Given the interest in this topic of other agencies already noted, it would seem logical to plan a comprehensive programme with the overheads shared among the relevant parties. This would allow frequent sampling of the suspended sediment, with sufficiently large volumes to permit not merely determination of sediment concentration, but also particle size analysis, and possibly analyses of nutrients and some contaminants. Further discussion of this is deferred until points #3 and #4. Shared funding could permit a basic in-field laboratory near all three sites, allowing filtration in the field, and thus reducing the volume of water needed moved to the main laboratories.

In addition to monitoring stage and water discharge, water temperature should also be measured. Given the strong change from 0° to 16° (or more) Celcius noted by Davies (1975) between May and July, temperature may have a significant effect on the fall velocity of the wash load, and hence partially control sediment concentration.

2. SUSPENDED SEDIMENT INPUT TO THE MACKENZIE DELTA

Together with the data for outputs to the Beaufort Sea, data on inputs to the Delta will permit some indication of the gross deposition of suspended load over the Delta surface, contributing towards points (b) and (e) of Lewis (1987).

2.1. <u>Mackenzie River above Arctic Red River.</u>

Lewis emphasizes the need to continue monitoring suspended sediment concentrations at Station 10LA003 (Mackenzie River above Arctic Red River). This is desirable if other work on the Delta, such as monitoring of sediment output to the Beaufort Sea, is undertaken. However, in the longer term, continued sampling at 10LA003 is probably not needed, and if additional work on the Delta is not to be undertaken in the near future, <u>routine</u> sampling at 10LA003 could be halted now, <u>provided that</u> a thorough review is done to assess the quality and sampling reliability of existing data.

The important point is that a good sediment rating relationship has now been obtained for this site (Lewis, in prep.). The coefficient of determination of concentration on discharge (using logarithmic transformations) is reported as 63% for 206 data points. Instead of continuing routine sampling at 10LA003, future loads can be predicted using this relationship, especially if improvement in the precision of prediction can be made by inclusion of other variables. This would allow redeployment of resources elsewhere.

One cautionary note is in order though. The reasonably strong correlation that exists between mean concentration and water discharge, on a daily basis, at this site merely means that the precision of predictions using this approach is good. We have no assurance about any possible bias that might exist in the data.

A particular concern in regard to the daily sampling procedure is that sampling is restricted to the top 4.5 m of the water column. This would be expected to introduce bias. Specifically, the concentration in the sample relative to the concentration in the full vertical would be expected to vary with stage: at lower stages, sampling extends closer to the bed (where concentrations are higher) than at high flows. This may explain why the sand fraction component (greatest in the lower part of the water column) shows a decrease at high discharges (> 20,000 cms). Because determination of the K factor (relating concentration in the daily vertical to concentration in multiple verticals) is only undertaken once a year, there is no check provided on the stability of K with stage, season or any other variable.

Recommendation 2.1. A full sediment station review be undertaken for Station 10LA003 following the approach used at other stations across Canada.

Particular attention should be focussed on the stability of the K factor, and, almost certainly, this will necessitate a detailed sampling season to assess the variability of K. Attention will also have to be given to other matters, such as the magnitude of the "unsampled" suspended sediment discharge (Colby, 1957). The review should also examine means of improving the sediment rating curve predictions by stratifying the data, e.g. separation according to month of the year, position on the hydrograph etc., and inclusion of other variables, e.g. rate of change of discharge. Some thought will also have to be given to the errors associated with lack of data in the early stages of spring breakup. Finally, attempts should be made to develop predictive equations for concentration by size class and not merely by total suspended sediment.

The assessment of the accuracy of existing data for this site is urgent, and the sampling programme should not be abandoned until such a review has been done. Ultimately, however, it may be possible to discontine routine sampling, and replace it by spot samplings, e.g. once or twice a year, to indicate any shift in the rating relationship.

2.2 Arctic Red River near the mouth.

The sediment rating relationship for this site (10LA002) appears to be be slightly better than that at 10LA003. On the other hand the Arctic Red River supplied less than 6% of the 126 million tonnes (Mt) per year total input of suspended sediment to the Delta during 1974-83 (Lewis, in prep.). Given this, it would seem that long-term continuation of sampling at this site is not warranted, though it should be undertaken during any period of detailed sediment work on the Delta as outlined in Section 1. The more important task is to undertake a statistical analysis of the existing data to see if the sediment rating predictions can be improved by stratification of data and inclusion of other variables.

> Recommendation 2.2. A sediment station review be undertaken for Station 10LA002, along the lines of that for 10LA003, with the goal of improving accuracy of predictions, thus justifying the decision to terminate sampling at this site in 1975.

2.3 Peel River above Fort McPherson.

Based on present data (Lewis, in prep.), the Peel River accounts for almost 25% of the total suspended load entering the Delta, slightly more than a third of the Mackenzie River input at 10LA003. Its importance is thus much greater than that of Arctic Red River, and it is therefore especially unfortunate that its sediment rating relationship is so poor. The coefficient of determination for concentration against discharge (on logarithmic transformations) is only 35% based on 77 data points. Whether this is due to greater inherent fluctuations of concentration on the Peel River, or larger errors in sampling or in discharge estimation is not known. A major effort must be made to determine the cause of this problem and to rectify it if possible. If that cannot be done, it may prevent the use of a sediment rating approach at this station and necessitate long-term routine sampling.

> Recommendation 2.3. A comprehensive sediment station review be undertaken for Station 10MC002, following the pattern of 10LA003, in order to assess if predictions of concentration can be improved sufficiently to justify continued inoperation of the sampling programme (last done in 1976).

These recommendations refer to items directly within the terms of reference of the present study. Together with those in Section 1, they will enable determination of gross sediment accumulation within the Delta, information that simply does not exist at the present time. Other aspects of sedimentation within the Delta are addressed by Lewis (1987).

3. TRANSPORT OF NUTRIENTS WITHIN THE WASH LOAD OF THE MACKENZIE RIVER TO THE DELTA AND THE BEAUFORT SEA

Inputs of nutrients to the Delta and to the Beaufort Sea are of concern to many parties since they exert a major effect on the biological productivity of both areas. The topic is of relevance here because a considerable part of the nutrient flux occurs within the wash load of the Mackenzie River. Brunskill et al. (1975a,b) and Campbell et al. (1975) have made estimates of the fluxes of carbon, nitrogen and phosphorous during the 1971-73 period. Discharges in these years seem to be representative of the post-1970 period. Their data indicate total fluxes to the Delta (from the Mackenzie, Arctic Red and Peel rivers) of these three elements in particulate form amounting to 3.12, 0.13 and 0.05 Mt, respectively, per year. The particulate component accounted for 60% of the total nitrogen input and 88% of the total phosphorous flux. Approximately 92% of the total N and P loads, combined for the Mackenzie (Norman Wells data only), Peel and Arctic Red rivers, originated in the Mackenzie.

These figures are derived from a very small data base. They were also computed from the sum of monthly means which, in turn, were derived from the product of mean discharge and mean concentration for each month. Brunskill (1988, pers. comm.) comments that the mean concentrations were discharge-weighted, not simple means. Use of simple means, a common practice, would have led to bias, probably underestimating the monthly loads (Church, 1978; Ferguson, 1987).

Given the limited data, an alternative approach would be to utilize the logarithmic relationship between concentration and discharge, applied to the flow duration data, to estimate annual nutrient loads. Unfortunately, the relationships obtained are not particularly strong: coefficients of determination generally averaged only 50 percent. On the other hand, this may be partly due to the limited variance in discharge sampled. Moreover, the correlation of instantaneous load (rather than concentration) with discharge would be stronger.

In any case the data presently available are inadequate for many of the purposes required, especially in the context of <u>timing</u> of the fluxes and the <u>spatial</u> nature of the inputs from the Delta distributaries to the Beaufort Sea. These issues are just as crucial in terms of biological productivity as annual loads.

Recommendation 3.1. The detailed sediment sampling programme at Station 10LA003 on the Mackenzie upstream of Arctic Red River, recommended previously (2.1), include sampling of sufficient water to allow additional analyses of nutrients, with emphasis on changes throughout the course of the year including the ice season.

(It should be borne in mind that primary productivity in the Mackenzie estuary is thought by some to be highest before and during ice break-up.)

Recommendation 3.2 Similar sampling be undertaken at outflow sites from the Delta as part of the sediment sampling programme outlined in Recommendation 1.

By combining this nutrient programme with the direct sampling programme outlined in Sections 1 and 2, overheads will be reduced, and other agencies would be expected to contribute to funding.

One warning must be introduced here. Attention should be directed very closely to conditions of storage and mode of nutrient analysis. Normal IWD procedures for the former may be adequate or may have to be modified in consultation with other interested parties. It is assumed that nutrient analysis would be done by DFO, at the same time as their analyses of Beaufort Sea samples, though other organizations concerned with nutrient inputs to the Delta may be interested. What is extremely important is that the same methods are used on the river samples as on the sea water samples. This is essential if the river data are to be used to interpret the Beaufort Sea data.

One of the conclusions to emerge from the literature is that data interpretations are hampered by the fact that different parties use different sampling procedures, modes of storage, and methods of analysis. Coordination is essential to minimize duplication of effort and ensure consistency of data.

It is beyond the mandate of this report to specify methods of chemical analysis. It is sufficient here to point out that previous work has not always clearly differentiated between nutrients that exist in "available" form and those that are not available for biological uptake. The Mackenzie River Basin Committee (1985), for example, noted that a large portion of the nutrients measured in its study was not available for biological uptake, this being indicated by the poor correspondence spatially, within the entire basin, between nutrient levels and biological productivity. (Other factors, of course, affect the latter.)

4. TRANSPORT OF CONTAMINANTS ADSORBED TO WASH LOAD IN THE MACKENZIE RIVER

4.1 Transport of hydrocarbons

Data on hydrocarbon concentrations in the Mackenzie river are available from pilot studies undertaken by the National Water Research Institute in 1985 and 1986 (Nagy et al., 1986, 1987). The former refer to low flow conditions of late summer; the latter to high discharges in early summer. The studies were prompted by abnormalities in the condition of fish reported by local fisheries, and the suspicion that these conditions may be related to intake of hydrocarbons.

The limited data collected are not easy to interpret, though the NWRI report argues that diffuse inputs of organics by spring runoff throughout the drainage basin overwhelmed any inputs from the Norman Wells refinery or from oil seeps. Previously Peake et al. (1972) had concluded that the origin of organic substances (amino-acids, chlorins and n-alkanes) in the Mackenzie lies solely in the soil environment from which the drainage occurred. Total concentrations in the NWRI study of both n-alkanes and selected polycyclic aromatic hydrocarbons (PAH's) were greatest on the Mackenzie upstream of the Liard confluence and just downstream of Fort Good Hope. Upstream of the Liard virtually all organics were part of the water rather than the suspended sediment; downstream the percentage associated with suspended material (as inferred from centrifuged specimens) averaged 20-30% for alkanes and 5-20% for PAH's, increasing markedly by the Lower Ramparts in both cases, as total hydrocarbon concentration (dissolved and particulate) decreased towards the Sea.

Lockhart et al. (1987) have examined the case for implication of hydrocarbons in the abnormalities reported in the liver of burbot and "watery" flesh of whitefish. The problem is extremely complicated (much like the mercury pollution of fish in the James Bay rivers of Quebec). Their investigation notes that there is widespread contamination of fish from the Mackenzie River with low levels of several organochlorine compounds, but whether this is significantly worse than other subarctic watersheds is not known. In any case it is not at all clear what the role of sediment is in this problem. Most of the hydrocarbons investigated occur freely in the water (the role of colloidal particles that pass through filter pores and do not settle in centrifuging is not known) rather than as part of the wash load, at least upstream from Arctic Red River. Moreover, hydrocarbon concentration in fish appears to be greatest during periods of winter ice cover, when sediment concentrations are low, but when evaporation is impeded.

Studies of the deterioration of fish quality in the Mackenzie clearly need to be continued, but as part of a much broader investigation of fish health and environmental contamination in the subarctic (as recognized by Lockhart et al.), rather than as an item peculiar to the Mackenzie, and one that is intimately related to suspended sediment in the river.

