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1992 PROGRESS REPORT ON SEDIMENT-RELATED ASPECTS OF NORTHERN HYDROCARBON DEVELOPMENT

(IWD-NWT NOGAP Project C.11)

by

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for

Inland Waters Directorate
Environment Canada
Yellowknife, NWT

under contract
KE521-1-0085/01-XSG
Supply & Services Canada, Edmonton

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1992 Progress Report on Sediment-Related Aspects of Northern Hydrocarbon Development: IWD-NWT NOGAP Project C.11

Background

The Mackenzie is one of the worlds largest, ecologically important deltas, due to the outflow of warm, sediment laden water to the Arctic Ocean. Each year's runoff produces delta flooding, melting and breakup of sea ice cover for distances of 150 to 250 km offshore, and nutrients for aquatic and marine life. The delta reflects a delicate balance between hydrologic and aquatic sediment regimes of the Mackenzie River, nearshore Beaufort Sea marine conditions, and local climate and terrain conditions.

Past experience in Canada and elsewhere has demonstrated the sensitivity of deltas to changes in the magnitude, timing, and character of annual inputs of water and sediment. Significant impacts have occurred from disturbance of the complex linkages between delta physical and biological processes, and subsequent socio-economic effects.

Construction of major pipeline gathering networks and onshore collection facilities will occur in low-lying, flood prone and unstable terrain if delta area hydrocarbon development proceeds. The widespread presence of permafrost increases the area's sensitivity to disturbance from climatic change, human activities, and river channel migration, thus posing additional problems to development. Recent research has also shown the importance of sediments in the transportation, fate, and effects of industrial contaminants.

Lack of knowledge and clear understanding of delta processes raise serious concerns over potential impacts from development of local hydrocarbon resources on delta ecosystems. Alteration of the flow regime of the Mackenzie River due to upstream development or climate change is also a concern, due to potential impacts on stability of delta channels and the Beaufort Sea coast.

NOGAP Study Focus

Environment Canada's mandate to characterize, protect, and monitor the environment originates in the Canada Water and Environmental Protection Acts. The Inland Waters Directorate (IWD) produces water level, streamflow, water quality, sediment flux, hydraulic, and geomorphologic information, to support the department's broad Green Plan (GP) ecosystem environmental effects monitoring approach. Knowledge of the Mackenzie Delta's hydrologic and sediment regime is clearly required to understand and manage impacts from major development.

Requirements for additional information and in-house IWD expertise to assess and regulate development projects and provide timely environmental advice, are the focus of IWD-NWT NOGAP studies. The 1990-1994 IWD-NWT NOGAP project is designed to address deficiencies in delta knowledge, by building on past data collection and study efforts by IWD and others. These include the delta component of 1978-1981 Mackenzie River Basin, 1980-1983 BC Hydro Liard project, 1983-1987 IWD NOGAP, and other studies.

The main objectives of IWD's current NOGAP work are: to develop a model of delta hydrology and hydraulics, investigate and model delta sediment flux, document contaminant levels, and develop a hydrologic information database system for the Mackenzie Delta.

Hydrologic, hydraulic, and sediment transport aspects of NOGAP studies are being handled by IWD-NWT technical and professional staff. Investigation of certain aspects of sediment-related topics, particularly those involving source fate and effect of contaminants bound to sediment, sediment source and deposition areas, delta sedimentation, and delta channel stability, require outside expertise. This expertise is being accessed through partnerships with other agencies and contracts with university and private sector consultants.

Sediment-Related Aspects

M. A. Carson and Associates of Victoria, British Columbia were contracted to review past and present sediment related data and information for the Mackenzie River and Delta, under the 1991-1992 IWD-NWT NOGAP Project. Objectives of the contract included:

> **Investigation of past and present morphologic stability of channels within the Mackenzie Delta, with particular emphasis on potential pipeline crossing sites.**
>
> **Synthesis of historic sediment data for the Mackenzie River, to provide insight on the source, distribution and fate of sediment and sediment-borne contaminants within the basin.**

Advice on selection of sites and operation of sediment monitoring stations within the Mackenzie Delta, to ensure that representative samples are collected at major inflow and outflow locations of the delta.

A series of five reports were produced under this contract, including:

Suspended Sediment Sampling in the Mackenzie River, Northwest Territories: Review and Recommendations;

Sedimentation Measurements in the Mackenzie Delta, Northwest Territories: Review and Recommendations;

Channel Stability in the Mackenzie Delta, Northwest Territories: A Review;

Proposals for Hydraulic and Morphologic Surveys in the Mackenzie Delta, Northwest Territories; and

Sediment Station Analysis in the Mackenzie Basin, Northwest Territories.

These reports synthesize current knowledge of Mackenzie River basin and delta area sediment processes, and make recommendations on IWD NOGAP studies to resolve aspects important to hydrocarbon development.

Although each report is a stand alone document, they progress logically from sediment sampling, to delta sedimentation, channel stability, channel surveys, and upstream sediment sources, and have been printed as a single product of 1991- 1992 IWD NOGAP work, as well as a sediment reference for the Mackenzie Delta.

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Further copies of this report, or other IWD-NWT NOGAP study documents, can be obtained by writing to:

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TABLE OF CONTENTS

SECTION I: SUSPENDED SEDIMENT SAMPLING IN THE MACKENZIE DELTA

SECTION II: MACKENZIE DELTA SEDIMENTATION STUDY

SECTION III: CHANNEL STABILITY IN THE MACKENZIE DELTA

SECTION IV: HYDRAULIC AND MORPHOLOGIC SURVEYS

SECTION V: SEDIMENT STATION ANALYSIS IN THE MACKENZIE BASIN, NORTHWEST TERRITORIES

SUSPENDED SEDIMENT SAMPLING IN THE MACKENZIE DELTA, NORTHWEST TERRITORIES: REVIEW AND RECOMMENDATIONS

by

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Supply & Services Canada, Edmonton

February, 1992

Acknowledgements

This report was prepared as one part of Contract KE521-1-0085/01-XSG administered by Supply and Services Canada. F. M. Conly of Inland Waters Directorate, (IWD), Yellowknife, NWT acted as Scientific Authority. The assistance provided by Malcolm Conly and Jesse Jasper in the preparation of the report is duly acknowledged.

Thanks are also extended to Moe Hansen and staff at IWD, Inuvik for providing a field perspective to some of the problems involved in working in the outer Mackenzie Delta; to John Kerr, IWD, Yellowknife for information regarding the 1-d model; to Henry Hudson, IWD, Winnipeg for comments on an earlier version of the report; and to Richard Yungwirth, IWD, Regina for provision of sediment laboratory data.

Executive Summary

1. A review is provided of the 1970s and 1980s suspended sediment sampling program in the Mackenzie Delta. Examination is also made of the initial part of the 1991 program. Recommendations for future sampling operations are provided.

2. Mid-delta sampling has been done on a transect between Aklavik and Inuvik. Past stations (continued today) are located on Peel Channel, Middle Channel and East Channel. Discontinued stations occur on West Channel, Aklavik Channel and North Kalinek Channel. The purpose of this program is to determine the quantitative importance of different sediment pathways through the delta.

3. Analysis of the mid-delta data indicate several problems: sediment rating diagrams are mediocre; there are gaps (unsampled tributaries) in the 1990s program; and the mid-delta sediment flux is dominated by Middle Channel. The latter problem is compounded by the difficulty of choosing a representative single-vertical (SV) sampling site in the reach.

4. It is recommended that the financial advantages of abandoning the mid-delta program (and replacing it with increased sampling at the outer-delta sites) be examined. If the mid-delta program is continued, the limitations of the data must be clearly recognized; suggestions are made for improvement in the sampling program.

5. Sediment sampling in the outer-delta is being undertaken to estimate the sediment flux to Beaufort Sea and, indirectly, the sediment accumulation on the landward delta surface. Sediment stations are located on Reindeer Channel, Middle Channel and East Channel.

6. The outer-delta program also contains "gaps" in the sample design, though these may be countered by limited miscellaneous sampling on the small channels involved. Another problem in the program is the great difficulty in selecting appropriate single-vertical sampling sites: most potential cross-sections in the outer delta are either downstream of distributary confluences or downstream of bends. In both cases, non-uniform distribution of suspended sediment in the cross-section can be expected. The limited k-value data so far available at these three sites are relatively encouraging, but more assessment of the SV locations is required at high flows.

7. It is recommended that, as far as possible, multi vertical (MV) sampling be given preference at the outer-delta sites until such time as the location of a suitable SV point has been clearly determined. This comment is made particularly for the East Channel site downstream of Tununuk Point.

8. The delta-head sediment stations (Mackenzie at Arctic Red River, Arctic Red River and Peel River) are not included in this review. The conclusions of previous reports are, however, summarized in the last section.

9. At all stations in, and at the head of, the delta, the problem of developing a reliable algorithm for prediction of daily sediment concentration from hydrograph data must be clearly recognized. Rainstorm-induced floods tend to produce higher sediment concentrations than snowmelt floods, but the amount and timing of excess sediment is highly variable depending on location and intensity of runoff-production within the Mackenzie drainage basin. The sediment rating for Mackenzie at Arctic Red River is acceptable for estimation of long term data: this reflects the large body of data collected at this site. The data sets for the in-delta sites need much more data before they will attain comparable precision.

1. SUSPENDED SEDIMENT SAMPLING IN THE MACKENZIE DELTA: INTRODUCTION

1.1 Preamble

Sampling of suspended sediment within the Mackenzie Delta has been undertaken only sporadically by Inland Waters Directorate, (IWD), in contrast to the Mackenzie River itself at the head of the Delta. At the latter station (just upstream of Arctic Red River) a sediment sampling program has been in operation since 1972, and a detailed analysis of the program was recently undertaken (Carson, 1988). In the light of this information on the sediment flux to the Delta, attention is now being directed more to the pathways of sediment movement through the Delta and the extent of sediment output from the Delta to the Beaufort Sea.

It is with this perspective that the present report has been commissioned. Its purpose is to (a) review past data for suspended sediment in the Delta, and (b) provide recommendations regarding the current and future program of sediment sampling within the Mackenzie Delta.

1.2 Past sediment sampling in the delta

Apart from a one-day sampling program in 1982 which covered 19 sites in the Delta, suspended sediment sampling has been concentrated in two main areas (Fig. 1.1):

(a) along a mid-delta transect between Aklavik and Inuvik;
(b) in the outer delta.

The number of days of sampling done at these sites, since the sediment program began in the mid-1970s, is indicated in Table 1.1.

The mid-delta program operated primarily in 1974 and 1975. The 1974 data (and some of the early 1975 data) are given in the report by Davies (1975). The full 1975 data set is included in the publication of miscellaneous sediment data by Inland Waters Directorate (1988).

The outer-delta program is in its infancy and no publication appears to exist describing either the operation of the program or the preliminary results.

Both programs are reviewed in detail in the following two chapters.

1.3 Rationale for the present program

The rationale for the present suspended sediment program in the Mackenzie Delta is set out in two documents by Wedel (1990 a,b) describing possible IWD strategies in connection with the Northern Oil and Gas Action Program (NOGAP) of the 1990s.

The mid-delta sampling program is an attempt to determine the pathways of suspended sediment through the delta complex. It will be related to other work designed to map the pattern of overbank sedimentation across the delta. In turn, this information will be useful in any future attempts to determine the distribution of sediment-bound hydrocarbon pollutants originating from the Mackenzie Basin.

The outer-delta sampling program is an attempt to determine the sediment flux from the Mackenzie Delta to the Beaufort Sea. This is of direct interest in itself, especially to workers in the Department of Fisheries and Oceans, in the Geological Survey of Canada, as well as to the Canadian Coast Guard (in connection with dredging) and to pipeline companies. It is also of interest in comparison with the sediment flux into the Delta (from the Mackenzie, Arctic Red and Peel rivers): examination of the two fluxes would allow some assessment of how much of the sediment delivered to the delta actually accumulates on the landward delta surface.