On the other hand, the role of the wash load in terms of adsorption of hydrocarbons, its degree of control on the timing and geography of inputs to the Beaufort Sea, and the extent of "undersaturation" of suspended sediment (with respect to hydrocarbons) as it enters the Sea, are matters of some importance to parties working offshore. Currently there are little data available from river sampling to assist in the interpretation of offshore studies. Arctic Laboratories did some sampling of Delta distributaries in April 1985 and February 1986; the Institute of Ocean Sciences (DFO) sampled the three main Delta channels in the summer of 1987.

Recommendation 4.1.1. Suspended sediment sampling just upstream of Arctic Red River (10LA003) should be broadened in scope to include sampling of both water and sediment for analysis of hydrocarbons, throughout the year, in order to assess the changing flux of hydrocarbons to the Delta and the Beaufort Sea, and the degree of association with the wash load. Sampling should also be undertaken at the mouths of Delta distributaries identified as part of Recommendation 1.

Comparison of the two data sets should indicate (a) the amount of settling of hydrocarbons within the Delta; (b) the feasibility of using just one site (10LA003), rather than three, for assessing inputs to the Beaufort Sea. The purpose of this work is twofold: (a) to provide background levels on hydrocarbon fluxes prior to further oil and gas development, (b) to acquire land-based data essential to the interpretation of offshore studies.

In the latter context, the timing of the work, and its mode of conduct, should take into account the research investigations in the Beaufort Sea. To date it seems that only minimal liaison has occurred in this respect. In particular, it seems that, in general, quite different sampling, storage and analytical procedures are being used: for example most of the offshore specimens were filtered for particulate material, whereas river specimens were centrifuged.

In the pilot studies by NWRI, samples were taken during a single boat passage downriver during both field seasons. These results are hard to interpret because the boat speed is not the same as that of the water. Hence the same "parcel" of water is not being sampled, and differences between sampling locations along the river may, to some extent, reflect fluctuations in sediment composition during the hydrograph rather than differences between sites. While the initial studies by NWRI have been useful, it would seem that the time is now ripe to establish fixed sampling stations that are monitored on a regular basis. In this way, genuine comparisons can be made between sites and changes are more easily interpreted in terms of, for example, dilution effects due to inflow of "clean" tributary water, deposition or augmentation of hydrocarbon loads between sites etc.

The pilot studies indicated a marked decrease in total hydrocarbon concentrations between the Mackenzie upstream of the Liard and Fort Norman; an increase between Fort Norman and Fort Good Hope; and a marked decrease downstream from Fort Good Hope. There appears to be little known about the stability of hydrocarbons in transit along a watercourse, notwithstanding its obvious importance in the context of oil spills. The preliminary data might be indicative of localized inputs upstream of the Liard, and in the Norman Wells region, followed by losses from the load either by sedimentation or degradation of hydrocarbons in transit. Sampling at regular suspended sediment stations and analysis of certain key hydrocarbons would allow examination of this issue.

Recommendation 4.1.2. Sampling of water and suspended sediment should be undertaken at the mouth of the Liard, and on the Mackenzie upstream of the Liard, at Wrigley, at Norman Wells and at Fort Good Hope for measurement of the concentration of selected hydrocarbons.

Sampling should be undertaken throughout the year to identify seasonal patterns, changing importance of dissolved and particulate phases, and to permit computation of monthly yields. The sites indicated either belong to the existing WSC sediment sampling programme or are recommended for inclusion in it in the next section (5).

4.2 Transport of heavy metals

In light of the wealth of mineral resources in the Mackenzie basin, and their inevitable exploitation in the years ahead, it is not surprising that concern has been expressed regarding the contamination of aquatic resources by heavy metals.

Studies to date have determined concentrations of aluminum, barium, cadmium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, nickel, silver, strontium, thallium, vanadium and zinc, in both "dissolved" and "extractable" forms. As defined by Water Quality Branch laboratories of Inland Waters, the former refers to concentrations in water passed through a 0.45 µm filter, and thus includes free metal ions, those in solution as complexes and those that are part of colloidal material (Mackenzie River Basin Committee, 1985, p. 94). The latter represents both "dissolved" material and that which is associated with solids (organic as well as inorganic) and which may potentially be released to solution. This "particulate" material includes not only metals that are sorbed to the surface of minerals, but also some of the metals incorporated in the mineral crystalline structure. Thus, while "extractable" concentrations are less than "total" concentrations (derived by complete dissolution of the particulate components of a suspension), they do, nonetheless, yield an overestimate of the amount of potentially bioavailable metal.

The data indicate that metal concentrations in river water in the basin are at natural levels, often below the level of detection. Iron, aluminum and manganese are almost entirely tranported in association with the wash load; copper, chromium, lead and mercury were found to be largely (55%-84%) in the particulate phase. Arsenic, often found in wastes from industry and mining activity (Hem, 1959) is reported to occur in elevated concentrations in the sediment of Yellowknife Bay, from gold mining waste, but no data appear to be available for the mainstem Mackenzie.

A major problem with metal data is their interpretation in terms of potential toxicity to organisms: there is no unambiguous measure of bioavailable metal. Until further research in laboratory procedures produces more meaningful indices, the impact of metals in river water on the aquatic ecosystem is not easily determined. Nonetheless, it is clear that benchmark data are needed to characterize the level of metals being released from the Mackenzie basin into the main stem, the Delta and the Beaufort Sea, prior to accelerated development of the watershed. The logical sampling sites would be the Mackenzie River upstream of Fort Simpson (10GC004); upstream of Arctic Red River (10LA003); and, if possible, at outlets of the Mackenzie Delta distributaries as indicated in Recommendation 1. The former would allow monitoring of metals not only from Great Slave Lake, but also from that reach of the Mackenzie (upstream of Fort Simpson) that will experience the greatest dredging activity in the immediate future. The 10LA003 site allows monitoring of water and sediment as it enters the Delta en route to the Beaufort Sea.

Because metal analyses have already been undertaken for the Beaufort Sea by DFO, and will probably continue in the future, it is extremely important that sampling procedures, methods of storage and laboratory analysis be the same within the basin and offshore. Moreover the exacting requirements for sampling and storage, in the case of many of these metals, may mean that onshore sampling and analysis be done by the same parties as those responsible for offshore work. Thus direct involvement of Sediment Survey staff in the sampling programme may be minimal. On the other hand, it is clearly advantageous to have this work done at regular WSC sediment sampling sites, so that the data from these metal samples can be seen in an appropriate context: discharge conditions at the time of sampling in relation to the long term discharge record; sediment concentrations at the locations and times of sampling in relation to spatial variability of concentrations and particle size within the cross section, and fluctuations over time, etc.

Recommendation 4.2. Routine monitoring of heavy metals in solution and suspension be undertaken on the mainstem Mackenzie at stations 10GC004 and 10LA003 to establish background concentrations under a variety of flow conditions. The work should be supplemented by measurements at the mouths of the three main Delta distributaries (See #1) and timed to coincide with years in which measurements are made offshore. Planning should take into account the precautions noted above.

5. SOURCES OF WASH LOAD IN THE MACKENZIE RIVER BASIN

Upstream of station 10LA003 (Mackenzie River upstream of Arctic Red River) the only suspended sediment data available for the Mackenzie are at Norman Wells (10KA001: 1973 only) and upstream of the Liard (10GC004: 1972-75). The only data for tributaries near the confluence with the main stem are for the Harris (10GC002: 1972-76), the Liard (10ED002: 1972-76; 1979-84), the Martin River (10GC003: 1973-76), the Redstone River (10HB001: 1973 only), the Trout (10FA002: 1973-75) and Willowlake River (10GB001: 1973-74 only). The yields of the Harris, the Martin, the Trout and the Willowlake are so small that they are of little significance in any interpretation of the sediment load of the Mackenzie.

Of the others, only in the case of the Liard are sufficient data available to allow derivation of reasonably reliable statistical formulae for the prediction of sediment concentrations. The actual sediment rating curve of the Liard near its mouth is itself quite strong, though scatter occurs at high flows, especially in association with floods from intense summer storms (BC Hydro, 1984).

Recommendation 5.1. A full sediment station review be undertaken for the Liard (10ED002) to find out whether there are grounds for suspecting any bias in the data and to find out if precision of predictions can be increased by stratifying the data (e.g. by month) or by inclusion of additional variables (e.g. temperature, rate of change of discharge, etc.).

(Hopefully, accuracy of predictions will be sufficiently good to allow abandonment of a full sampling programme at this site (until major land use changes occur in the basin) and replacement by spot checks to assess the stability of the predictive equation.)

At best, the present data in the Mackenzie basin are adequate to assess the fraction of the Mackenzie's wash load at 10LA003 contributed by the Liard (assuming no settling of Liard sediment). Estimates by BC Hydro (1984) indicate that the Liard accounted for 17-75% of the yield of the Mackenzie at 10LA003 between 1973 and 1979, averaging slightly more than 40 percent.

The major part of the Mackenzie's input to the Delta is thus from sources whose contributions have yet to be assessed.

Downstream of the Liard confluence, fine sediment is supplied to the Mackenzie by erosion of banks along the main stem and by tributaries. The relative importance of these two sources is unknown.

It is clearly impractical to accurately determine contributions from bank scour along the full length of the Mackenzie. At the same time, those areas in which the river is cut into thick deposits of fine grained glaciolacustrine sediment are known from the surficial geology maps, and it would be a worthwhile exercise to attempt to determine how much sediment is contributed by erosion of banks in these, the most sensitive, areas.

Recommendation 5.2. A search be made of the listings of large scale aerial photographs in those regions of the Mackenzie Valley flanked by unstable glaciofluvial lacustrine muds. Comparison of aerial photographs be made, where available in the same reach over a given period of time, to enable some assessment of the average annual contribution to the Mackenzie load from in stability and erosion of the valley sides.

With regard to tributary contributions, thorough sampling of all major tributaries is not practicable. Nonetheless, some indication of the collective inputs of the North Nahanni and Root rivers, the Redstone-Keele rivers and that of the Mountain River could easily be obtained by establishing additional stations on the main stem at Wrigley, Norman Wells and Fort Good Hope (Fig. 1).

Establishment of stations at Wrigley and Fort Good Hope has already been recommended (4.1.2) as part of the study of hydrocarbons. Implementation of a regular suspended sediment sampling programme at Wrigley is also advocated in 6.5.3 in the belief that much of the bed material of the Liard-Mackenzie confluence reach is thrown into suspension in the Wrigley reach. (Frequent particle size analyses will be needed to allow partition of the bed material load and wash load in suspension at Wrigley.) Resurrection of the sampling programme at Norman Wells is also suggested in Recommendation 7 in connection with estimates of infill rates of the proposed dredging channel at that location. A gauging station already exists at Norman Wells (10KA001) and water level recorders appear to be already in existence at Wrigley and Fort Good Hope.

Recommendation 5.3. Regular suspended sediment sampling programmes, comparable in scope with that at 10LA003, be established at Wrigley, Norman Wells and Fort Good Hope for the purpose of assessing tributary inflows of sediment.

Because the concentrations in the Mackenzie upstream of the Liard are small, the upper river contributes only a small load to downstream. With concentrations of about 20 mg/L, and discharges of the order of 6,000 cms, this amounts to only about 10,000 tonnes per day over much of the ice free season. Admittedly this figure is comparable with spot determinations of loads on the Redstone in 1973 during a much shorter high flow period. There is, however, little incentive to extend the fairly large data set at this site on a routine basis. Additional data would in any case be forthcoming if Recommendations 4.1.2 (dealing with hydrocarbons) and 4.2 (dealing with heavy metals) are implemented.

Recommendation 5.4. No further sampling at station 10GC004 be undertaken, except as part of the investigations of hydrocarbon and metal contaminants. Statistical analysis be undertaken to find out whether concentrations are capable of adequate prediction on the basis of hydrological variables.