The two sediment programs just noted are described, together with monitoring of sediment inputs to the delta, more fully in the NOGAP budget statement for project C11.3 (Jasper, 1991). The preliminary sampling design for the delta stations (based on a three year program) is shown in Table 1.2. The program would thus yield about 12 full sediment (multiple vertical: MV) measurements at each delta site, together with about 15 single vertical (SV) samples.

Together with pre-existing data, this information would hopefully be suitable for establishing a sediment "module" for the 1-dimensional flow model for the delta (Wedel, 1990 a,b). In conjunction with discharges predicted for each station by the 1-d hydrological model, the sediment module would allow determination of sediment fluxes at the mid-delta and outer-delta sites. The nature of this sediment "module" has not been specifically established: the topic is pursued below.

1.4 Nature of the delta sediment module

The task of predicting sediment concentrations on days when no samples have actually been taken has usually been approached by IWD in one of two ways: (a) interpolating between sampled days (using the hydrograph as a guide) when gaps are small, generally no more than a few days; (b) using a statistical relationship between discharge and sediment concentration (a sediment rating plot), developed from days on which sampling has been done, so that concentration can be predicted from discharge when samples have not been taken.

In connection with the development of the 1-dimensional hydrodynamic model in other areas of Canada, a computer module has also been established for the prediction of sediment concentrations (Morse, 1991; Wisner & Associates Inc., 1991). This module provides the user with a choice of various sediment transport functions: the Ackers-White equation; the Yang equation; a sediment-velocity rating curve; a sediment-(velocity/depth) rating curve; a sediment-velocity rating curve including an initiation of motion criterion; and an excess shear-stress rating curve.

The module provides abundant flexibility. It is, however, only as good as allowed by the assumptions embodied in the individual transport functions. The problem in the context of the Mackenzie Delta is quite simple. The sediment transport issues are largely those related to suspended load, of which more than 95% (at Arctic Red River) is wash load (sediment which is finer than that found in the channel bed). No satisfactory sediment transport function exists for wash load: all the functions listed in the sediment module above refer to bed-material load. Indeed, Morse (1991, p. 249) specifically notes in his review of the One-D-Sed module: "ONE-D-SED should be further developed to include the modelling of the wash load, sediment sorting processes, and bed armouring."

The problem here is that a large body of data exists to show that wash load transport is largely river-specific, being based on sediment production from catchment slopes and river banks, and not directly related to bed-material movement. It requires empirical analysis of large amounts of data: this is essentially what the conventional sediment rating approach (log concentration plotted against log discharge) involves. Therefore, notwithstanding frequent reference in IWD reports to the "sediment module" of the 1-dimensional delta model, the task of calculating sediment loads at individual stations in the delta is likely to remain one that is based on the development (and extension) of satisfactory c-Q sediment ratings at each site using data collected by Inland Waters Directorate. This report is therefore directed primarily to the assessment of suspended sediment data for that purpose.

2. MID-DELTA STATIONS

2.1 Review

2.1.1 1974-75 sampling program

The main period of sampling along the mid-delta transect (Fig. 2.1) was during the summers of 1974 and 1975. The data for the former include daily estimates of both discharge and sediment concentration, and thus sediment loads also, for the period June through September inclusive (Davies, 1975). The 1975 results have been published only as miscellaneous data by Inland Waters Directorate (1988), i.e. as instantaneous discharge and concentration at the time of sampling.

The 1974 data are particularly important because they coincide with some of the biggest sediment-transporting flows in the Mackenzie Basin since sediment monitoring began in the early 1970s. It has been estimated that the annual wash load of the Mackenzie during 1974 at the entrance to the delta (the station upstream of Arctic Red River) was 142 Mt, slightly higher than in 1975, and much higher than any other year in the period 1974-86 for which the mean load was 98 Mt (Carson, 1988). (The 1988 annual load has since been estimated at about 150 Mt also (Carson, 1992)). Much of the sediment load in 1974 was moved during the month of August.

A summary of the 1974 monthly loadings, given by Davies (1975), is provided in Table 2.1. The raw data are given in Appendix A. Though the data are generally based on only two or three samples in each month, the overall pattern conveyed by the data - the dominance of Middle Channel - is unlikely to be misleading because of any errors in interpolation between sampled days. Though the data of Table 2.2 indicate some differences among the channels in terms of sediment concentration, the statistical reliability is severely limited by the small number of samples. Peel Channel (with only a small amount of water from the Mackenzie River) seems to have generally lower sediment levels. The dominance of Middle Channel in terms of sediment load simply reflects its huge discharge, with more than 85% of the total flow through the mid-delta transect. A more detailed analysis of the sediment concentrations at these sites is provided in Section 2.2.3.

The 1974-75 mid-delta program was well-planned in terms of sediment station locations with sampling on almost all major distributaries on the transect between Aklavik and Inuvik. One, perhaps minor, flaw seems to be that the Kalinek station was not actually located on the main Kalinek channel (which joins Middle Channel just downstream of Horseshoe Bend) but on a distributary that branches off to the north, and entering Middle Channel via Oniak Channel (Fig. 2.1). To avoid confusion, this station (10LC6) is referred to as North Kalinek channel in this report. The significance of this point depends on the exact location of the Middle Channel station. Though the latter was labelled "Middle Channel above Napoiak Channel", the map of Davies (1975, Fig. 2) shows the site at Raymond Channel, just downstream of Horseshoe Bend. Assuming that this was the actual site of the Middle Channel station, it means that the sediment flux along the true Kalinek Channel was not sampled. It should also be noted that the old hydrometric station "Middle Channel above Napoiak" has the designation 10LC8, and not 10MC6 used by Davies (1975).

The report by Davies (1975) distinguishes between multiple-vertical and single-vertical sampling, but does not include the raw data for the individual verticals. These data have not been found elsewhere, except for the case of Peel Channel above Aklavik Channel. Thus, unfortunately, with the exception of Peel Channel, no assessment can be made of the representativeness of the single vertical sampling site. Some effort should be made to find the comparable data sheets for the other sites - especially for Middle Channel - if the 1974-75 data are to be used in subsequent sediment rating analyses.

Bed material samples were taken in 1991 at the three current mid-delta stations (Peel Ch. 10MC3; Middle Ch. 10MC8; and East Ch. 10LC2), but data were not available at the time of preparation of this report.

2.1.2 Individual stations

10MC3: Peel Channel above Aklavik

The data for sediment concentrations sampled at this site are given in Table 2.3. They include 7 MV sampling during the 1974-75 period. No statement has been found regarding the location of the SV sampling during 1974-75. The 1991 sampling used a SV site 195 m from the right bank. The location of the sediment sampling cross-section is shown in Fig. 2.2, taken from Hydrographic Chart 6437.

The channel at the sampling site is about 250 m wide and straight. The hydrographic chart (based on an undated survey, believed to be mid-1960s) shows the thalweg against the left bank. Soundings during the MV sampling of the mid-1970s confirm this asymmetry in the cross-section (Fig. 2.3), but no indication has been found in the notes as to which side corresponds to the left bank, except for the 1975 sampling.

The chart bathymetry is consistent with the soundings taken in the 1991 sampling (June 12) which show (Fig. 2.4) a shoal along the right bank. Bed material was sampled on five verticals across the channel (plus banks) in 1975 (Fig. 2.3) and indicates the bed to be more than 90% silt-clay along the left half of the channel, but less than 50% silt-clay in the right half. Unfortunately no depths were given in the 1975 bed material sampling. The impression gained is that the right part of the channel, at least in the mid-1970s, corresponded to a sandy lateral bar. The degree of stability of this bar might be expected to have some influence on changes in cross-sectional distribution of suspended sediment over time.

The cross-sectional distribution of sediment concentration in the 1970s MV sampling (Fig. 2.3) indicates a consistent pattern of increase towards the bank adjacent to the thalweg. The SV location - if it was the same as used in 1991 - would appear to have adequately represented mean sediment concentrations. The August 1 1974 MV samples were subject to grain size analysis, but showed no systematic pattern across the channel: the clay fraction ranged 61-65 percent. No obvious explanation exists for the cross-sectional pattern of total sediment concentration, but it may well be that levels along the right side were reduced by sedimentation in the slower moving water over the bar. The same cross-sectional pattern is found in the June 1991 sampling.

The available sediment data for the Peel Channel site are summarized in Table 2.3. The sediment rating diagram is given in Fig. 2.5.

10MC4: West Channel below Aklavik Ch.

The available sediment data for the West Channel site are summarized in Table 2.4. The location of the sampling cross-section is not known exactly, but the reach below Aklavik Channel is shown in Fig. 2.6. The channel widens (and shallows) appreciably in the reach, posing problems for both a hydrometric and sediment sampling program. No suspended sediment data have been found since 1975, though sampling was apparently done in 1982. The sediment rating diagram is given in Fig. 2.7.

10MC5: Aklavik Channel above Schooner Ch

The available sediment data for the Aklavik Channel site are summarized in Table 2.5. The location of the sampling cross-section is not known exactly, but the reach above Schooner Channel is shown in Fig. 2.8. The reach is highly sinuous; location of a representative SV site may be difficult in these circumstances. The sediment rating diagram is given in Fig. 2.9. Again, no sediment data have been found since 1975, though sampling was reported for 1982.

10MC6: Middle Channel above Napoiak Ch
10MC8: Middle Channel below Raymond Ch

These two sites are grouped together, representing the reach of Middle Channel between Horseshoe Bend and Napoiak Channel. As already noted, the exact location of 10MC6 (used in the 1970s) is unclear. The location of the 1980s-90s site is shown on Fig. 2.10. The hydrographic chart shows two sections for 10MC8: the older section at the bend apex was used for hydrometric measurements only. The new section, downstream of the bend, is the one currently used for sediment and hydrometric work.

The old 10MC8 section is certainly not suitable for sediment sampling. The right hand bank upstream of the site (and downstream of the Horseshoe cutoff) is subject to rapid bank scour (estimated by Lapointe (1984) to be in the range 10-30 metres per year between 1950 and 1981). This would lead to excess suspended sediment in the right half of the channel, posing difficulties in locating a suitable SV site that would be representative of the cross-section. There is also the problem that some of this locally-acquired sediment passing through the old section might be redeposited immediately downstream in the right bank point bar. Thus measurements of the suspended load flux at this site would be overestimates of the true flux for the reach as a whole.

The latter problem largely disappears at the new 10MC8 section, though it is clear that the right bank point bar is extending downstream through the new section; this means that some of the sediment sampled in the right side of the new section is still being deposited just downstream.

The problem arising from the asymmetric distribution of sediment in the cross-section is likely to persist for several kilometres downstream of the bend. The sampling on June 12 1991 (Fig. 2.11) confirms the existence of excess concentrations in the right half of the channel. (Note that there is some contradiction in the survey notes for this date. The hydrometric notes (which have been assumed to be correct) indicate the reference point for the section to be on the left bank. The sediment survey notes indicate the reference point to be on the right bank.) The SV location (in line with the Coast Guard marker), being to the left of the thalweg, is in the zone of less turbid water. The k-value for June 12 (using a simple mean concentration, not weighted by discharge) was 1.06, not appreciably above unity. It seems likely, however, that at higher flows and sediment concentrations, the k-value might increase substantially above unity.

In parenthesis, it is worth reflecting on the amount of sediment being scoured along the 3.5 km of bank along the right side of the channel immediately upstream of the old 10MC8 section. Based on a depth of 30 m (at low flow datum on the CHS chart) and an average retreat rate of about 15 m per year, the volumetric loss is at least 1.5 million cubic metres per year. Though the ground ice content of the banks is unknown, this figure would probably correspond to about 2 Mt of sediment per year. This increment in sediment loading on Middle Channel is thus more than the total load measured along East Channel at Inuvik in the 1974 high flow year!

The available sediment data for Middle Channel in this reach are given in Table 2.6. The sediment rating diagram is provided in Fig. 2.12.

10LC6: North Kalinek Channel above Oniak Ch

The exact location of the North Kalinek Channel site is unknown, but Fig. 2.13 indicates the approximate position based on the 1985 Hydrology Information Series Map for Aklavik. The available sediment data for the site are provided in Table 2.7. The sediment rating diagram is given in Fig. 2.14.

10LC2: East Channel near Inuvik

The location of the East Channel measurement section is given in Fig. 2.15. It is conveniently located close to Inuvik and occurs in a straight channel reach with a generally flat, symmetrical section. The available sediment data for East Channel are given in Table 2.8. As noted in Chapter 1, there are apparently additional data for 1976-77 and 1982, but these have not been located.

No field sheets for multiple vertical sampling from the 1970s have been found. The cross-sectional distribution of sediment in the 1991 June 6 sampling is shown in Fig. 2.16. Sediment concentration on that date peaked in mid-channel (the location of the SV sampling) producing a k-value of only 0.88 (using an unweighted mean concentration). The reason for this pattern is unknown and future MV sampling should be examined. The field notes for the June 6 sampling do have the comment "possible suspect because of wind".

The sediment rating diagram for East Channel near Inuvik is given in Fig. 2.17.

2.2 Assessment

2.2.1 Purpose of program

The 1990s mid-delta program, renewed through NOGAP funding, involves sampling at three stations:

Peel Channel above Aklavik Ch., 10MC3
Middle Channel below Raymond Ch., 10MC8
East Channel near Inuvik, 10LC2

The primary purpose of the mid-delta program, as outlined by Wedel (1990 a,b), is to produce a sediment module to integrate with the 1-dimensional model for river flow through the Delta. Though the specifics have not been outlined, the envisaged module would probably be a series of sediment rating relationships for these stations (Section 1.4), so that sediment concentration (and hence transport rate) can be inferred for each site from discharge (which is, in turn, inferred from the 1-d model). In this way the sediment pathways through the mid-delta transect can be quantified in terms of importance. The goal is a sound one. In practice, however, there are clearly major problems: these arise from the unsatisfactory sediment ratings; from "gaps" in the transect; and from the dominance of Middle Channel.

2.2.2 Adequacy of sediment rating relationships

A summary of the sediment rating statistics for all mid-delta sites is provided in Table 2.9. With the exception of West Channel (which has the best rating, but smallest sample size), all channels have fairly high standard errors of estimate (SEE), an index of the amount of scatter, averaging close to 0.30 log units. The variability in the percentage prediction of concentration (r^2) among the various sites is greater than for the SEE and reflects differences in the variance (range) of concentrations at the different sites. The formula for r^2 is:

$$r^2 = 1 - [SEE^2.(n-2)]/[s^2_y.n]$$

or

$$r^2 \approx 1 - [SEE/s_y]^2$$

where s^2_y is the sample variance of log(c). The East Channel sediment rating, for example, is probably not inherently better than that of Middle Channel, as they have identical SEE values. The higher percentage prediction in the case of the East Channel simply reflects the fact that more samples were taken in late September and October than in the Middle Channel, providing a larger "spread" in discharge (one full log cycle on East Channel, Fig. 2.17) and hence a large variance in log concentration values.

The SEE values of the mid-delta stations (excepting West Channel) are about 50% greater than that of the Mackenzie at Arctic Red River. The sediment rating relationships, as developed so far, are, in fact, generally so mediocre that, with the exception of Middle Channel, the error in estimated annual loads at each site is likely to be comparable with the differences between the sites. The mid-delta sampling strategy so far adopted cannot be justified unless there are strong grounds for believing that improved sediment ratings can be established; and this requires some consideration of why the ratings are currently unsatisfactory.

The appropriate standard to take here is the sediment rating for the Mackenzie River at Arctic Red River. Its rating relationship is also not strong: only 66% of the variance of log concentration is predictable from log discharge (Carson, 1988), but it is generally better than those for the mid-delta stations. Actual discrepancies between predicted and measured loads in 15 months of frequent WRB sampling ranged -90% to +58%, the standard deviation being 37 percent. The latter can be used as an estimate of the imprecision in the sediment rating approach in predicting the suspended loads of individual months. Estimates of the imprecision of the sediment rating in terms of prediction of longer term loads are as follows: in the range 17-24% for loads of individual years, 9-11% for mean monthly loads (1974-90) and 5% for the mean annual load (Carson, 1992). The latter two are certainly acceptable.

One of the problems with the Mackenzie delta-head sediment rating is that summer storms tend to produce higher concentrations, for given flow levels, than snowmelt. It had been hoped that use of water temperature as a second predictor would improve the rating, but this was not the case. Temperature data for the mid-delta stations are incomplete, but do not appear to be a significant control. The problem is compounded by the fact that storms produce different sediment responses according to where within the catchment they are located. Both of these factors would also produce scatter in sediment ratings in the delta channels.

Understanding (and eliminating) the scatter in the mid-delta sediment ratings therefore requires an understanding of sediment fluctuations at the delta-head. This issue was pursued in a separate study (Carson, 1992, p. 22-23 and Fig. 4.2). The sediment and discharge data at the site were broken down to the level of individual flood events (pulses between hydrograph low points) for the post-snowmelt period. There was, as expected, a clear tendency towards high positive residuals (actual log(c) greater than predicted log(c)) in the early part of floods, followed by a decrease to negative residuals (actual concentration less than predicted). At the same time, however, there was considerable scatter in the first twelve days or so of a flood: while all floods tended to follow the same general pattern, the timing and the magnitude of the peak positive residual varied appreciably between floods. In part this seemed to be related to the steepness of the rising limb (and hence intensity of the rainstorm); in part it seemed to be related to location of the storm and geographic source of the floodwater. Modelling these residuals is no simple task, but until it is done, sediment ratings at the delta-head, and in the delta, will not improve beyond the level already noted for Mackenzie at Arctic Red River.

There is the separate problem of explaining why scatter is generally even greater in the mid-delta channels than at the delta-head. This is pursued in the remainder of this subsection.

Examination of the various mid-delta sediment ratings indicates that the scatter is not confined to SV values: data based on MV sampling plot with large scatter also, especially at higher discharges. The main control on the scatter diagrams appears to be timing of the samples. Those samples taken in June tend to plot well below any "best-fit line" whereas many samples in July and August show higher than average concentrations for any given discharge. The similarity between stations is indicated in Table 2.10 which shows that strong positive residuals are concentrated in July and early August in 1974, while strong negative residuals are concentrated in June of both years.

The pattern of Table 2.10 is not repeated to the same intensity in the data for Mackenzie at Arctic Red River (Fig. 2.18: top), but this seems to be due to the lack of June data at that station in 1974-75: the only June sample is June 29, 1975. The general pattern noted above (the contrast between June and August samples) is nonetheless characteristic of the Mackenzie delta-head site (Fig. 2.18: bottom).

In addition, at the Mackenzie River (at Arctic Red) site, the year 1974 still had the largest scatter of all years: actual extremes in 1974 (as residuals from the rating) were no higher than in many years in the 1980s, but there were much fewer "normal" flows with low residuals (Fig. 2.18: bottom). The higher scatter for the mid-delta stations (compared to the Mackenzie delta-head station) may, therefore, simply reflect the much greater proportion of the scatter diagram taken from 1974. It seems likely that additional data will improve the mid-delta ratings to a level where they are comparable with that for the Mackenzie at Arctic Red River.

Predictions at the mid-delta sites might be further improved by using monthly coefficients to adjust sediment concentrations in different months, as at the delta-head, but more data are needed to establish reliable values for these coefficients.

2.2.3 Gaps in the transect

Ideally, comparison of the total sediment loading at the mid-delta stations with that of the delta input sites (Peel River, Arctic Red River and Mackenzie River) would provide an estimate of how much of the sediment supply to the delta is deposited in the upper delta. Indeed, Hirst et al. (1987) attempted this using the 1974 data, but the comparison was of dubious value because of probable errors in the Mackenzie River loadings (Carson, 1990).

Unfortunately, with the present sampling program based on only three sites, the comparison is still difficult because of "gaps" in the transect, i.e. sediment pathways through the mid-delta that are not sampled.

The two main gaps are Aklavik Channel and Kalinek Channel(s). Presumably, though, there will be occasional hydrometric measurements at both of these sites in order to calibrate the 1-d flow model, and in this case it would seem worthwhile to at least undertake SV sampling at these times. The extra samples could then be used to strengthen the sediment rating relationship.

Alternatively, if additional sampling is not possible, it might be expected (on the basis of the source of the water) that concentrations in Aklavik Channel would show some similarity to those of Middle Channel, while the concentrations in Kalinek Channel should be related to those in East Channel. A comparison is made between the sites in Fig. 2.19a (using only data collected on the same day or on successive days), and shows that there is, indeed, a reasonable relationship. In both cases, however, the concentrations in the currently-unsampled channel are only about 60% of those in the sampled channel. In the case of Aklavik and Middle Channels, this difference may reflect more rapid settling of sediment in the smaller channel and/or a smaller increase in sediment inputs from bank scour in the smaller channel. The same situation prevails in comparing East Channel with Middle Channel (Fig. 2.19b). On the other hand, the opposite relationship prevails in the other case of Fig. 2.19a: the larger North Kalinek Channel has smaller concentrations than East Channel. (The discharges reported by Davies (1975) for the North Kalinek Channel are surprisingly large at about twice those of East Channel.)

The relationship between North Kalinek and East Channels is contrary to what would be initially expected on the basis of stream size. The general relationships in Fig. 2.19, do nonetheless, offer a potentially useful approach for interpolating the sediment flux at the two unsampled sites. They also indicate the value of collecting samples at the different sites essentially at the same time: this point should be borne in mind in the present sampling program.

As noted in Chapter 1, the 1974 loads on these two small channels (Aklavik and North Kalinek), though much smaller than Middle Channel, were roughly comparable with that of Peel Channel and larger than East Channel, and should not be ignored in any estimate of the sediment flux across the mid-delta transect.

2.2.4 Dominance of Middle Channel

The third problem arises from the dominance of Middle Channel, along which 80%-90% of the sediment flux through the mid-delta occurs (based on the 1974 data).

This observation means that, in any attempt to quantify the sediment flux across the mid-delta transect, a great deal of attention needs to be directed to accurately determining the load of Middle Channel. There would seem to be little point, for example, in sampling the stations along the mid-delta transect with more or less equal accuracy: a 20% error at each site would amount to perhaps 0.5 Mt error at most stations, but about 20 Mt in Middle Channel. Much greater accuracy is required for Middle Channel, and this needs to be reflected in the sampling design: more frequent sampling and more multiple-vertical sampling.

This conclusion is especially relevant in view of (a) the marked cross-sectional variation in sediment concentration at this site, and (b) the non-central location of the SV point. Emphasis will have to be placed on MV sampling at this site, at least until a consistent pattern for the k-value emerges.

2.2.5 Cost of mid-delta sampling program

The problems noted above make it unlikely that the present sampling program will attain its goal without a dramatic increase in budget which probably cannot be justified. This raises the question of whether any sampling should be done on the mid-delta transect at all. One possibility is to sample only on Middle Channel in an attempt to quantify the sediment flux there, for comparison with the upper and outer delta stations. The increased frequency of sampling at Middle Channel would enable a more rapid buildup of the sediment rating diagram for the site. On the other hand, there is no guarantee that the more detailed diagram would produce a more satisfactory sediment rating.

An alternative strategy is to abandon the mid-delta sampling program completely and to redeploy resources to allow increased sampling at the outer delta stations. These, after all, are the sites (together with the input sites at the delta head) for which, as IWD has consistently recognized, sediment data are of primary importance, and where accuracy is crucial. The mid-delta program would produce data that, while of interest, are not as generally significant as those at the outer stations.