BED MATERIAL ISSUES

6. BED MATERIAL TRANSPORT ALONG THE MACKENZIE RIVER

6.1 Input of sandy bed material to the Beaufort Sea.
6.2 Input of sandy bed material to the Delta.
6.3 Accumulation of sandy bed material within the Delta.
6.4 Sources of sandy bed material in the lower Mackenzie River downstream of Wrigley.
6.5 Movement of sandy bed material in the Mackenzie River in reaches upstream of Wrigley.
6.6 Accumulation of gravel in the Mackenzie River.

In discussing bed material transport along the main stem, it is useful to refer to both a map of the river course (Fig.2) and its long profile (Fig. 3). These outline a subdivision of the Mackenzie into twenty distinctive reaches, based on channel morphology and low-water gradient. The proposed sampling programme for sandy bed material load is illustrated in Fig. 4.

6.1 Input of sandy bed material to the Beaufort Sea.

Virtually no data exist on this matter, and yet, since the bays at the mouths of the delta distributaries act as sinks for bed material, the opportunity clearly exists for assessing inputs by repeated surveys. Unfortunately no reliable bathymetric survey exists; one is urgently required. Because of the difficulties of vertical control on water (tidal and storm surge effects, wave chop), the problems of grounding in shallow water, and the turbidity of the water in the open-water season, conventional echo-sounding by boat may not be the most appropriate method. Instead it may be more advantageous to attempt soundings from a smooth, level ice surface (by snowmobile) in the winter.

> Recommendation 6.1. An assessment be made of the feasibility, accuracy and cost of a bathymetric survey of the bay areas. If the results are encouraging, a survey should be undertaken as soon as possible, followed by a resurvey in about 10 years time.

6.2 Input of sandy bed material to the Delta.

Information on bed material delivery rates to the Delta at Point Separation is also virtually non-existent, yet it is a vital concern for reasons already given. The logical method to compute these rates is by morphometric analysis (Church et al., 1986). The approach taken by those investigators was very much a pioneer one, and substantial refinements can be made in the actual methods used. In particular, where repeat CHS charts are available for a given reach, rather than simply compute changes in mean depth for successive 2 km long sub-reaches, and use these values to estimate short-term degradation and aggradation in the whole reach (and thereafter bed material transport rate), more sophisticated computer software should be utilized. This would allow, for example, interpolation of depths at actual sounding points to intersections of a superimposed grid, repetition of the process with the data of a later survey, and mapping of actual changes in depth at grid intersections. The latter is not only conveniently used for calculating gross volumetric change in the reach with more accuracy, but also allows the spatial pattern of change to be shown. That pattern is extremely important in understanding the mechanisms of bed material transport.

6.2.1 The Mackenzie between km 1350 (Barrel Crossing) and km 1435 (just upstream of Lower Ramparts) displays a classic pattern of alternating pool-riffle units. These are clearly displayed on existing CHS field sheets for Charts 6425 and 6426 surveyed in 1973 and 1977/78. Preliminary manual computation of morphological change on two such units indicates an average transport rate of about 4.5 million cubic metres per year in this period. These are tentative: manual calculations are time consuming and liable to more error than computer analysis.

Recommendation 6.2.1a. Existing CHS field sheets for 1973 and 1977/78 for Charts 6425 and 6426 be digitized and the data file subjected to analysis to determine spatial pattern of scour and fill over the pool-riffle system, and mean bed material transport rate calculated for the period.

Recommendation 6.2.1b. An immediate resurvey should be requested of CHS for km 1350-km 1435 (Charts 6425-26) to allow calculation of bed material yield since 1977/78. Data should be provided in digital form.

6.2.2. The downstream part of the Peel River has been sounded fully only once: (Charts 6440 and 6438) in 1973. There is some semblance of an alternate pool-riffle pattern, especially in a 15 km stretch at and upstream of Fort McPherson, but depth changes are not as strong as on the Mackenzie.

No bathymetric data at all are shown on the CHS chart of the lower Arctic Red River. Moreover, no well-developed meander belt exists on the Arctic Red (unlike the Peel between Husky Channel and Peel Channel). According to Lewis (in prep.), the Arctic Red accounts for less than 6 per cent of the suspended load entering the Delta, and, given this (and by inference), determination of the bed material load of the Arctic Red must be low priority,

Recommendation 6.2.2. Attempts to calculate the input of sandy bed material from Arctic Red River should be deferred for the moment. Calculation of the Peel load should be attempted using morphometric analysis of meander migration in the reach between Husky and Peel channels.

Suitable photographs taken in 1950 and 1971/72 have been examined previously by Outhet (1974a,b) and should be supplemented by a new coverage. The morphometric approach would need to be supplemented by field investigation of bank heights and stratigraphy, including ice content, and bar sediment, to ensure that the calculated yield refers entirely to bed material.

6.2.3. Ideally, an attempt should be made to establish some relationship between annual bed material yield on the lower Mackenzie and hydraulic conditions in that year. In effect, this would amount to a bed-material sediment rating curve, or, alternatively, testing of various bed-load formulae. The magnitude of change in the pool-riffle reach between km 1350 and km 1435 is sufficient to warrant annual resurveys of selected pool-riffle units. These units are about 12 km long. Visual comparison of changes on the 1973 and 1977 sheets indicate a mean annual travel distance of about 300m; though this may be above-average, given the high flows in that period, it suggests annual surveys of a 15 km reach, with transect spacing of about 50 m, would give results of acceptable accuracy. Though this may seem to be a huge undertaking, the increased cost of using closely-spaced sections (compared to, say, the standard 250 m interval) is minimal relative to the overheads involved in survey work in the North.

Because most sediment deposition appears to be over a large area in the lee of bar crests, rather than simply by forward advance of the crest, it should be clearly recognized that monitoring movement of bar crests by aerial photography will provide only a crude measure of transport volume.

Recommendation 6.2.3. After complete analysis of the results of 6.2.1, a pair of pool-riffle units, corresponding to a river length of about 15 km, should be selected on the lower Mackenzie and a programme of annual resurveys on this reach be initiated.

One possibility is to request CHS to include such surveys in any furthre work on the Mackenzie. Alternatively, the work could be done by the Water Resources Branch, assuming it possess the appropriate equipment and computer hardware and software. The annual field programme would be sufficiently short that the work could be done at high water allowing topographic changes over bar tops to be monitored. Data should be provided in digital form. The programme should last at least five years, though the important factor here is to ensure inclusion of years with widely different flow conditions.

6.3 Accumulation of sandy bed material within the Delta

The gross volumetric accumulation can be derived simply by comparison of the results from 6.1 and 6.2. On the other hand, what also matters is some idea of the spatial distribution of aggradation within the delta distributaries. Apart from selected key areas, such as the entrance to East Channel from Middle Channel, however, it would seem sensible to defer a detailed mapping of changes within the delta distributaries until a gross figure has been obtained.

6.4 Sources of sandy bed material in the lower Mackenzie River downstream of Wrigley.

The preliminary estimate of sandy bed material transport on the lower Mackenzie of 4.5 million cubic metres per year is substantially higher than that of Church et al. (1986) for the river at Norman Wells between 1950 and 1971, based on aerial photograph analysis. In part the difference may result from the above average flows between 1973 and 1977. Nonetheless it is highly probable that long-term rates near the Lower Ramparts are greater than at Norman Wells, where the channel is not fully alluvial, but takes the form of sand bars and islands moving over a clay or till platform.

Furthermore, the Mountain River is expected to supply a substantial addition of sandy bed material. Set against that fact, however, it seems likely that aggradation is occurring in the flat reach (12) of the Mackenzie above Sans Sault Rapids, so that some of the load from Norman Wells may not be reaching the lower river. Some investigation is therefore needed of the pathways taken by sandy bed material before it reaches the lower Mackenzie.

6.4.1 Upstream of the alternate bar reach (18), as far as Fort Good Hope, CHS charts exist for 1972 (or 73) and 1979. Mackay and Mathews (1973) suggested that aggradation may well be occurring in the Mackenzie downstream of Fort Good Hope at the present time. It would thus seem sensible to utilize the CHS charts to produce a map of patterns of short-term aggradation and degradation in this period, and to estimate transport rates in the Fort Good Hope trench.

Recommendation 6.4.1. CHS charts 6422-23 be digitized and subjected to the same analysis as recommended in 6.2.1. See Table 1, summarizing existing and recommended CHS full chart surveys.

6.4.2 Upstream of Fort Good Hope, the only CHS chart with repeat surveys is 6419 (1971 and 1978). This is the chart analyzed by Church et al. (1986) from km 909 to km 945. The difference between the bed material load in this reach and that in the Fort Good Hope trench will reflect two main factors: (a) any changes in storage in bed material upstream of the Ramparts (in the Hume River Crossing reach) and upstream of Sans Sault Rapids; and (b) input from Mountain River. Neither is easily estimated, but they are important.

Recommendation 6.4.2. Two new surveys should be initiated as soon as possible. One should be of parts of Charts 6419 and 6420, between km 965 and km 1014, this being an extremely gentle reach in which aggradation is likely. The other should be Reach 14 (km 1030 - km 1080) between Sans Sault and Ramparts Rapids.

This is high priority work. CHS has the technical facilities to undertake such surveying.

6.4.3 Estimation of the sandy bed material input of Mountain River is fraught with many difficulties: e.g. the bed material is mixed sand and gravel, not sand alone; e.g. morphometric analyses based on repeated aerial photography would require flights after every flood period, otherwise the loads would be drastically underestimated because of non-systematic changes in channel pattern; e.g. most of the Mountain River sand that becomes incorporated into the Mackenzie bed material load may, in fact, be wash load in the lower reaches of the Mountain River, not bed material load.

Recommendation 6.4.3. Initially, the input of sand from Mountain River to the bed material load of the Mackenzie River be calculated indirectly from the sediment budget of the area: the bed material input at Norman Wells, the bed material output rate below Fort Good Hope and changes in bed sand volumes upstream of the Ramparts and upstream of Sans Sault Rapids. (See schematic map: Fig. 5.)

In the longer term, direct estimates of suspended load from Mountain River are needed as part of understanding the wash load of the Mackenzie (Item 5), and thought should be given to establishing a full sediment station (bed and suspended load) near the mouth of Mountain River. On the other hand, it may be preferred to compute the Mountain River <u>suspended</u> load indirectly as well (See item 5).

6.5 Movement of sandy bed material in the Mackenzie River in reaches upstream of Wrigley.

Upstream of Norman Wells, some partition of the sandy bed material load is needed between the upper Mackenzie (upstream of

Fort Simpson), the Liard, North Nahanni, Root, Redstone and Keele rivers.

6.5.1 No full CHS survey exists for Chart 6410 downstream of the Liard. Nonetheless the combined Mackenzie-Liard load could be determined from morphometric analysis of CHS chart 6411 (surveyed in 1979) provided that a new survey were undertaken.

Recommendation 6.5.1. A new survey of Chart 6411 should be initiated as soon as possible.

6.5.2 The combined sandy bed material load of the Mackenzie, Liard, North Nahanni and Root rivers (and by comparison with 6.5.1, the combined input of the latter two) could be assessed morphometrically using CHS Chart 6412 which was completely surveyed in 1972 and repeated, at least between km 489 and km 511, in 1978. The reach is unfortunately short, but would provide a first estimate of the input of these rivers. Downstream of km 511, the gradient steepens and the bed material becomes non-alluvial for 160 km through the Wrigley (8) reach.

Recommendation 6.5.2. Existing sheets for CHS chart 6412 should be digitized between km 489 and km 511, partly to assess the extent of possible aggradation in this gentle reach, and partly to establish the combined sandy bed material load of the rivers noted above.

6.5.3 The apparent absence of large areas of sand on the bed in the Wrigley reach suggests an alternative strategy to computing the input of sediment from upstream to the sandy bed material of the Mackenzie in the Norman Wells reach. If the sand load downstream of km 511 has been converted to wash load, then a suspended sediment sampling programme at Wrigley, with grain size analysis, would provide the necessary information. In effect this reach seems to provide an ideal opportunity to determine bed material loads by suspended sediment sampling at "contracted sections", long ago advocated by Colby (1957) in the USA. The town of Wrigley itself would provide an ideal base.