The key question here, though, is exactly how much would be gained, financially, by abandoning the mid-delta sediment program. The point is that, presumably, field visits to the mid-delta sites are needed in any case for the calibration of these stations for the 1-d hydrometric model. The only saving would be in terms of (a) the extra time required for the post-hydrometric sampling program, (b) the cost of laboratory analysis of the samples, and (c) the cost of data analysis and interpretation.

The cost of laboratory analysis alone is certainly substantial. The total laboratory cost for the full delta program (outer stations, mid-delta stations and delta-head stations) was estimated at $20,000 per year, based on 4 MV sampling at each station and 18 SV sampling. The calculations assume a particle size analysis cost of $77 and a filtration cost of $18 per sample. Estimates for the mid-delta program would indicate an annual cost of close to $10,000. This reflects the fact that a full MV sampling program at Middle Channel requires 17 samples (using split sampling), with 9 more samples from Peel Channel and 6 from East Channel.

The other costs are more difficult to assess. It is recommended, however, that a detailed costing of the mid-channel sediment program (over and above the hydrometric work) be prepared, with a view to assessing how much of the budget would be available for the outer-delta program, if the mid-delta program were abandoned. It is possible that the savings would be insufficient to justify the reallocation of resources. After all, an increase in sampling at the outer stations will involve extra field visits there, at substantial additional expense.

In the event that it is decided to maintain the mid-delta sampling program, then the limitations in accuracy (and hence usefulness) of the program must be clearly borne in mind.

3. OUTER DELTA STATIONS

3.1 Review

Sediment stations in the outer delta would ideally be as close to the front of the landward delta surface as possible. In practice, the need to minimize tidal influences, on both current flow and sediment suspension, requires the stations to be located inland of the delta front. This, therefore, has been an important influence on the locations of the stations.

The three channels sampled - Reindeer Channel, Middle Channel east of Langley Island, and East Channel downstream of Tununuk Point - represent the main water (and presumably sediment) pathways to the Beaufort Sea.

In comparison with the mid-delta transects, there are, however, gaps in sampling the total outflow to the Beaufort. The seaward branches of West Channel are not sampled; nor is Napoiak Channel, leading off Middle Channel (Fig. 1.1). These are relatively minor components of the total outflow, and would require considerable logistical effort and budgetary support if they were to be sampled; detailed sampling in them is not justified. Some indication of the maximum flux to Shallow Bay from the branches of West Channel will be indicated by the mid-delta sampling on Peel Channel and estimates from Aklavik Channel. Presumably, though, discharge measurements will be made on Napoiak Channel, and it would seem worthwhile to at least undertake SV sampling at these times.

Sampling by IWD of these three outer delta stations were begun in 1987 (1 MV sampling per station), continued in 1988 (9 SV sampling per station) and resumed in 1991 (3 MV and about 10 SV) after a break in the program in 1989-90. Only the data set from the initial 1991 sampling was available at the time of preparation of this report.

Unfortunately, discharge data are not yet available for times of SV sampling, the stations being water-level monitoring sites not discharge measurement sites. Discharge data will become available only with the application of the 1-dimensional flow model to the delta. Thus, sediment rating diagrams cannot be constructed until that time.

3.2 Reindeer Channel below Lewis (Louie) Ch. 10MC902

The sampling reach for Reindeer Channel is shown in Fig. 3.1, taken from Hydrographic Chart 6434 which was surveyed in 1977. The old measurement section (used in 1987-88 and numbered 10MC12) was located immediately downstream of the bend apex. The new 1991 section is located further downstream from the bend. A summary of suspended sediment data for the site is given in Table 3.1.

The 1987 MV sampling on the old section showed a strong increase in concentrations (from 300 mg/L to 450-500 mg/L) from the left bank to the right bank (Fig. 3.2: top), as would be expected from the movement of bed material, in suspension, along the inner bank of the bend. No data were found for the SV point at the time of the 1987 MV sampling. The 1988 laboratory sheets indicate, that the SV point was located at "1QRB". On the basis of the 1987 MV sampling (Fig. 3.2: top), this SV location would correspond to a k-value of about 0.9 (using a simple mean for the cross-section, not weighted by local discharge). All 1988 SV values should probably be adjusted downwards. Unfortunately, it is not really justifiable to assume that the k-value remained constant in 1987-1988: the cross-sectional pattern of sediment concentration at bend sites is notoriously unstable, meaning that the k-value could have varied appreciably.

The new measurement section in the reach is located about 1500 m downstream of the old section. By this point in the reach, the cross-section has become more symmetrical. The excess sediment flux along the right half of the channel may be expected to have decreased somewhat by deposition along the inner bank, though above-average levels along the "upvalley" bank typically persist for some time in most meandering channels.

The single 1991 MV sampling so far available is illustrated in Fig. 3.2 (bottom). It is evident that there is still a cross-sectional gradient in the sediment levels (especially near the bed), though not to the same extent as in the 1987 sampling at the old section. The main feature of the MV sampling of June 20 1991, however, is the marked increase in concentrations downward through the sampling column. The pattern is, for example, a marked contrast to Middle Channel below Raymond Channel, sampled a week earlier (Fig. 2.11).

The strong increase in suspended sediment concentration with depth implies that the settling velocity of the particles is high relative to the shear velocity. This would suggest that there was either a high percentage of sand in suspension, or that turbulence (and shear velocity) were reduced so much that even finer particles were settling out of suspension. Kostaschuk and Luternauer (1989) observed a similar marked increase in sediment concentrations towards the bed in the Fraser River delta, and in that case were able to relate it to the role of the salt-wedge in reducing turbulence. In Reindeer Channel, however, the pattern of increasing concentrations with depth is not repeated in the dissolved solids: these concentrations are essentially invariant with depth. There is therefore no landward intrusion of saline water along the bed of the channel in this case.

The notable feature about the near-bed excess sediment concentrations is that they increase strongly towards the right bank. This suggests that the feature is the result of the meander bend helix (deflection of near-bed current towards the inner bank). Why the excess near-bed concentrations are so much greater on the inner bank here than in the comparable location on Middle Channel below Raymond Channel (Fig. 2.11) is not clear. It may reflect a difference in grain size of near-bank sediment.

The k-value for the June 20 1991 sampling (based on the simple mean of sediment concentrations, not weighted by local discharge) is 0.94. The SV point is well-located in the changeover part of the section between the lower left-side concentrations and the higher right-side concentrations. Again, however, the changeover point may shift depending on the intensity of the flow, and careful monitoring of the k-value will be necessary. At present, however, the sampling site seems acceptable. Additional MV data collected on July 30 and September 20, 1991 should be examined before any decision is made regarding the 1992 program.

3.3 Middle Channel near Langley Island, 10MC901

The Middle Channel of Mackenzie River splits abruptly into three channels at the southeast side of Langley Island (Fig. 3.3): Reindeer Channel turns off to the left; Middle Channel continues to the northwest, but bifurcating in the process; and Neklek Channel turns off to the northeast to merge with East Channel at Tununuk Point (the south end of Richards Island). Some of the flow of Neklek Channel is deflected left at Tununuk Point (along a channel which is not named) to join with Middle Channel.

The 10MC901 site is just downstream of the junction of the twin Middle channels and the Neklek Channel extension (Fig. 3.4). The waters of these three channels will certainly not be well mixed on passing through the 10MC901 site, though presumably the main flow component is from the south branch of the Middle channels.

The same measurement section for this reach was used in 1987-88 (labelled 10MC10) as in 1991 (now 10MC901). The Hydrographic Chart (6435), surveyed in 1972/73, indicates some kind of instability along the right bank immediately upstream of the section, where the flow impinges on the southern end of a lake. The left side of the section is part of the broad point bar built up by the south branch of the Middle channels.

A summary of the suspended sediment data so far collected is given in Table 3.2. WRB staff at Inuvik advise that the SV site used in 1991 is the same as that used in 1988.

The 1987 MV sampling is shown in Fig. 3.5 (top). It indicates a systematic, but weak, increase in concentrations towards the left bank. This would be expected in view of the bend flow of the south branch of the Middle channels, though the possibility of lower sediment levels in the input channels on the right side of the section cannot be dismissed. The concentrations were marginal for grain size analysis, but the analysis done indicated 55-72% of the sediment in the clay size fraction; less than 8% was sand, except for the sample with 344 mg/L. The discharge was only 4,200 m3/s.

The k-value for the 1987 MV sampling (based on a simple mean for the section) would have been 1.08, indicating a slight underestimate by the SV point, which is located over the thalweg, near the right bank.

On the right side of the channel there is no increase in concentration with depth. On the contrary, there is a weak, but consistent, decrease with depth. The left verticals do show an increase with depth, as would be expected from their location downstream of the inner-bend point bar. The reason for the contrast in vertical distribution of sediment between the left and right sides of the channel is unknown. In view of the location of the section just downstream of the bend in the larger (south) branch of the Middle channels, it is possible that surface water from this channel has drifted over to the right bank. This would be consistent with the bend geometry.

It should be noted, however, that the MV sampling on this date was done systematically from top left (at 1813 hr) to bottom right (at 1900 hr). Though it seems unlikely that the cross-sectional differences are due to a gradual decrease in concentrations over time (rather than through the section), this possibility cannot be ruled out. It is recommended that all MV sampling end with a repeat sampling at the point of the first sample. Ideally this would be at the SV site.

The initial 1991 MV sampling is shown in Fig. 3.5 (bottom). There is a similar, but weak, increase in concentration from the right bank to the left. All verticals show an increase with depth. The k-value (based on the simple mean for the section) is 1.04, again indicating a slight underestimate by the SV sample.

The two MV sampling so far available are encouraging in that they show reasonable agreement between SV and mean MV concentrations, but both sampling have been done at relatively low sediment levels. The MV sampling of July 30 and September 20, 1991 will provide more data, but additional MV sampling are needed at higher flows and concentrations.

3.4 East Channel below Tununuk Point, 10LC901

The station East Channel station 10LC901 is located about 2 km downstream of Tununuk Point (Fig. 3.6). The channel is much wider (about 1000 m) than both Reindeer and Middle channels, and is also appreciably shallower. The flow through the section originates from both Middle Channel (via Neklek Channel) on the left side and East Channel on the right side. Some turbidity contrast might be expected between the sides of the channel, but it should be remembered that by the time East

Channel approaches Tununuk Point, it has already received some inflow from Middle Channel via Oniak Channel (Fig. 1.1) and a number of other small distributaries further downstream.

The 1991 field notes indicate that the SV samples were taken at the Coast Guard buoy, about 600 m above the section and about 375 m from the right bank. This corresponds with a point on Fig. 3.6 between the depths marked 2.8 and 5.6 (metres above LWD) upstream of the section. It is assumed that the location of this buoy (reinstalled each year) is relatively fixed, but no information on this point has been obtained.

Sediment data are available for the site in both 1987-88 (labelled as 10LC10) as well as 1991 under the station number 10LC901. These data are summarized in Table 3.3.

The two MV sampling for which data are currently available are illustrated in Fig. 3.7. The cross-sectional patterns are quite different.

The 1987 sampling shows peak concentrations towards the left side of the channel. The sampling gives a cross-section mean of 82 mg/L based on a simple mean: this would yield a k-value of about 0.96 using a concentration at 400 m from the RB for the SV value, though the actual SV site (no 1987 data) is upstream of this point. These data are, however, for very low flows and sediment levels.

The 1991 sampling was done at slightly higher flow, and shows a systematic increase in sediment concentration towards mid-stream. The concentration near the right bank (in water from East Channel upstream of Tununuk Point) is half that at midstream. The SV sample at the Coast Guard buoy gives a k-value of 1.08 based on a simple mean concentration of 144 mg/L for the section.

As at the other two sites, the actual MV/SV comparisons so far available are relatively encouraging, but it needs to be emphasized that neither of these two MV sampling was done at high sediment levels (hence no data on particle size are available). Additional MV sampling were done on July 31 and September 19 and need to be examined. An obvious concern is whether the degree of mixing of the flows of Neklek Channel and the incoming East Channel will produce stronger cross-sectional variability in concentrations at higher flows. Comparative SV-MV sampling at higher flows are therefore needed.

Of the three SV sites in the outer delta, the East Channel SV site is potentially the most unstable in the degree to which it represents the full cross-section, because of flow convergence already noted. Fortunately the channel is not deep in this section, and all verticals can usually be sampled with one depth-integration.
MV sampling is, therefore, not as time consuming at this section as at the other two

sites, and it is recommended that, when possible, sampling in the 1992 program be MV sampling rather than SV collection.

3.5 Comments

3.5.1 Suitability of SV sites

Selection of sediment sampling sites within the delta is no simple task because of the continual splitting and rejoining of channels, as well as their sinuous character. Bend sites and sites immediately downstream of distributary confluences must be expected to show lateral variability in the cross-sectional distribution of suspended sediment. None of the three sites is ideally located in this respect.

The few SV-MV comparisons analyses to date are relatively encouraging in showing reasonable agreement between SV concentrations and simple mean values for the cross-sections at all three stations. None of them has really been at high flow, however, and, given that much of the sediment transport is at high flows, additional data are needed.

For this reason it is suggested that as many of the sampling as possible in the early part of the program (especially at high flows) be MV sampling. This is needed to assess the accuracy of past and future SV sampling at these sites.

3.5.2 Prediction of sediment concentrations

It is unlikely that sufficient resources will exist in the near future to allow designation of any of these three stations as a "full-program" sediment station. This means that data for actual sediment concentrations will be available for about a dozen days per year only. Thus some procedure is necessary for utilizing actual data to predict sediment concentrations on other days during the year, and for past years in which no sampling has been done.

The normal procedure at such "miscellaneous" stations is the development of a sediment rating equation (as in the case of the mid-delta stations), predicting concentrations from discharge, and from supplementary information (e.g. month, hydrograph steepness, etc.) if necessary. The limited data already collected for the mid-delta stations indicates that reasonably large scatter exists in the sediment rating diagrams: mid- and late-summer concentrations tend to be higher (for given discharge) than early-summer values. More data, and more analysis, are required for these stations. In the case of the outer delta stations, the same problems will likely exist.

Development of sediment rating relationships for the outer delta stations cannot be undertaken, however, until hydrographs have been simulated by the 1-dimensional flow model.

4. DELTA-HEAD INPUT SITES

4.1 Introduction

It is beyond the mandate of the present report to deal in detail with the three delta-head sites: Mackenzie River at Arctic Red River, Arctic Red River near the mouth, and Peel River above Fort McPherson. In any case, the existing sediment data to 1986 have been reviewed by Carson (1988, 1989), and recommendations already made for the operation of these stations. Subsequent data (to 1990) have been included in the review by Carson (1992). It is worthwhile, however, reviewing the conclusions and recommendations concerning these stations in relation to the planned NOGAP work.

4.2 Mackenzie River at Arctic Red River

(a) The SV samples were concluded to be representative of the full cross-section in terms of wash load (<0.125 mm) but not in terms of the coarser fraction. The problem with the latter relates to the variable local flux of sand towards the SV site associated with elongation of the bar upstream.

(b) The rating of wash load concentration against discharge is barely acceptable (66% prediction of log(c)) and needs to be improved by weighting summer floods more heavily than snowmelt. Using a procedure which adjusts predicted concentrations on a monthly basis, the resultant imprecision in loads of individual months seems to be about 35%, reducing to about 20% for loads of individual years, 10% for mean monthly loads and 5% for the mean annual load (1974-1990). Additional improvements are desirable, but the imprecision in the long-term is acceptable.

(c) Discharge data during spring runoff at the site needed to be reviewed (as at 1988). This has now been done (Carson, 1992). There was no significant change in the rating (there being few sampling at breakup), but there were some changes in predicted loadings. Additional sediment sampling during breakup would be useful.

(d) It was thought that little benefit would accrue from further regular SV sampling at this site given the large body of data already collected, and given the marked change in bathymetry (and hence representativeness of the SV point) in the major floods of 1988.

(e) A special program for 1989 was suggested to investigate specific aspects of the sediment at the site (Carson, 1988, p. 44-5).

(f) A limited miscellaneous sediment program was recommended for the station in subsequent years to assess the stability of the sediment rating and to acquire additional data on particle size. It was recommended that all these sampling be MV not SV sampling (at times of routine hydrometric visits) because of uncertainties about the SV site after the 1988 high flows.

(g) The same channel changes that affected the SV site apparently led to relocation of the measurement section. One proposal was to shift the section downstream of Arctic Red River confluence. In that case, great care would be needed in the sampling and interpretation of the sediment data because of inputs from the turbid tributary stream.

4.3 Arctic Red River near the mouth

(a) A good sediment rating exists for this site (percentage prediction of log(c) of 76%) based on sampling done in 1972-1975. Most of the data were from SV samples near the mouth, whereas discharge measurement and MV sampling were done at Martin House, about 75 km upstream. No k-values have been determined for the SV site, but SV and MV concentrations plot in the same swarm on the sediment rating diagram. This suggests that the SV samples are valid.

(b) Additional MV data are needed at high flows, however, and it was recommended that a limited event-based program (perhaps 5 dates in the next 5 years) be established to allow MV sampling at Martin House (with concurrent SV sampling at the mouth allowing for flow time lag) at these high flows. The work could be done as part of routine hydrometric visits to the site.

(c) It was also recommended that information on water surface slope be obtained at both the SV and MV cross-sections to assist in interpretation of bed material data. The same recommendation was made for the Peel sediment site.

4.4 Peel River above Fort McPherson

(a) Inspection of the sediment data collected at this site in the 1972-1976 period indicated that much of it was suspect and should not be used.

(b) A renewed sampling program was begun in 1988 and continued to date. There is, however, some concern about the representativeness of the SV site now being used (at the right bank at the ferry crossing), and frequent MV sampling is needed in order to provide confidence in the use of SV concentrations.

(c) The strong sediment rating shown by the 1988 data was not matched by 1989 and 1990 in which large floods produced marked scatter in the sediment rating diagram. The same problem exists as on the Mackenzie at Arctic Red River:

rainstorms produce sediment levels above those associated with snowmelt; and the timing and magnitude of the peak positive residual change from one rainstorm flood to the next. Nonetheless, modelling floods on an individual basis (and adjusting predicted concentrations according to elapsed time from start of the flood) has improved the sediment rating, especially at high flows. The algorithm has not yet been tested against WRB-computed monthly loads in 1989 and 1990.

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APPENDIX A

COMMON AND SCIENTIFIC NAMES FOR THE PLANTS ENCOUNTERED DURING THE STUDY

(from Boyes, 1991)

SCIENTIFIC NAME	COMMON NAME
Trees	
Picea glauca	White spruce
Populus balsamifera	Balsam poplar
Shrubs	
Alnus crispa	Speckled Alder
Salix alaxensis	Feltleaf willow
Salix pulchra	Arctic willow
Salix Richardsonii	Richardson's willow
Forbs	
Hedysarum alpinum	Hedysarum, Bear Root
Moneses uniflora	One-flowered pyrola
Petasites frigidus	Coltsfoot
Pyrola grandiflora	Large-flowered Wintergreen
Pyrola secunda subsp. secunda	One-sided Wintergreen
Horsetails, Sedges and Grasses	
Arctophila fulva	Pendent Grass
Carex aquatilus	Sedge
Carex Garberi	Sedge
Carex bicolor	Sedge
Equisetum arvense	Horsetail
Equisetum fluviatile	Horsetail
Heaths	
Arctostaphylos rubra	Arctic Bearberry
Empetrum nigrum	Crowberry
Ledum decumbens	Labrador Tea
Rosa acicularis	Prickly Rose
Rubus chamaemorus	Cloudberry
Vaccinium uliginosum	Alpine Bearberry
Mosses and Lichens	
Bryum pseudotriquetrum	Moss
Cladina spp.	Lichen
Drepanocladus uncinatus	Moss
Hylocomium splendens	Feather Moss
Leptobryum pyriforme	Moss
Tomenthypnum nitens	Moss

(Sources: Porsild and Cody, 1980; Pearce, 1986; Trelawny, 1988)

APPENDIX B

DENSITY AND CS-137 PROFILES IN LAKE SEDIMENT CORES IN BC HYDRO STUDY AREAS

(from Cordes and McLennan, 1984)

Core No.	Core Depth (cm)	Sample Volume (gm)	Wet Weight (gm)	Dry Weight (gm)	Wet Density (gm/cm³)	Dry Density (gm/cm³)	Water (%)	137Cs (pCi/gm)
III.35.1	4	2	2.84	2.22	1.42	1.11	22	0.1
	8	2	2.89	2.20	1.45	1.10	24	0.50
	12	2	3.23	2.44	1.62	1.22	24	0.30
	16	2	3.33	2.57	1.67	1.29	23	0.1
	20	2	3.41	2.65	1.71	1.33	23	0.1
III.35.2	4	2	2.69	2.00	1.35	1.00	26	0.1
	8	2	3.09	2.30	1.55	1.15	26	1.1 ±
	12	2	3.32	2.55	1.66	1.28	26	0.4
	16	2	3.38	2.49	1.69	1.25	26	0.4
	20	2	3.41	2.61	1.71	1.30	23	0.1
IV.14.1	4	2	3.10	2.09	1.55	1.05	33	0.09
	8	2	3.13	2.13	1.56	1.06	32	0.1
	12	2	3.23	2.18	1.61	1.09	32	0.57
	16	2	3.40	2.32	1.69	1.16	32	0.92
	20	2	3.31	2.25	1.65	1.13	32	0.10
	24	2	3.05	2.09	1.52	1.05	32	0.14
IV.14.2	4	2	3.44	2.41	1.72	1.21	30	0.1
	8	2	3.73	2.69	1.86	1.35	28	0.1
	12	2	3.72	2.87	1.86	1.44	33	0.1
	16	2	4.06	2.98	2.03	1.49	36	0.1
	20	2	3.69	2.77	1.85	1.39	25*	0.30
	24	2	3.76	2.81	1.88	1.41	25*	0.1
VII.3.1	4	39	55.0	35.2	1.41	0.90	36	0.32
	6	39	109	73.1	2.79	1.87	33	0.80
	8	39	95.6	62.9	2.45	1.61	34	1.02
	10	39	116.3	77	2.98	1.97	34	0.55
	16	4	6.29	4.79	1.57	1.20	24*	0.1
	24	4	6.28	4.75	1.57	1.19	24*	0.20
VII.3.2	4	2	3.47	2.32	1.73	1.16	33	0.30
	8	2	3.15	2.14	1.58	1.07	32	0.11
	12	2	3.26	2.15	1.63	1.08	34	0.36
	16	2	3.51	2.30	1.75	1.15	34	0.69
	20	2	3.21	2.05	1.61	1.03	36	0.50
	24	4	5.92	4.50	1.48	1.11	24*	0.1±0.
	28	4	6.27	4.71	1.57	1.18	25*	0.1±0.1