Recommendation 6.5.3. A detailed bed material sampling programme be undertaken on the Mackenzie in the vicinity of Wrigley to verify that, indeed, sand deposits are minimal in this reach, as implied by the CHS charts. If this is confirmed, a suspended sediment sampling station should be established in this area, to provide data on total loads of sand (and finer) sediment.

If extensive sand deposits are found on the bed near Wrigley, reliance will have to be placed on resurveys of km 489- km 511. Another possible "contracted" reach would be the even steeper gravel-bedded stretch of the Mackenzie downstream of the Redstone river. However this is not as accessible, and, furthermore, would include inputs from the Redstone and possibly the Keele, depending on the location. In that case it would merely constitute a check on the estimates for the Norman Wells reach, rather than attempting to partition the load at Norman Wells into its source areas. Establishment of a station at Wrigley would allow determination of the Redstone-Keele inputs through the difference between loads at Wrigley and Norman Wells.

6.6 Accumulation of gravel in the Mackenzie River.

One of the distinctive features of the Mackenzie is that several west bank tributaries have created definite gravel fans in the main river. This is especially the case for the Redstone-Keele rivers in which a steep gravel-bed reach downstream of their mouths abruptly changes to a gentle sand-bed channel 75 km downstream. This reach therefore appears to act as a sink for gravel from these two rivers (but see Item 11 below). Measurements of aggradation and/or downstream advance of the wedge would enable calculation of present rates of gravel input. Unfortunately neither chart (6415-6416) has yet had a complete bathymetric survey undertaken. Moreover, preliminary estimates of the annual gravel yield (based on comparison with New Zealand rivers) suggest that accumulation of the load over such a vast fan surface would lead to changes in mean elevation of the bed that, even over a period of a decade, would not exceed measurement error.

On the other hand, there is no reason to believe that, in the short term, this aggradation is spatially uniform. It may well be localized just downstream of the confluences. Indeed the definite hump in the long profile at the Redstone confluence suggests that this is the case. Aggradation would be expected in years in which major rainstorm-induced flows occur in these tributary catchments, while the mainstem flow is relatively weak. Bathymetric mapping in the reach would at least provide a benchmark survey so that the gravel yield of future high-return period floods could be determined.

Recommendation 6.6. A bathymetric survey of the reach km 705 to km 790 (comprising part of Chart 6415 and most of 6416) be undertaken.

The work is of relatively low priority, but could, in the right circumstances, yield invaluable information on gravel yields from west bank tributaries.

6.7 <u>Overall comments on the use of bathymetric surveys to establish bed material yields on the Mackenzie River</u>.

If repeat surveys are to be made by CHS, it is highly desirable that they be done (a) at high water so that bar elevations are included and (b) in one, or at the most, two seasons, so that comparison of results from one reach to another is not complicated by differences in hydraulic conditions during the time periods between surveys. To some extent these two goals are incompatible: long field seasons will involve low water conditions. It is therefore important that the CHS work is supplemented by ground surveys of islands and bars above water.

As Table 1 indicates, no surveys of the Mackenzie River downstream of Fort Simpson have been undertaken since 1979. In the mid-80's, however, it had been hoped to undertake a major resurvey of the river using funds sponsored by NOGAP. A three year period of funding by NOGAP was, in fact, used to undertake new surveys between km 0 and km 208. The work was done by Terra Surveys Ltd of Sidney, B.C., and involved the development of new procedures for the direct transfer of echo-sounding records directly to digital format on tape. The report by Terra Surveys Ltd made the comment that "The CHS program to resurvey the Mackenzie was well-received by users of the Mackenzie charts". Unfortunately, further funding from NOGAP has not been forthcoming.

While competition for NOGAP funding is obviously keen, it would seem that a stronger case could be put forward for CHS work in charting the Mackenzie. In discussions with senior CHS staff, for instance, the potential use of CHS charts in computing bed material discharge, delineating areas of aggradation etc. had, understandably, not been appreciated. <u>Thus the overall value of the CHS programme to the scientific, engineering and environmental communities has not been recognized</u>. NOGAP is presently funding many other projects related to the Mackenzie, and yet some of these will be of dubious value until a better understanding of the sediment yield of the Mackenzie is attained. The relationship, for example, between sediment loads of the Mackenzie and the fate of the Mackenzie Delta seems to have been unrecognized by many concerned with the future of the North. The Sediment Survey Section should initiate a new attempt to lobby NOGAP and others regarding these general points, and, in particular, the major role that can be played by the Canadian Hydrographic Service through its updating of Mackenzie River charts.

Having said this, and noting that updated charts are needed also in connection with the increased traffic on the Mackenzie in the years ahead, it should be borne in mind that CHS itself may not be in a position to undertake additional work because of its other committments. On the other hand, there is no reason why this work could not be subcontracted to survey companies as has been done in the recent past.

Alternatively, given that bed material movement is already part of the domain of the Water Resources Branch, and given that conventional methods of sampling are costly and inaccurate, it may be more appropriate to consider expansion of the existing hydrographic unit within the Water Resources Branch. A stronger case for this, however, could probably be made when acceptable results using this method have already been obtained.

7. NAVIGATION PROBLEMS ON THE MACKENZIE RIVER

Most of the navigation difficulties on the Mackenzie occur in shallow, fast flowing, non-alluvial areas. Most of these (and shallow lacustrine tracts) occur upstream of Fort Simpson where bed material transport is assumed to be very small. Between Fort Simpson and Point Separation, the only problem sites identified by Acres (1987) are, in downstream sequence, McGern Island, near Blackwater River, above Saline River, Saline Island, below Smith Creek, Norman Wells (harbour access only), Rader Island, Sans Sault Rapids, Hume River Crossing and the Ramparts Rapids. Added to these should be Camsell Bend, Barrel Crossing and others, according to the Canadian Coast Guard. Several of these problem areas reflect difficulties arising from mobile bed material, and are discussed below.

7.1 Webber (pers. comm.) reports problems due to intermittently shallow conditions around Cameron Point (km 425) and

Camsell Bend (km 460), part of Reach 7. The possibility of aggradation in this reach associated with inputs from the North Nahanni has been noted. A preliminary assessment of this problem would be afforded by implementation of Recommendation 6.5.1.

7.2 The area around McGern Island (km 491-520: Charts 6412/13) is plauged by sand bars and shallow rock areas. The area is the downstream tract of Reach 7. The problems here may also be related to the North Nahanni River. Implementation of Recommendation 6.5.2 would at least provide some insight into processes operating between km 489 and km 511.

7.3 The problem area just downstream of Blackwater River (km 665-670: Chart 6415) corresponds to the marked step down in the long profile noted at the end of the Wrigley (8) reach. The bed here is gravel-covered, the channel widens appreciably at a sharp bend, and the low water profile drops dramatically at a gradient of 60 m/100 km over a distance of about 3.5 km. Depth reduces accordingly, and velocities increase. The cause of this stepdown is not known, but it seems to be a purely local phenomenon. The reach upstream is not considered to transport large quantities of gravel to the site. No investigation by the Sediment Survey Section is recommended, given the dominance of local conditions, though the Coast Guard may wish to investigate the matter further.

7.4 The reach above Saline and Redstone Rivers (km 707-712: Chart 6415) is a shallow sand-bed area in which the navigation channel hugs the right bank, even though the thalweg swings to the left bank and then back across the river. This does not mean, however, that navigation difficulties stem from bad alignment of the ship channel. Though the area is part of the relatively steep reach 9, it is immediately upstream of the Redstone-Keele gravel fan (Reach 10), and its slope is only 18 m per 100 km, much flatter than both upstream and downstream. It is possible that local aggradation at the mouth of the Redstone has raised local base level for the Mackenzie immediately upstream, leading to deposition of sand. Implementation of Recommendation 6.6, followed by repeat surveys when appropriate, and extended slightly upstream to allow examination of backwater effects, would assist in the analysis of this problem area.

7.5 The problem areas close to Saline Island (km 722-726: Chart 6415) and Smith Creek occur in Reach 10, the gravel fan of the Redstone and Keele rivers. The exact problems in these areas are not known. Implementation of Recommendation 6.6 would again provide a basis for further investigation.

7.6 Major dredging is planned to improve access to the Government Dock at Norman Wells from the navigation channel. Acres (1987) predicts a high infill rate here. However, sedimentation may be more from suspended load than bed load because the right side of the river here (to a large extent being water from Great Bear River) has a non-alluvial (glaciolacustrine clay) bed. Suspended sediment loads should also be less on this side of the river because of the dilution of the Mackenzie load by Great Bear water. Analysis of the matter is complicated by the recent artificial construction of islands near the downstream end of the proposed channel. The problem of future infill is primarily a local one and will require a detailed investigation of both mobile sediment on the channel bed upstream and the suspended sediment load in this part of the river.

Public Works Canada (1976) considered this to be a relatively high maintenance site "as the channel alignnment must be made at an angle to the flow, and high steep wave action can occur from time to time"; they estimated maintenance dredging of 143,400 cubic yards place measurement per annum.

To date the only suspended sediment data at Norman Wells (10KA001) are for 1973 with seven concentration values (maximum 513 mg/L at 20,500 cms). On four of the five sampling occasions more than two-thirds of the sample was silt and clay. Galay (1978, p. 60), however, claimed that "natural suspended sediment concentrations range from 300 mg/L to 8,000 mg/L". In neither case is the location of the sampling points relative to the proposed channel known. The Water Survey of Canada would seem to be in an excellent position to collaborate with Public Works Canada and the Coast Guard in estimating sediment infill at this site.

Recommendation 7. The Water Resources Branch seek funding from parties concerned to reestablish the suspended sediment programme at Norman Wells.

Special attention should be placed on the cross-channel variance in concentration and grain size, and on loads in the vicinity of the proposed channel. This work would need to be supplemented by a study of current speeds and directions upstream of the cut, and a survey of bed material, in order to establish the likely bed load infill rate. The Water Survey of Canada should also be involved in this aspect of the work to provide background material for the suspended load monitoring program. (See also item 10.)

7.7 The Hume River Crossing corresponds to the wide, shallow, sand-bedded 50-km Reach 14, downstream of Sans Sault Rapids. The problem area itself is given by Acres (1987) as between km 1030 and km 1033, but this is not the location of the mouth of the Hume River. On the other hand, this designated 3 km area does correspond to a previously documented problem zone at the start of Reach 14 (Public Works Canada, 1976: Priority Area 25). Acres (1987) notes that a grounding occurred here in 1985. The Hume River mouth (km 1065) corresponds to Priority Area 26 of the PWC 1976 report.

The problems in Area 25 (1976) again seem to be local ones arising from the fact that the navigation channel does not follow the main thalweg. The thalweg actually splits around Hardie Island; the navigation route follows the left side of the island, whereas the main thalweg takes the right hand route before crossing over to the left bank in the lee of Hardie Island. Although both thalwegs involve shallow crossings to the left bank, the right thalweg appears to be better, based on the 1983 chart.

It is not difficult to imagine that the relative advantage of the two thalweg routes varies from year to year. The problems at this one small area would seem to be indicative of more widespread shoaling problems throughout Reach 14. Though Mackay and Mathews (1973) believed that longterm degradation was still continuing upstream of the Ramparts, this is not completely consistent with the appearance of Reach 14. Aggradation, at least in the short term, may be occurring. As noted in 6.4.2, this general area is a crucial one in the sediment budget of the Mackenzie. Implementation of the recommendations there would assist in analysis of the more practical problems of navigation in the Hume Crossing shallows.

7.8 Problems have also been reported at Barrel Crossing (km 1350) at the end of Reach 17 (Woldmo, 1987, pers. comm) due to the shallowness of the entire channel and instability in the thalweg location.

7.9. General comments. Some of these problem areas are controlled by local conditions and require a detailed analysis of where the sediment that forms the shoals originates and how quickly it is supplied to the shoal area. This is possibly beyond the domain of the Sediment Survey Section except at Norman Wells. Monitoring would have to be done at a very detailed scale. Each location would require investigation by an expert in bed sediment movement and river hydraulics. This is a matter for the Coast Guard and Public Works Canada. On the other hand, it is also evident that most of the problems require far more information than is currently available on the general pattern of aggradation in certain reaches, the rates of bed material transport through those reaches, and the rates of migration of bedforms (and thalweg). Implementation of the recommendations in Section 6 is a vital first step in this regard, especially in view of the increase in barge traffic predicted in the years ahead.