Core No.	Core Depth (cm)	Sample Volume (gm)	Wet Weight (gm)	Dry Weight (gm)	Wet Density (gm/cm^3)	Dry Density (gm/cm^3)	Water (%)	^{137}Cs (pCi/gm)
VII.9.1	0	4	6.38	4.67	1.60	1.17	27	0.1±0.1
	4	2	3.32	2.05	1.66	1.03	38	2.02
	8	2	3.12	1.96	1.56	0.98	38	1.41
	12	2	3.45	2.18	1.73	1.09	37	0.89
	16	2	3.07	1.83	1.53	0.92	40	0.1
	20	2	3.09	1.90	1.54	0.95	39	0.1
IV.30.1	0-1	2	2.93	2.02	1.47	1.01	31	0.1
	1-2	2	3.33	2.37	1.67	1.19	29	0.1
	2-3	2	2.95	2.13	1.48	1.07	28	0.60
	3-4	2	2.98	2.07	1.49	1.04	30	0.1
	6	2	2.90	2.02	1.45	1.01	30	0.1
II.23.1	0-1.5	4	6.84	5.03	1.71	1.26	27	0.30
	1.5-2.5	4	6.76	5.12	1.69	1.28	24	0.20
	2.5-3.5	4	7.13	5.41	1.78	1.35	24	0.20
	3.5-5.0	4	6.60	4.66	1.65	1.17	29	0.40
	5-6.5	4	6.93	5.05	1.73	1.26	27	0.70
	6.5-8	4	6.80	5.18	1.70	1.30	24	0.30
	8-10	4	6.85	5.24	1.71	1.31	24	0.10
	10-11	4	6.57	5.24	1.64	1.31	20	0.10
I.27.1	0-1	2	2.78	1.51	1.39	0.76	46	0.25
	1-2	2	3.15	1.74	1.58	0.87	45	0.23
	2-3	2	3.60	2.02	1.80	1.01	44	0.55
	3-4.5	2	3.19	1.80	1.60	0.90	44	0.78
	4.5-6	2	3.00	1.72	1.50	0.86	43	0.20
	9	4	5.90	4.02	1.47	1.01	32*	0.30
I.1.1	0-1.5	2	3.20	1.91	1.60	0.96	40	0.14
	1.5-3	2	3.42	2.19	1.71	1.10	36	0.37
	3-5	2	3.41	2.09	1.71	1.05	39	1.22
	5-6	2	3.47	2.40	1.74	1.20	31	0.45
	6-7.5	2	3.49	2.45	1.75	1.23	30	0.15
	9-10	4	6.09	4.10	1.52	1.03	33	0.20

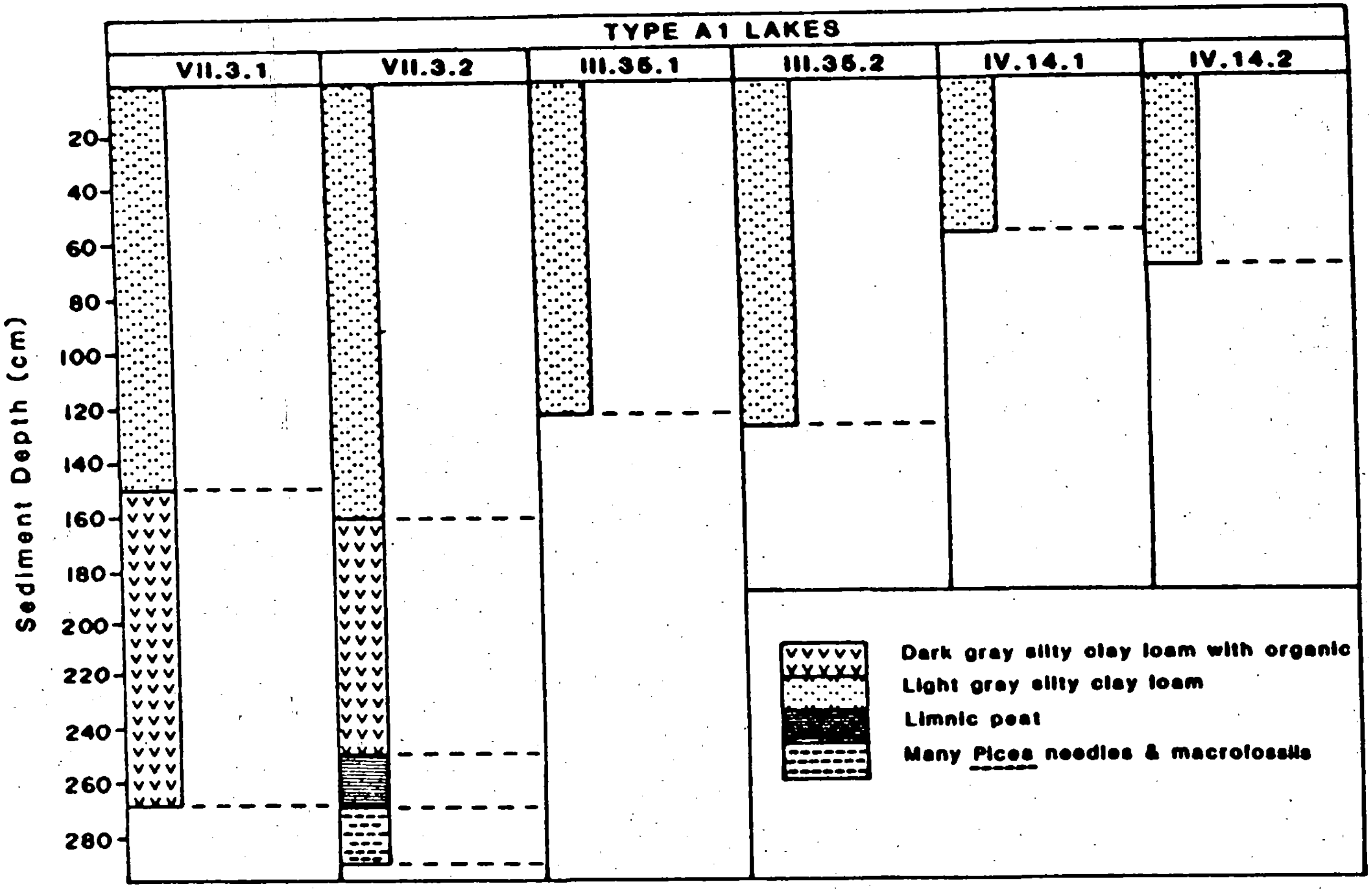
Core No.	Core Depth (cm)	Sample Volume (gm)	Wet Weight (gm)	Dry Weight (gm)	Wet Density (gm/cm3)	Dry Density (gm/cm3)	Water (%)	^{137}Cs (pCi/gm)
III.30.1	0-1	2	2.65	1.62	1.33	0.81	39	0.10
	2-3	3	4.28	2.52	1.43	0.84	41	1.00
	4-5	3	4.32	2.55	1.44	0.85	41	0.70
	6-7	4	6.59	4.45	1.65	1.11	32*	0.30
V.5.1	0-1	2	3.03	2.20	1.51	1.10	27	0.30
	2-3	3	4.37	3.26	1.46	1.09	25	2.00
	4-5	3	4.16	3.04	1.39	1.01	27	1.10
	6-7	4	6.09	4.69	1.17	1.52	23*	0.20
IV.22.1	0-1	2	3.38	2.05	1.68	1.03	39	1.67
	1-2	2	3.34	2.17	1.67	1.09	33	0.54
	2-3	2	3.79	2.45	1.89	1.23	35	0.10
	3-4	2	3.87	2.54	1.93	1.27	34	0.55
	4-5	2	3.46	2.29	1.73	1.15	34	0.24
	8-9	4	6.38	4.56	1.60	1.14	29*	0.30
IV.22.2	0-1	2	3.18	1.98	1.06	0.66	38	1.2
	1-2	2	3.06	1.96	1.53	0.98	36	0.1
	2-3	2	3.08	2.08	1.54	1.04	32	0.1
	3-4	2	3.06	2.05	1.53	1.03	33	0.40
	4-5	2	3.20	2.14	1.60	1.07	33	0.20
	8-9	4	6.43	4.61	1.61	1.15	28*	0.50
II.16.1	0-1.5	4	6.03	4.33	1.51	1.08	28	1.10
	1.5-3	4	6.68	5.20	1.67	1.30	22	0.40
	3-4	4	6.05	4.32	1.51	1.08	29	0.60
	4-5.5	4	5.26	3.65	1.19	0.91	31	0.20
	5.5-6.5	4	5.69	4.07	1.42	1.02	29	0.60
II.16.2	0-1	2	2.98	1.93	1.49	0.97	35	0.40
	1-2	2	2.69	1.87	1.35	0.94	31	0.10
	2-3	2	2.83	2.09	1.42	1.05	26*	0.1
	3-4	2	3.21	2.47	1.61	1.23	23*	0.1
	4-5	2	2.41	1.52	1.21	0.76	37	0.1

Core No.	Core Depth (cm)	Sample Volume (gm)	Wet Weight (gm)	Dry Weight (gm)	Wet Density (gm/cm^3)	Dry Density (gm/cm^3)	Water (%)	^{137}Cs (pCi/gm)
IV.8.1	0-1	2	3.44	2.12	1.72	1.06	38	2.05
	1-2	2	3.13	1.93	1.57	0.97	38	1.25
	2-3	2	3.49	2.18	1.75	1.09	37	1.43
	3-4	2	3.37	2.13	1.69	1.07	37	1.00
	4-5	2	3.27	2.05	1.64	1.03	37	2.22
	7-8	4	6.33	4.75	1.58	1.19	25*	0.60
	10-11	4	6.34	4.64	1.59	1.16	27*	0.50
VII.12.1	0-1.5	4	5.57	3.43	1.39	0.86	38	0.30
	1.5-2.5	4	5.59	3.53	1.40	0.88	37	0.50
	2.5-3.5	4	5.47	3.36	1.37	0.84	39	0.70
	3.5-4.5	4	5.91	3.78	1.48	0.94	36	0.60
	4.5-5.5	4	6.01	3.82	1.50	0.96	36	0.30
	5.5-7.0	4	5.83	3.74	1.46	0.93	36	0.1
	10	4	5.81	3.71	1.45	0.93	36	0.1