Environmental impacts of dredging have already been considered in some detail by Renewable Resources Consulting Services Ltd (1978), and no further study seems warranted at this time.

8. MAGNITUDE OF SCOUR AND FILL IN SAND BED REACHES

Apart from long-term degradation, which is of little significance in the context of pipeline crossings, scour may be classified as medium-term (associated with the shifting of thalwegs) and short-term, resulting from temporary localized channel deepening in pool areas during short periods of flood hydrographs (followed by infill as hydraulic conditions change).

Some indication of medium-term changes can be obtained directly from channel bathymetry using CHS charts. This would be usefully supplemented by changes in depth noted during repeat surveys (see Section 6). Short-term scour, especially under winter ice or during ice jams, is much more difficult to monitor.

There appears to be no simple technique available for monitoring short-term scour in rivers with depths as great as those in parts of the Mackenzie thalweg.

Recommendation 8.1. Research funding be sought for methods of measuring short-term thalweg scour and fill, particularly under ice breakup conditions.

An appropriate organization to conduct this work would be the National Hydrology Research Institute. Its practical significance should be obvious to any granting agency.

Irrespective of the findings of the research suggested above, the ultimate fate of any pipeline crossing will, to a large extent, depend upon where, along the Mackenzie, it is sited. Some areas are in relatively immobile bed material and do not constitute a worry. Other areas involve sediment that is mobile to depths of at least 20 m below low water datum, and are potentially hazardous.

Preliminary route selection of a pipeline by Gulf Canada (Townsend, pers. comm.) indicates a possible northern crossing of the Mackenzie East Channel near Swimming Point, and a recrossing about 9 km upstream of Fort Simpson. The proposed route for Polar Gas involves crossings in the same places (Kaustinen, pers. comm.). The Swimming Point site on the East Channel has been described by Cooper and Hollingshead (1973) based on studies by T. Blench and Associates Ltd. for Northern Engineering Services Ltd, engineers for Canadian Arctic Gas Study Ltd. It is worth pointing out that it coincides with the outer bank of a rather sharp bend. Presumably the potential instability at this site has been assessed by these consultants.

9. INFLUENCE OF SHOALING ON THE LOCATION OF ICE JAMMING

As with short-term bed scour under ice, the mechanisms involved in ice jam formation are still poorly understood. The formation of ice jams depends on three key factors: the morphology of the channel reach, the mechanical resistance of the ice, and the size and timing of the flood wave. Bedforms that result from sediment transport influence the first and second of these.

Wide shallow areas reduce water pressure at the upriver edge of intact ice, slowing down and even stalling the break up process. The presence of isolated tracts of shallow water (bars) causes sudden constrictions in the flow, thus increasing the probability of blockage of the fragmented ice floes from upstream. Both of these mechanisms contribute to so-called "floating" ice jams.

Possibly more important on the Mackenzie, however, are "dry" or "grounded" ice jams, in which floes become grounded in shallow water, or in which winter water depths were so shallow that bottomfast ice existed over large parts of the channel cross-section at the onset of breakup.

Examination of locations of high driftwood levels associated with ice jamming on the Mackenzie by Mackay and Mackay (1973) indicated many areas in which severe jams (driftwood more than 10 m above June 30, 1970 water level) occurred. Of 11 sites downstream of the Liard, only two seem unrelated to shoaling.

Monitoring of ice jam development by NHRI has so far been concentrated on the Liard River at its confluence with the Mackenzie. Given the problem of flooding at Fort Simpson, and the role of the Liard breakup in starting ice clearance on the Mackenzie itself, this emphasis is understandable. On the other hand this ice jam, a tributary or "estuary" type jam, does not seem to be representative of most jams along the Mackenzie.

Elsewhere on the Mackenzie, the obvious other area of practical concern is Fort Norman where flooding is also a problem. According to CHS Chart 6417, the thalweg shoals rapidly in this area from 11 m below low water datum to less than 4 metres. Most of the main channel on the right side of Windy Island is above the low water datum, and spot soundings near the narrow thalweg are only 2.8 m and 3.2 m. The changing spatial extent, from one winter to another, of bottomfast ice in the Mackenzie opposite Fort Norman, and its relationship to the degree of ice jamming, would seem to be a worthy area for investigation. Certainly, it would appear to be more representative of other ice jam locations on the Mackenzie than is the Liard site.

Recommendation 9.1 The cost/benefit value of a study of ice jamming near Fort Norman be considered by NHRI.

Identification of the exact importance of bottomfast ice and grounding of ice floes in shallow areas, including threshold amounts of bottomfast ice necessary for jamming under different conditions, and the relationship with winter temperatures, might provide not only a means of predicting the probability of ice jamming, but permit some assessment of whether dredging of critical areas could actually alleviate the problem. (See also point 10.2 in connection with Norman Wells.)

Whereas studies such as current work at Fort Simpson and suggested work at Fort Norman allow the identification of processes at work in ice jamming, it would seem worthwhile also to assess the pattern of ice jamming along the Mackenzie River, on an annual basis, to establish the consistency of that pattern and the correspondence with the locations identified by Mackay and Mackay (1973), as part of the general problem of bed material movement down the Mackenzie.

This kind of monitoring, by now, should be possible using images collected routinely by satellites. Certainly, as long ago as 1978, synthetic aperture radar from Seasat was being used to monitor sea ice movement, with images of areas 100 km square, resolution of 25 m and image repeats at 3 day intervals. Replies from the Canadian Centre for Remote Sensing (Game, pers. comm.) indicate that panchromatic imagery from the French satellite SPOT is now available with resolution in the range 10-20 metres, and with repetitive coverage of the order of 11 times in 26 days. Unfortunately the cost of each image is currently $930 and the cost would be prohibitive.

Recommendation 9.2 Further investigation of the possibility of using satellite imagery to monitor ice breakup be undertaken.

In the absence of reasonably priced satellite images of appropriate quality, resolution and frequency, other means should be explored for monitoring the locations of ice jams along the Mackenzie. Such a study would enable verification and refinement of the relationship between ice jam locations on the river and channel bathymetry.

10. ENLARGEMENT OF ARTIFICIAL ISLANDS AT NORMAN WELLS

10.1 Recently constructed artificial islands are indicated on CHS chart 6418 between Goose and Bear Islands and the right bank of the Mackenzie at Norman Wells. Their possible effects on channel pattern and bathymetry were previously considered by Northwest Hydraulics Consultants Ltd. (1979). The rate of growth of the islands and its influence on the overall growth of Goose Island and the stability of the inlet between Goose Island and Bear Island should certainly be monitored.

Such a project would be inexpensive and could provide a great deal of useful information. A simple programme would involve aerial photography each year taken at a constant low water stage on the Norman Wells gauge.

More detailed monitoring of the islands closer to Norman Wells, actually on the east side of the navigation channel, and presumably well away from the main flux of bed material on the west side of the Mackenzie, might provide a unique means of monitoring local bed material transport rates. The work would also need to establish flow trajectories in the channel upriver and bed sediment availability along these flowpaths, together with grain size of the deposits, their upstream sources, and that of incoming suspended load. The resultant data may not have general scientific value given the limited availability of mobile bed sediment on this side of the channel. Nonetheless, they would be very useful in any attempt to estimate local bed material fluxes towards the site of the proposed access channel to Norman Wells, as discussed under item 7.6.

Recommendation 10.1. A program of annual vertical aerial photography, at constant low-water stage, be implemented with the purpose of monitoring the enlargement of these islands. Availability of existing photographs should be checked to provide additional data.

10.2 Changes in the bathymetry of the Mackenzie also raise questions regarding the propensity for ice jamming. This issue was also addressed by Northwest Hydraulic Consultants Ltd (1979). They concluded that the changes would be far too minor, relative to the size of the river channel, to trigger formation of a dry ice jam, but that floating jams might become more severe. Specifically they remark: "It seems possible to envisgage a situation whereby, under worst ice conditions, high water levels upstream from Bear Island might be raised a few metres above the record high conditions of 1974." These conclusions are based on the fact that typical break-up velocity at Norman Wells is close to the critical value above which ice floes will just be carried under a cover, if sheets are keyed to form a surface obstruction, and that, while keying did not appear to be a serious problem under natural conditions, large sheets might occasionally key between some of the artificial islands.

Recommendation 10.2. It would seem appropriate that NHRI consider at least a nominal monitoring programme for ice breakup at Norman Wells.

This, together with monitoring of channel bed changes, would provide, over the long term, the opportunity to assess the impact of systematic bed changes on the propensity for ice jamming.

11. EXPLOITATION OF SAND AND GRAVEL RESOURCES

Based on the report by EBA (1987), mining of sand and gravel from the Mackenzie river bed looms as a major disturbance of the Mackenzie sediment system. As might be expected, however, most of the river reaches with high potential coincide with areas in which abundant granular material is available on the valley flanks (usually the right bank). Close inspection of the EBA (1987) report, in fact, indicates only two reaches in which the river bed potential is high or moderately-high <u>and</u> the adjacent valley flank is deficient in granular material. These are km 450-475 (Camsell Bend) and km 1017-1030 (Sans Sault Rapids). Reference to the surficial geology maps of the Mackenzie corridor indicates that glaciofluvial granular material is actually found in both these areas, though on the left bank in both instances.

It might seem, therefore, that the potential for borrow material in the Mackenzie river bed, relative to that on the north bank, is limited. However, the key issue here is cost, and, for hauls greater than 7 km, river operations appear to be more economical than land exploitation (EBA, 1987). The demand for river bed granular material is therefore likely to be great.

The scarcity of bed material data for the Mackenzie makes accurate determinations impossible. Certainly, it would seem desirable to assess whether any areas designated as priority for dredging for navigation purposes coincide with areas indicated as deficient in granular materials on the adjacent valley flanks.

Recommendation 11.1. Given the scarcity of reliable bed material data for the Mackenzie River, and given the demand for such data for dredging purposes (for both extraction and channel deepening), the Water Resources Branch should assume the initiative in establishing a programme for verifying the nature of the bed sediment at strategic locations along the river.

This should be done in liaison with both INAC (responsible for borrow material extraction) and the Coast Guard (responsible for navigation). Surficial sampling alone will be inadequate. Geophysical methods will need to employed to assess thickness of the alluvium, and geotechnical drilling will be needed to verify bed sediments in selected areas.

In terms of the environmental implications of dredging and extraction, the most serious appear to be those involving (i) downstream scour or (ii) impacts on fish, especially in spawning areas. The severity of these impacts simply cannot be assessed without (i) much more information on bed material transport rates along the length of the Mackenzie, and (ii) much more knowledge of the use of the mainstem Mackenzie by the major fish species. In the latter context, EBA (1987) emphasize that while information regarding fish utilization of tributaries has become available in the last twenty years, a great deal of ignorance remains regarding the main stem. The environmental lobby cannot be taken seriously until it provides much more data on the utilization of the Mackenzie by the major fish species.

SUMMARY AND OVERALL RANKING OF RECOMMENDATIONS IN TERMS OF PRIORITIES

In most cases, the importance attached to each recommendation has been indicated above. Nonetheless, in examining the recommendations as a whole, it is worth emphasizing two points: 1. analysis of existing data be undertaken before new data are collected; 2. in many cases, timing is critical in the implementation of these recommendations as is the coordination among different subprojects.

A. The most urgent needs are full sediment station reviews for stations 10LA002, 10LA003, 10MC002, 10ED002 and 10GC004 as outlined in Recommendations 2.1, 2.2, 2.3, 5.1 and 5.4. These will allow assessment of whether routine sampling at these stations can be abandoned allowing redeployment of resources elsewhere.

B. Equally urgent is an analysis of bed material yields in different reaches along the Mackenzie, using available bathymetric sheets from the Canadian Hydrographic Service, as outlined in Recommendations 6.2.1a, 6.4.1 and 6.5.2. This will provide a clearer indication of the potential of this method, prior to embarking upon further survey work.

C. Assuming that the results of the previous set of analyses (B) are acceptable, further bathymetric survey work should be undertaken as outlined in Recommendations 6.1, 6.2.1b, 6.2.3, 6.4.2, 6.4.3, 6.5.1, 6.6. There is some additional urgency for this work in connection with proposals for dredging and mining of the Mackenzie bed. Related to this topic is further investigation of the actual composition and thickness of the bed alluvium in key areas of the main stem (Recommmendation 11.1).

D. Also urgent is the establishment of new suspended sediment sampling stations near the mouths of the three main Delta distributaries (Recommendation 1) and at Wrigley, Norman Wells and Fort Good Hope (Recommendations 5.3, 6.5.3, 7).

E. After an initial year's sampling at the new sites listed above (D), in which cross-sectional variance in concentration and particle size has been established (together with patterns in the temporal fluctuation), sampling at these new sites, along with relevant established sites, should be expanded to include nutrients (Recommendations 3.1, 3.2), hydrocarbons (Recommendations 4.1.1 and 4.1.2) and heavy metals (Recommendation 4.2).

F. Basic research into ice-jamming in relation to channel shoaling and into the effects of an ice cover on short term bed scour should be increased (Recommendations 8.1, 9.1, 10.2).

G. The remaining recommendations dealing directly with sediment issues are 5.2 (determination of sediment contributions from bank erosion along the main stem) and 6.2.2 (estimation of the bed material load of the Peel near its mouth). The photogrammetric component of these two studies is not likely to be costly and should be done soon. Field verification may be much more expensive and should be deferred until the phogrammetric results have been appraised.

H. The need for a more thorough understanding of the utilization of the Mackenzie main stem by major fish species is of vital importance in any assessment of the impact of land use change on the native peoples of the region. It is listed at the end of this summary, only because it is not obvious that the major impacts on fish resources are sediment-related. This does not mean that the work is neither important nor urgent; it is.

CONCLUSION

One point that clearly emerges from reviewing the literature dealing with the Mackenzie, including reports from ongoing research, is that much of the data being collected could be more useful than it currently is. The problem is that numerous projects are being undertaken, by different government departments, without, it would seem, any clear coordination of policy. Indeed, in many cases, one department does not know what another is doing even though their work is directly related.

A clear, overall, monitoring programme in terms of sediment and water quality must be set up for the entire basin, at least downstream of Great Slave Lake and offshore to the Beaufort Sea. This should go some way to ensuring that data collected upstream can be related to data being collected in the Delta and offshore. In the same way, methods of analysis have to be standardized. If, for example, hydrocarbon fluxes from the river are to be related to hydrocarbon concentrations in the Beaufort Sea, then this requires that the same hydrocarbon compounds be measured upstream and offshore, and by the same sampling, storage and analytical procedures. Similarly, it is clear that parts of the Mackenzie river bed will need to be dredged to increase navigation capacity, while some parts may be desirable as sources of granular material for on-land construction. It is not obvious that these two topics have previously been seen as two sides of the same coin.

In general, what is indicated by this analysis is that some agency, even if only one person, should be responsible for coordinating research and development within the Mackenzie basin. Without this there will be both unnecessary duplication of effort and failure to perceive that the action of one organization has implications for others.

Such a philosophy is not entirely without precedent. The holistic view with regard to river basin management is the raison d'etre, for example, of the River Authorities in the United Kingdom and the Catchment Authorities in New Zealand. While it may be unnecessary to adopt this kind of approach for each major basin in Canada, certain key catchments, such as the Mackenzie, would seem to be ideal candidates for action along these lines.

In fact the Mackenzie Basin Intergovernmental Liaison Committee was formed in 1972 largely for this purpose: to exchange information concerning project planning, research and potential developments. It was reestablished in 1977 as the Mackenzie River Basin Committee, the immediate purpose of which was implementation of a three-year study agreement (1978-81) comprising research into various aspects of the water-related resources and hydrological behaviour of the Mackenzie basin, including its tributaries upstream of Great Slave Lake. Since that time it is not clear that the Committee has played a major role in the coordination of work in the basin, as distinct from reporting the results of such work.

Overall recommendation. An organization be established, or an individual appointed, whose full-time responsibility is the coordination of sediment and water-related issues in the Mackenzie basin.

REFERENCES CITED

Acres International Ltd., 1987. Mackenzie River Economic Study. Prepared for Canadian Coast Guard, North Vancouver, B.C.

BC Hydro, (1984). Liard River Development: Downstream sediment regime and channel morphology. BC Hydro Rept. No. H1281. Unpub. report.

Brunskill, G.J. Campbell, P., Elliott, S.E.M., Graham, B.W., Dentry, W.J., and R. Wagemann, 1975a. The chemistry, mineralogy and rates of transport of sediments in the Mackenzie and Porcupine river watershed, NWT and Yukon, 1971-73. Fisheries and Marine Service, Environment Canada, Winnepeg, Tech. Rept. No. 546, 69 pp.

Brunskill, G.J., Campbell, P. Elliott, S.E.M., Graham, B.W., and G.W. Morden, 1975b. Rates of transport of total phosphorus and total nitrogen in Mackenzie and Yukon River watersheds, NWT and YT, Canada. Verh. Internat. Verein. Limnol., 19, 3199-3203.

Campbell, P. Dentry, J., Morden G.W., Elliot, S., Brunskill, G.J., Wagemann, R. and B.W. Graham, 1975. General physical and chemical data for water and sediment of the Mackenzie and Porcupine watersheds and rates of transport of dissolved and suspended elements at selected stations in the Mackenzie and Porcupine waters, 1971-74. Fisheries and Marine Service, Environment Canada, Tech. Rep. 556, 396 pp.

Church, M., 1971. Reconnaissance of hydrology and fluvial characteristics of rivers in northern Alaska and northern Yukon Territory. Prepared for Mackenzie Valley Pipeline Research Ltd, 197 pp.

Church, M., 1978. Discussion of "Sediment and nutrient loadings to Lake Ontario: methodological arguments." Canadian Journal of Earth Sciences, 15, 668-9.

Church, M., Miles, M and K. Rood, 1986. Sediment transfer along the Mackenzie River : a feasibility study. Sediment Survey Section, Environment Canada, Ottawa.

Colby, B.R., 1957. Relationship of unmeasured sediment discharge to mean velocity. Transactions, American Geophysical Union, 38, 708-717.

Cooper, R.H. and A.B. Hollingshead, 1973. Riverbank erosion in regions of permafrost. In: Fluvial processes and sedimentation, Proc. of Hydrology Symposium, Inland Waters Directorate, Dept. of the Environment, Ottawa, 272-283.

Davies, K.F., 1975. Mackenzie River input to the Beaufort Sea. Dept. of the Environment, Beaufort Sea Project, Victoria, Tech. Rep. No. 15, 72 pp.

EBA Engineering Consultants Ltd, 1980. Geotechnical engineering overview of Mackenzie Valley route data. Prepared for Polar Gas Project.

EBA Engineering Consultants Ltd, 1987. An evaluation of the feasibility of developing granular borrow material from the bed of the Mackenzie River. Prepared for Indian and Northern Affairs Canada, Ottawa. 66 pp.

Ferguson, R.I., 1987. Accuracy and precision of methods for estimating river loads. Earth Surface Processes and Landforms, vol. 12, 95-104.

Galay, V., 1978. Sedimentation. In: "Environmental Review and Assessment: Proposed Mackenzie Dredging. Volume 2". Renewable Resources Consulting Services Ltd, 838 pp.

Hem, J.D., 1959. Study and interpretation of the chemical characteristics of natural water. US Geological Survey Water Supply Paper 1473.

Inland Waters Directorate, 1985. Hydrology Information Series: 12 maps sheets (1:250,000). IWD, Yellowknife, NWT.

Lapointe, M.F., 1984. Patterns and processes of channel change, Mackenzie Delta, NWT, 1983-84 progress report. National Hydrology Research Institute, Environment Canada, Ottawa, 52 pp.

Lapointe, M.F., 1986. Deep scour holes on the bed of Mackenzie Delta channels, NWT. National Hydrology Research Institute, Environment Canada, Ottawa, 36 pp.

Lewis, C.P., 1987. Mackenzie Delta Sedimentary Environments and Processes: Issues and Recommendations. Prepared for Water Resources Branch, Inland Waters Directorate, Ottawa. 17pp.

Lewis, C.P., in prep. Sedimentary environments and processes on the modern Mackenzie Delta. Report to Canada Dept. of Environment and Canada Dept. of Indian and Northern Affairs.

Lockhart, W.L., Metner, D.A., Murray, D.A.J., Danell, R.W., Billeck, B.N., Baron, C.L., Muir, D.C.G. and K. Chang-Kue, 1987. Second cumulative data report of studies to determine whether the condition of fish from the lower Mackenzie River is related to hydrocarbon exposure. Draft report, Dept. Fisheries & Oceans, Winnepeg, Manitoba, 179 pp.

Mackay, D.K. and J. R. Mackay, 1973. Locations of spring ice jamming on the Mackenzie River, NWT. In: Hydrologic aspects of northern pipeline development, Environmental Social Committee , Northern Pipelines, Task Force on Northern Oil Development 73-3, 233-237.

Mackay, J.R. and W. H. Mathews, 1973. Geomorphology and Quaternary history of the Mackenzie River Valley near Fort Good Hope, NWT, Canada. Canadian Journal of Earth Sciences, 10, p. 26-41.

Mackenzie River Basin Committee, 1985. Water Quality. Mackenzie River Basin study report, Supplement 9.

Nagy, E., Carey, J.H., Hart, J.H., Ongley, E.D. and J. Tisdale, 1986. Hydrocarbons in Mackenzie River suspended sediments. National Water Research Institute Contribution 86-65, Burlington, Ontario.

Nagy, E., Carey, J.H., Hart, J.H. and E.D. Ongley, 1987. Hydrocarbons in the Mackenzie River. National Water Research Institute Contribution No. 87-52, Burlington, Ontario.

Northwest Hydraulics Consultants, Ltd, 1979. Regime of Mackenzie River at Norman Wells in relation to artificial island scheme. Report for Esso Resources Canada Ltd, 34 pp. (Proprietary)

Outhet, D.N., 1974a. Bank erosion in the southern Mackenzie River Delta, NWT, Canada. Unpub. M.Sc. thesis, Univ. of Alberta, 85 pp.

Outhet, D.N., 1974b. Progress report on bank erosion studies in the Mackenzie River Delta, NWT. In Environmental Social Committee, Northern Pipelines, Task Force on Northern Oil Development 74-12, p. 292-345.

Peake, E., Baker, B.L. and G.W. Hodgson, 1972. Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada - II The contribution of amino acids, hydrocarbons and chlorins to the Beaufort Sea by the Mackenzie River system. Geochimica et Cosmochimica Acta, 36, 867-883.

Public Works Canada, 1976. Mackenzie River Investigation: proposed navigation channel improvements, 4 volumes. Design and Construction Branch, Edmonton.

Renewable Resources Consulting Service Ltd, 1978. Environmental review and assessment of proposed Mackenzie River dredging project. Prepared for Canada Dept of Public Works and Dept of Transport, Edmonton, 838 pp.

	km	chart	dates		
Point Separation	1480				
Arctic Red River		6426	1973	1977.78	New
	1400				
Barrel Crossing		6425	1973	1978	New
	1325				
		6424	1972	1979	
	1240				
		6423	1973	1979	
	1180				
		6422	1972	1979	
Fort Good Hope	1100				
Hume River		6421	1971		New
	1040				
Mountain River		6420	1971		New
	980				
		6419	1971	1978	New
Norman Wells	910				
		6418	1973		
	850				
		6417	1973		
	810				
Keele River		6416			New(P)
	730				
Redstone River		6415			New(P)
	650				
		6414			
	580				
Wrigley		6413	1972		
	510				
		6412	1972	1978(P)	
N. Nahanni River	460				
		6411		1979	New
	390				
		6410			
Liard River	330				

N.B. (P) denotes part of sheet

TABLE 1 FULL CHART SURVEYS BY CANADIAN HYDROGRAPHIC SERVICE Existing and recommended.