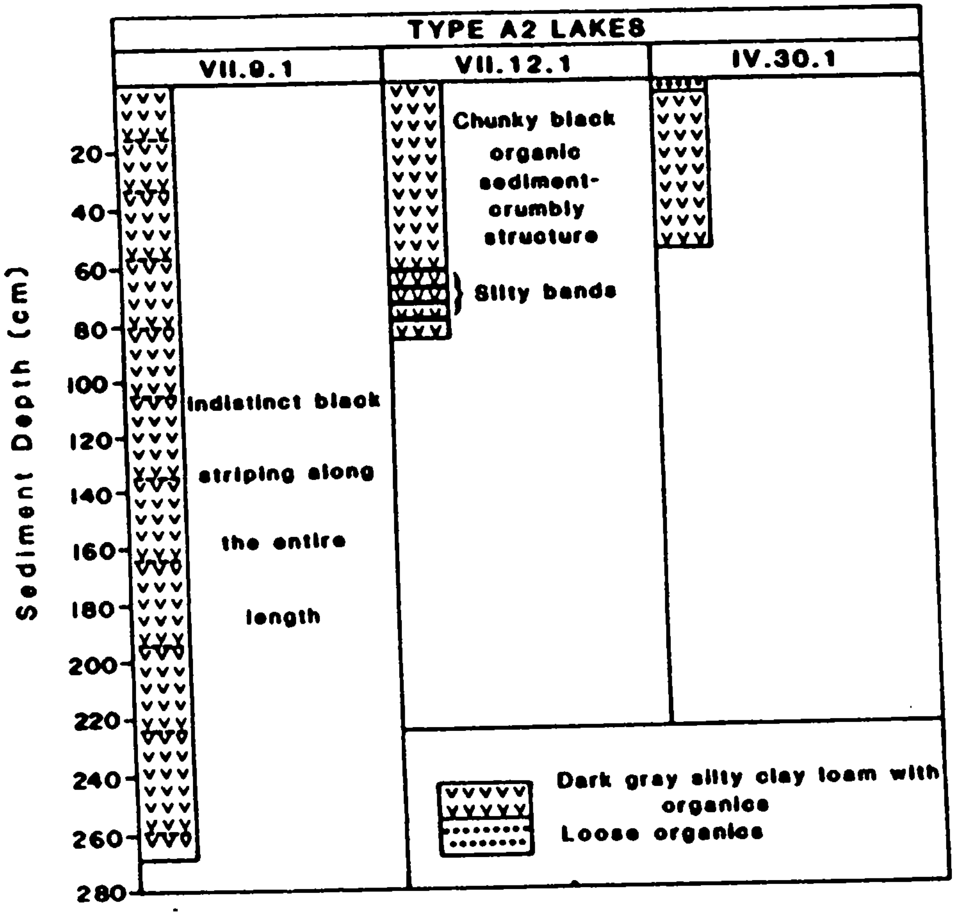
APPENDIX C

STRATIGRAPHY OF LAKE SEDIMENT CORES IN BC HYDRO STUDY AREAS

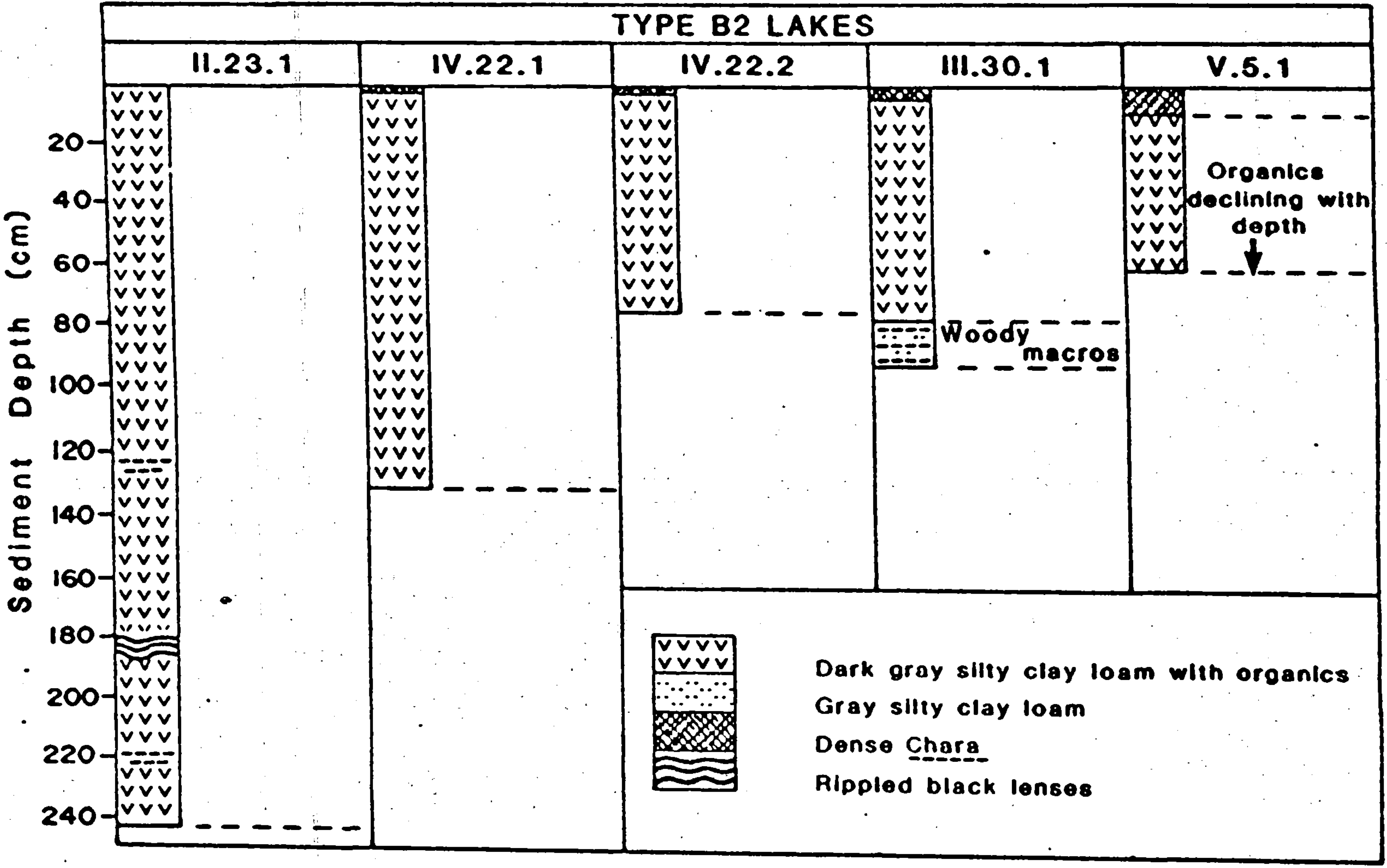
(from Cordes and McLennan, 1984)



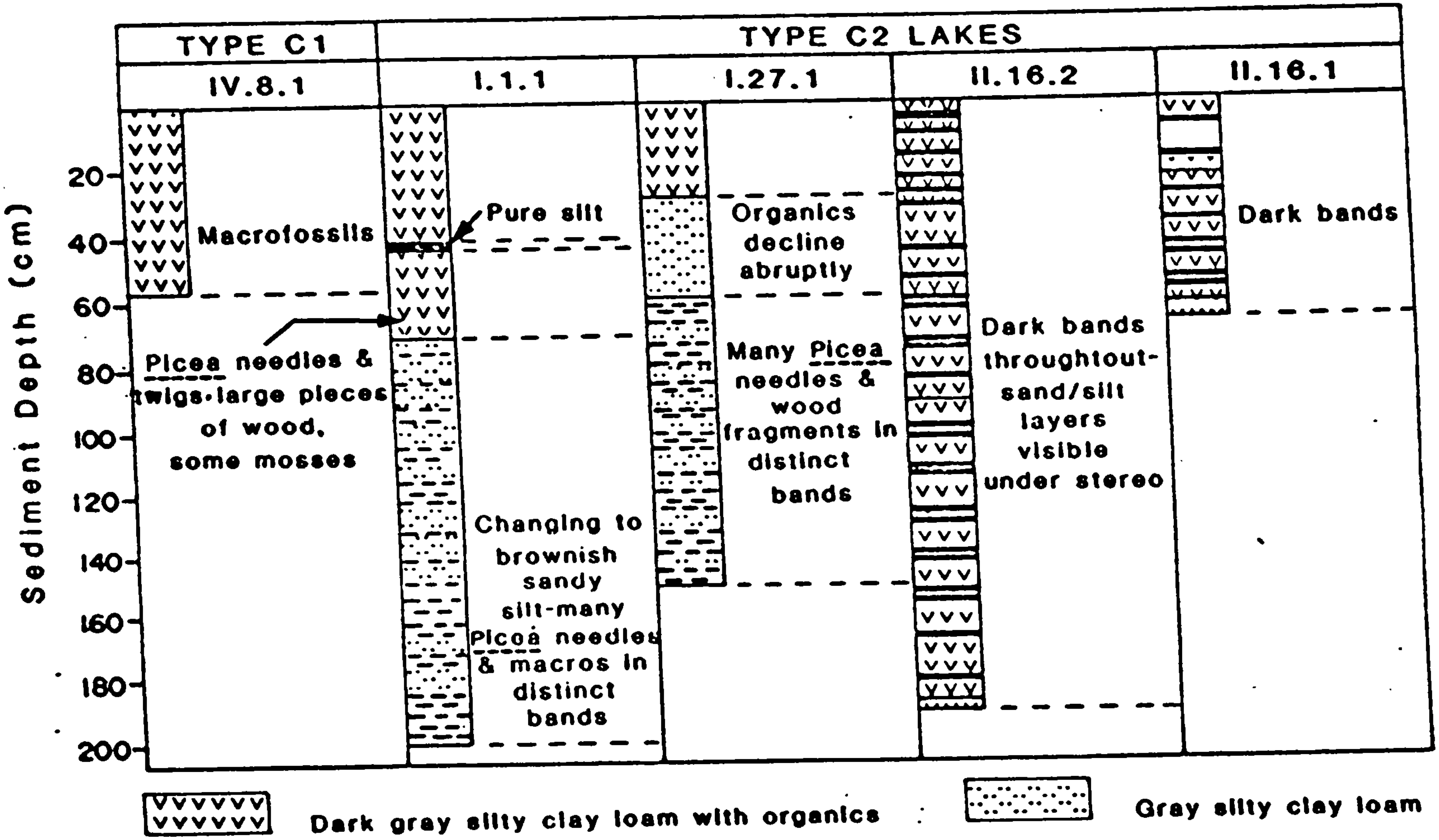
Lithology of sediment cores in Type A1 lakes.



Lithology of sediment cores in Type A2 lakes.



Lithology of sediment cores in Type B2 lakes.



Lithology of sediment cores in Type C lakes.

List of Tables

Table 2.1 Characteristics of the major plant community types (Ecophases) in the high subarctic coastal plain (Blachut *et al.*, 1985; Cordes *et al.*, 1985; Pearce and Cordes, 1985; Pearce, 1986) synthesized in Hirst *et al.* (1987). (from Boyes, 1991)

Plant Community	Location	Flood Frequency (/10 years)	Flood Duration (days/yr)	Sedimentation Rate (cm/yr)	Colonization Method	Active Layer Depth (cm)	Age (years)
Emergents							
Horsetail, Sedge, Pendent Grass	point bars arcuate depressions basin deltas distributary channels basin shores basin shoals connecting channels	high (10)	high (15 - 85)	moderate to high (0.5 - 20)	rhizomes, fragmentation, adventitious roots	60-150	-
Shrubs							
Arctic Willow	arcuate depressions basin deltas basin shores basin shoals connecting channels	low to moderate (2 - 6)	low (0 - 28)	low to moderate (0 - 6.5)	seeds, stump suckers	60-175	17-60
Feltleaf Willow	point bars alluvial sand plains distributary channels	low to moderate (2 - 6)	low (0 - 40)	moderate to high (0 - 20)	seeds, stump suckers		
Alder	point bars alluvial sand plain distributary channels basin shores basin shoals connecting channels	low to moderate (2 - 6)	low (0 - 2)	low (0 - 2.5)	seeds, stump suckers	64-112	20-60
Trees							
Balsam Poplar	point bars alluvial sand plain distributary channels	low (1 - 2)	low (0 - 2)	low to very low (0 - 0.5)	seeds	79-140	50-200
White Spruce Forest	point bars distributary channels basin shores delta plain	low (0 - 2)	low (0 - 2)	very low (0 - 0.2)	seeds	17-114	150-400
White Spruce/ Lichen Woodland	delta plain	very low (0)	very low (0)	none	seeds	15-55	250-475

TABLE 2.2

PERCENTAGES OF AREA OCCUPIED BY EACH SUB-TYPE
MACKENZIE DELTA STUDY AREAS

		Areas				
	Sub-Types	1	2	3	4	5
1a	Point Bars	7.62	5.05	10.68	9.18	1.44
1b	Levees	2.55	2.58	2.83	1.30	13.19
1c	Arcuate Depressions	0.38	0.58	0.93	0.83	0.39
2a	Basin Deltas	0.48	0.96	0.91	3.90	--
2b	Distributary Channels	3.99	4.77	2.04	3.24	--
3a	Basin Shore	9.36	4.19	12.55	7.20	54.36
3b	Basin Shoal	0.26	0.81	0.30	1.08	--
3c	Connecting Channel	0.13	0.79	0.15	2.31	--
4	Mesic Delta Plain	44.23	41.57	28.07	26.36	--
4	Pingoes	--	--	--	--	0.06
5	Hygric Delta Plain	--	2.56	--	--	--
	Lakes	23.86	24.93	24.00	38.58	24.39
	Major Channels	6.54	10.99	16.07	5.39	4.39
	Distributary Channels	0.60	0.22	1.47	0.63	1.78

(from Cordes et al., 1981)