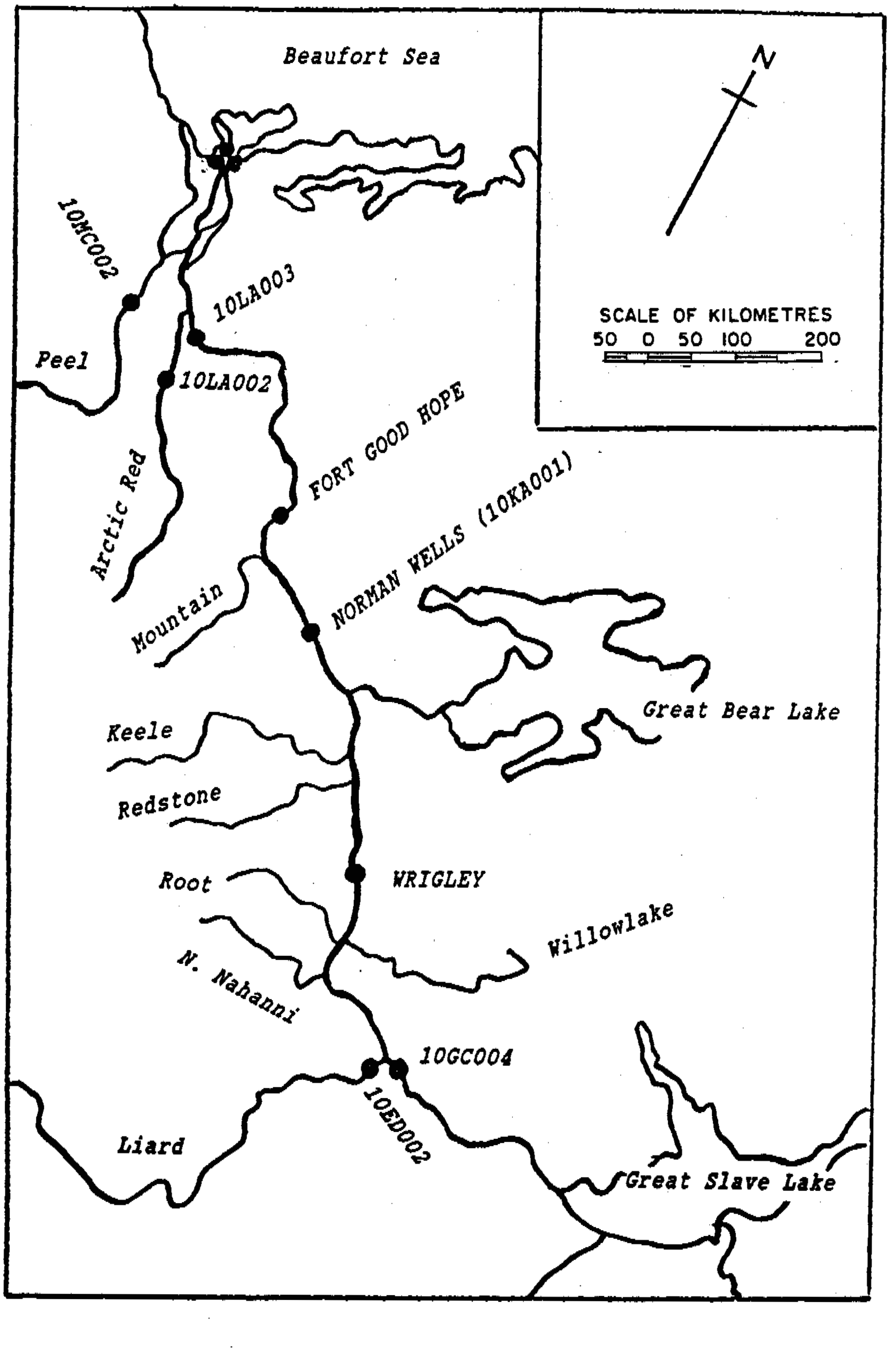


FIGURE 1 EXISTING AND PROPOSED SUSPENDED SEDIMENT SURVEY STATIONS

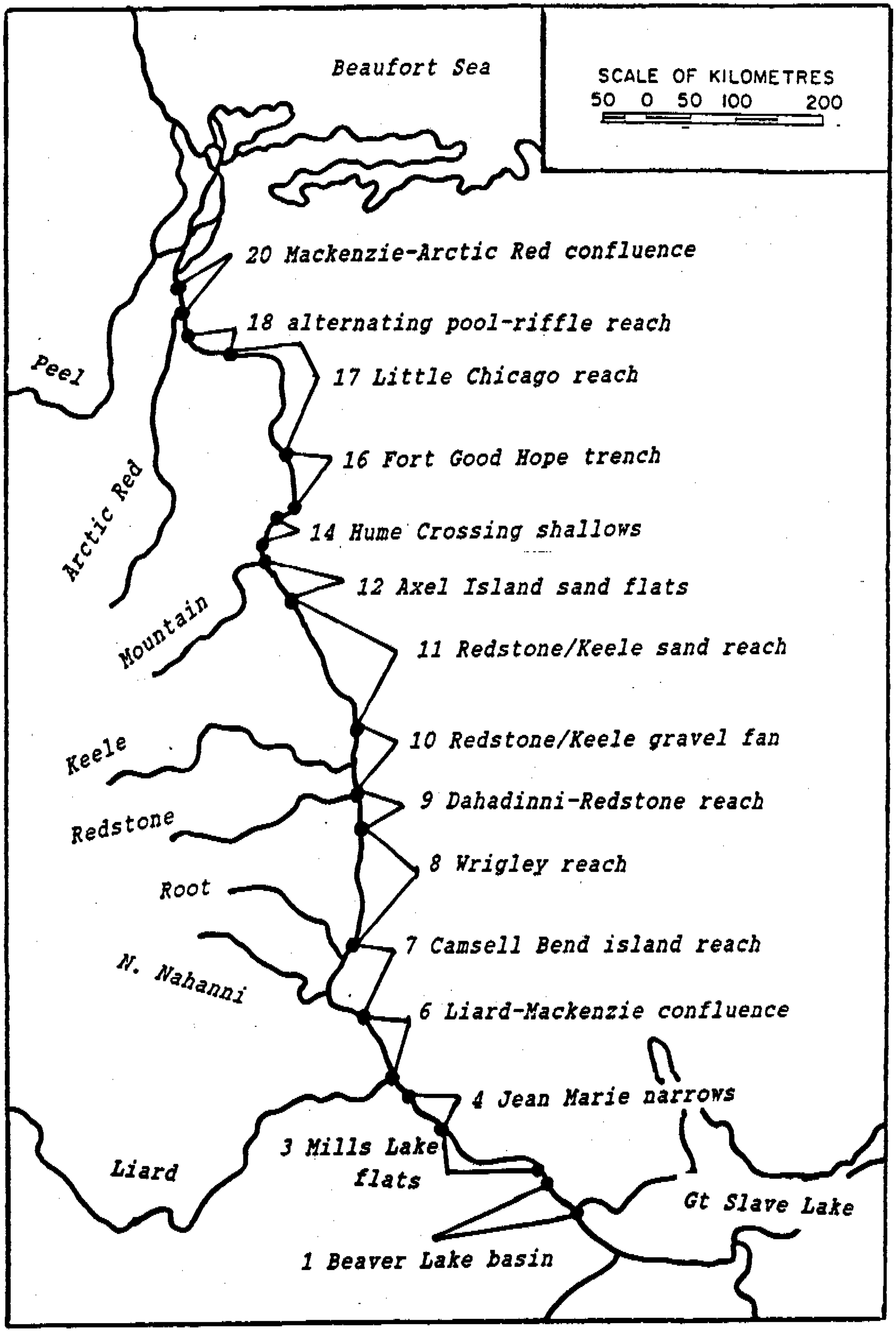


FIGURE 2 REACHES OF THE MACKENZIE RIVER

unnumbered reaches are rapids: 2: Providence 5: Green Island 13: Sans Sault 15: Ramparts; 19 is Lower Ramparts bend

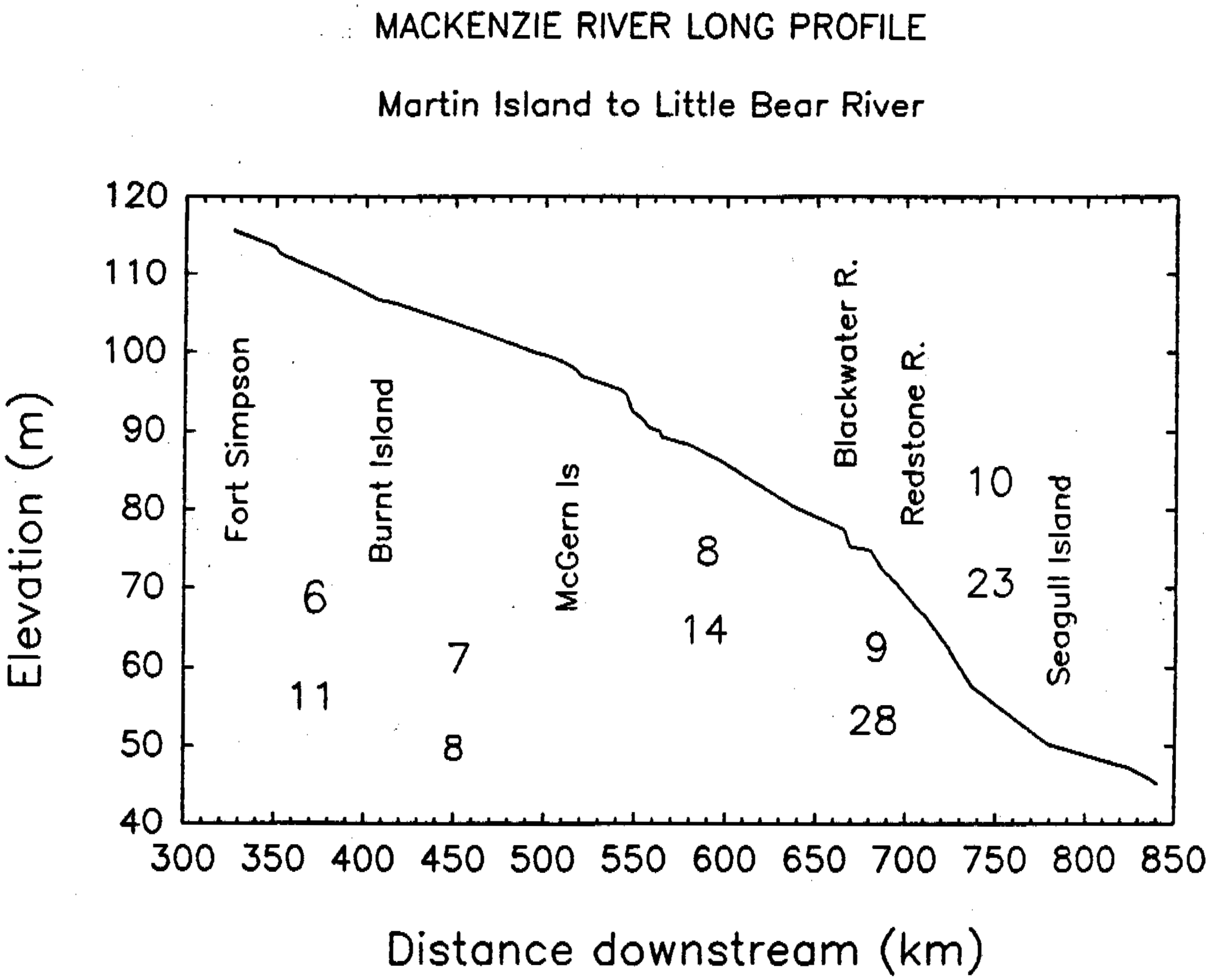


FIGURE 3a MACKENZIE RIVER LONG PROFILE: Martin Island to Little Bear River

(based on data from Geodetic Survey of Canada <u>in</u> Public Works Canada, 1976)

Values are reach number (top) and gradient in m/100 km

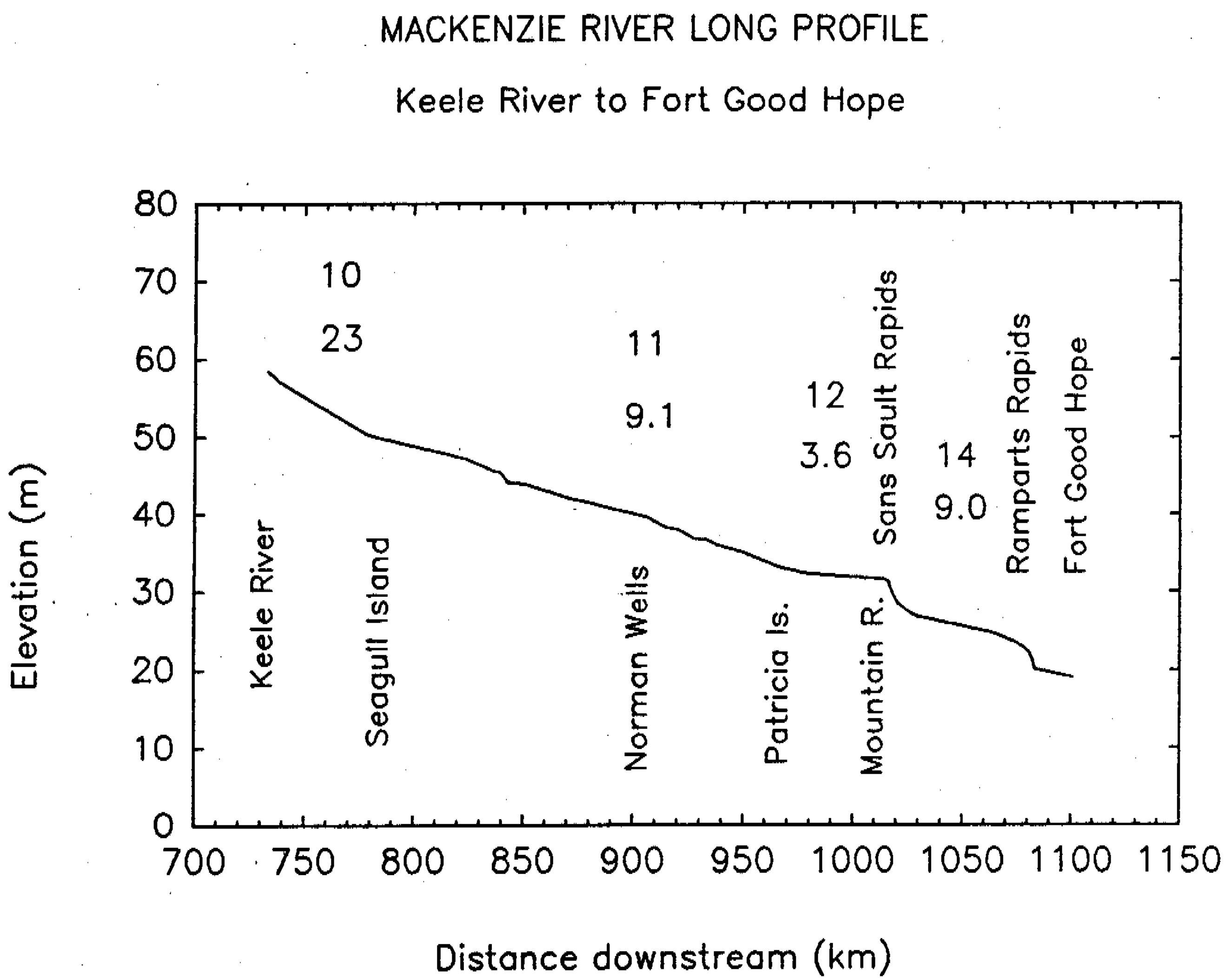


FIGURE 3b MACKENZIE RIVER LONG PROFILE: Keele River to Fort Good Hope

(based on data from Geodetic Survey of Canada in Public Works Canada, 1976)

Values are reach number (top) and gradient in m/100 km

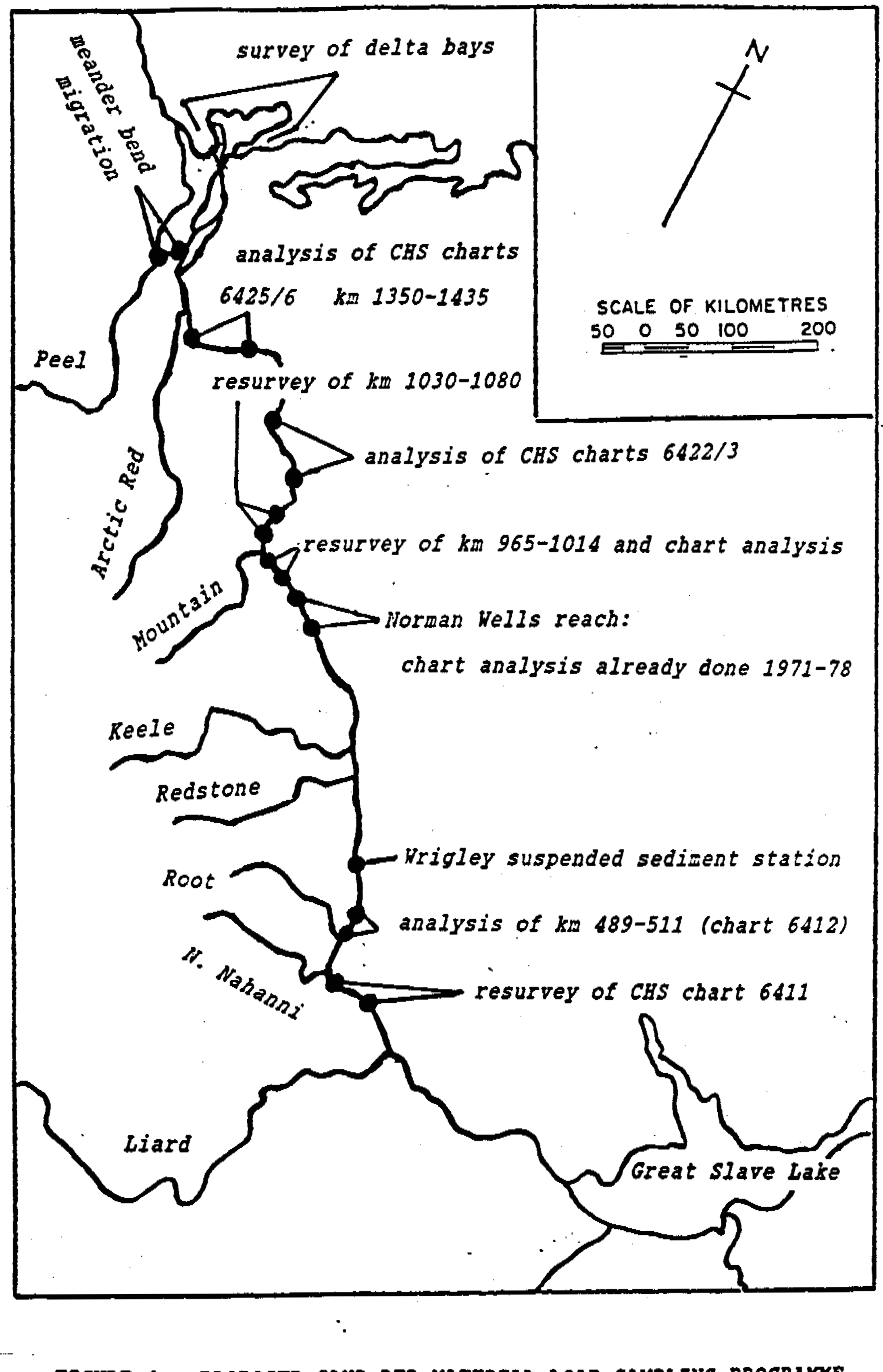
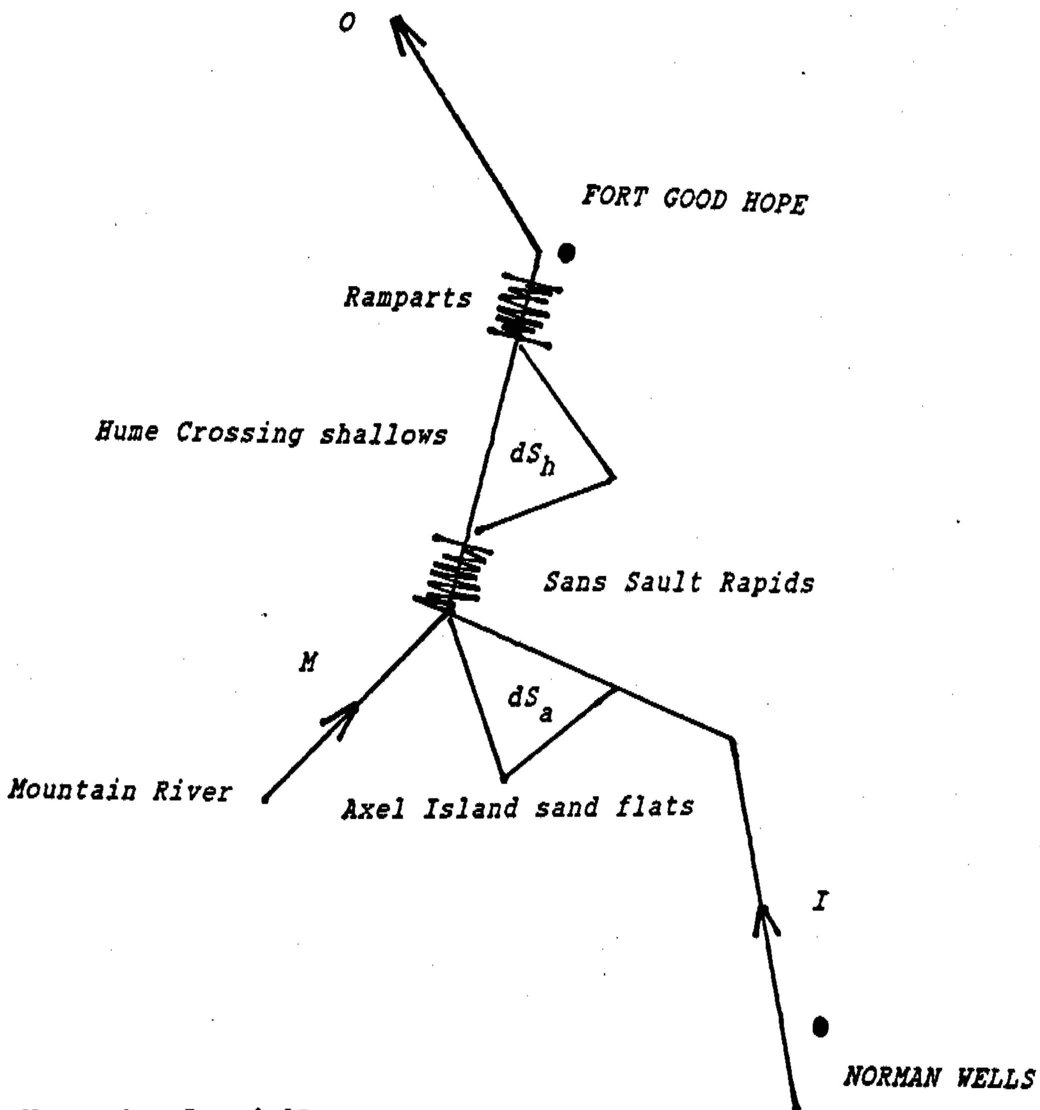


FIGURE 4 PROPOSED SAND BED MATERIAL LOAD SAMPLING PROGRAMME

FIGURE 5 CALCULATION OF CONTRIBUTION OF MOUNTAIN RIVER TO SANDY BED MATERIAL LOAD OF MACKENZIE RIVER BELOW FORT GOOD HOPE



$$M = O - I + (dS_a + dS_h)$$

where

M = contribution of Mountain River

O = sandy bed material load downstream of Fort Good Hope

I = sandy bed material load at Norman Wells

dS_a dS_h = aggradation in Axel Is and Hume reaches