TABLE 2.3

MEASURED AGGRADATION AND PROGRADATION RATES IN THE MACKENZIE DELTA

Sedimentary Environment	Location/ Study Area	Aggradation Rates (cm/a)	Progradation Rates (m/a)	Source
Point Bars	Area 1	0.2 - 8.8*[1]	0.75	Cordes and Assoc. '84b
	Area 2	0.2 - 9.2*[1]	0.63	Cordes and Assoc. '84b
	Area 3	4.7	0.81	Cordes and Assoc. '84b
	Area 4	3.0	0.26	Cordes and Assoc. '84b
	Area 5	2.3	2.1	Cordes and Assoc. '84b
	Area 7	5.9	0.52	Hardy Assoc. Ltd. '81
	Area 1	7.6	2.3	Hardy Assoc. Ltd. '81
	Area 3	4.2	2.1	Hardy Assoc. Ltd. '81
	Area 5	3.6	2.1	Hardy Assoc. Ltd. '81
Levees	Area 1	3.9	N/A	Cordes and Assoc. '84b
	Peel River	0.3 - 1.3	-	Strang '73
	Area 3	1 - 15*[1]	-	Cordes and Assoc. '84e
	Area 7	1 - 18*[1]	-	Cordes and Assoc. '84e
Basin Deltas	Area 1	3.3	1.7	Cordes and Assoc. '84b
	Area 4	0.8	1.6	Cordes and Assoc. '84b
	near Reindeer Station	9.0	-	Kerfoot '75
	Area 3	5.0 - 12.0	-	Mackay '63
	Area 3	0.3 - 2.0*[1]	-	Cordes and Assoc. '84e
	Area 7	0.1 - 13.0*[1]	-	Cordes and Assoc. '84e
	Area 4	2.5 - 8.0*[1]	-	Cordes and Assoc. '84e
Lake Basins (lake bed)	near Peel Channel	2.5 - 5.0	N/A	Mackay '63
	Areas 1 - 7	0.03 - 1.05*[1]	N/A	Cordes and Assoc. '84c
Basin Shores	Area 3	5.0 - 6.5 cm*[1]	-	Cordes and Assoc. '84e
	Area 7	1.5 - 7.0 cm*[1]	-	Cordes and Assoc. '84e
	Area 5	0.2 - 2.5 cm*[1]	-	Cordes and Assoc. '84e
Basin Shoals	Area 4	0.1 - 5.0 cm*[1]	-	Cordes and Assoc. '84e
	Area 7	0.4 - 14.0 cm*[1]	-	Cordes and Assoc. '84e

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*[1] Range of values given for different elevations. Band of vegetation.

(from Blachut et al., 1985)

TABLE 2.4

Summary of Ranges of Mean Annual Deposition (cm)[1] Onto Mackenzie Delta Shoreline Associations

Plant Association	point bar	levee	sand plain	delta	distrib. channel	basin shore	basin shoal	connect channel
	1a	1b	1d	2a	2b	3a	3b	3c
Sparsely Vegetated Mudflats	0-23[2.]	0-6[2.]	1-2	0.1-2	-	-	0-2[3.]	1-3[4.]
Equisetum fluviatile	5-15+	5-15+	-	2.5-5	-	0.5-5	-	-
Equisetum arvense	5-20	2+	-	0.3-1	-	-	-	-
Salix-Equisetum (Pion.)	0.5-15+[5.]	1-10+[5.]	1-5	-	-	1.5-5[6.]	-	-
Salix-Equisetum (Mat.)	0-12	0-10	1-5	-	0.5-6.5	5-7[6.]	-	-
Arctophila	-	1-5	-	0-10	-	-	0.5-1	-
Carex	-	2-18	-	1-5	2-8	0-5	0.5-5	1-3 [4.]
Salix-Carex (Pioneer)	-	-	-	0.2-1	-	1-6.5	0-2	-
Salix-Carex (Mature)	-	-	-	0.2-0.5	-	0-1	-	-
Salix richardsonii	-	-	-	-	0-0.5	0-1	-	-
Alnus-Salix	0-2.5	0-0.2	-	-	-	0-1	-	-

1. Based on actual measurements in 1982 and 1983.
2. Erosion.
3. One shoal in Area VII appeared to have received 14 cm during the 1982 breakup but this was not confirmed because of frost heaving on the site.
4. Estimated from one sample in Area VII.
5. Measurements of as high as 60 cm were recorded on 2 sites adjacent to Peel Channel in Area II.
6. On low closure levees close to main channels only.

\- = Association not sampled or not present on ecosite in 1982 or 1983.

(from Pearce, 1986)

TABLE 2.5

Plant community flood tolerance groups

(from Boyes, 1991)

Group Number	Flood Regime	Plant Communities
1	No flooding	White Spruce/Lichen Woodland
2	Infrequent flooding (about 1 to 2 years out of every 10) for a few days	White Spruce
3	Occasional flooding (about 2 to 5 years out of every 10) for a few days	Alder
4	Flooded annually or every two years for more than one week but less than two weeks	Willow, Sedge
5	Flooded annually for more than two weeks	Pendent grass, Horsetail

Lake Type	Core No.	Depth of 1963 ^{137}Cs Peaks	Sedimentation Rate (cm.yr^{-1})	Mean Sedimentation Rate
A1	III.35.1	8.0	0.42	
	III.35.2	8.0	0.42	
	VII.3.1	8.0	0.42	0.67 cm/yr
	VII.3.2	16	0.84	
	IV.14.1	16	0.84	
	IV.14.2	20	1.05	
A2	IV.30.1	2.5	0.13	0.17 cm/yr
	VII.9.1	4.0	0.21	
B2	III.30.1	2.5	0.13	
	V.5.1	2.5	0.13	0.13 cm/yr
	VII.12.1	3.0	0.16	
	II.23.1	6.0	0.32	
	IV.22.1	0.5	0.03	
	IV.22.2	0.5	0.03	
C1	IV.8.1	5	0.26	0.26 cm/yr
C2	II.16.1	0.5	0.03	
	II.16.2	0.5	0.03	0.12 cm/yr
	I.27.1	4.0	0.21	
	I.1.1	4.0	0.21	

TABLE 2.6

Sedimentation Rates in Mackenzie Delta Lakes
(from Cordes and McLennan, 1984)

TABLE 2.7

PERCENT DELTA PLAIN AREA IN LAKES

Lake Type	Study Area 1	2	3	4	5	7	Average All Samples
A - No-closure	0	2.6	16.3	32.4	14.2	10.9	12.7
B - Low closure	14.0	9.5	13.5	8.7	11.6	15.1	12.1
C - High closure	8.8	15.3	1.0	0.2	0.0	5.0	5.05
Total Closure	22.8	24.8	14.5	8.9	11.6	20.1	17.1
Total	22.8	27.4	30.8	41.3	25.8	31.0	29.8

(from Blachut et al., 1985)

LAKE	SEDIMENT BUDGET		SEDIMENTATION PLATE (A)		CESIUM 137 (B)
	dates	depth	dates	depth	depth
NRC	May 12-Sept 3	0.2 mm	May 16-July 10	1.1 mm	2.0 mm
SOUTH	May 11-Sept 3	1.3	–		2.0
	June 24-Aug 31	0.5	June 24-Aug 31	0.5	
SKIDOO	May 12-Sept 3	0.5	–		3.7
	June 24-Aug 31	0.2	June 24-Aug 31	0.4	

NOTE: (A) Sedimentation Plates are:
(1) weighted for area to determine a mean value for Skidoo and South Lakes;
(2) value for NRC is the mean for 2 sedimentation plates located in the centre of the lake;
(B) Cesium 137 depths are an average depth deposited since 1963.

TABLE 2.8

SEDIMENTATION RATES FOR SKIDOO, SOUTH AND NRC LAKES, NEAR INUVIK (from Ferguson, 1990)

TABLE 4.1

WATER LEVELS AND AREAL EXTENT OF FLOODING 1981 TO 1983

Study Area	Date of Photography	Areal Extent of Flooding (%) Net*[1]	Areal Extent of Flooding (%) Total*[2]	Water Level (m.asl) on Day of Photography Max	Water Level (m.asl) on Day of Photography Mean	Water Level (m.asl) on Day of Photography Study Area Mean	Camera Site	Peak	Date
I	30 May/80	5.40	34.68					11.29	25 May
	21 May/81	0.00*[3]	29.25	9.60	9.60E		1-1	11.4E	
	29 May/82	34.57	63.89				1-1	11.7E	
	4 Jun/83	17.16	46.48	10.27	10.27	10.47	1-1	10.27	4 Jun
				10.67	10.67		1-3	10.67	4 Jun
II	30 May/80	5.29	43.41						
	21 May/81	0.00*[3]	35.54				2-2		25 May
	29 May/82	38.31	76.43	8.46	7.96		2-2	9.01	31 May
	4 Jun/83	7.23	45.35	8.73	8.59		2-2	8.73	4 Jun
III	29 May/80	17.29	61.78						
	12 Jun/81	0.00*[3]	44.33	2.25	2.25	2.36	3-1	4.16	29 May
				2.13	2.10		3-2	4.28	28 May
				2.74	2.72		3-3	4.23	29 May
	5 Jun/82	49.21	93.71	5.15	5.04	5.06	3-1	5.58	3 Jun
				5.40	5.34		3-2	6.82	4 Jun
				4.88	4.80		3-3	5.68	2 Jun
	5 Jun/83	20.48	64.98				3-1	3.70E	7 Jun
				4.18	3.61		3-2	4.18	5 Jun
							3-3		
IV	3 Jun/80	17.23	65.06						
	12 Jun/81	6.20	55.32	2.53	2.52		4-1	4.05	28 May
							4-2		
	5 Jun/82	49.12	98.22	5.00	5.00E		4-1	5.00E	5 Jun
				5.00	5.00E		4-2	5.00E	5 Jun
	5 Jun/83	12.13	61.23	2.25	2.20		4-1	3.30	8 Jun
				2.20	2.20E		4-2	3.30E	8 Jun
V	5 Jun/80	71.22	98.34						
	1 Jun/81			0.73	0.67		5-1	1.93	1 Jun
VII	12 Jun/81	2.46	38.21	3.02	2.99		7-1	4.85	25 May
	5 Jun/82	60.02	95.77	7.00	7.00E	6.25	7-1	8.00	4 Jun
				5.50	5.50E		7-2	5.74	4 Jun
	5 Jun/83	2.04	37.79	5.74	5.72	5.33	7-1	5.74	5 Jun
				4.94	4.94		7-3	4.94	5 Jun

---

*[1] Net flooding = flooded areas - summer areas.

*[2] Total flooding = flooded areas (all water surface during breakup)

*[3] Date of photography missed flood peak.

E = Estimated.

(from Blachut et al., 1985)

TABLE 4.1

WATER LEVELS AND AREAL EXTENT OF FLOODING 1981 TO 1983

Study Area	Date of Photography	Areal Extent of Flooding (%)		Water Level (m.asl) on Day of Photography			Camera Site	Peak	Date
		Net*[1]	Total*[2]	Max	Mean	Study Area Mean			
I	30 May/80	5.40	34.68					11.29	25 May
	21 May/81	0.00*[3]	29.25	9.60	9.60E		1-1	11.4E	
	29 May/82	34.57	63.89				1-1	11.7E	
	4 Jun/83	17.16	46.48	10.27	10.27	10.47	1-1	10.27	4 Jun
				10.67	10.67		1-3	10.67	4 Jun
II	30 May/80	5.29	43.41						
	21 May/81	0.00*[3]	35.54				2-2		25 May
	29 May/82	38.31	76.43	8.46	7.96		2-2	9.01	31 May
	4 Jun/83	7.23	45.35	8.73	8.59		2-2	8.73	4 Jun
III	29 May/80	17.29	61.78						
	12 Jun/81	0.00*[3]	44.33	2.25	2.25		3-1	4.16	29 May
				2.13	2.10	2.36	3-2	4.28	28 May
				2.74	2.72		3-3	4.23	29 May
	5 Jun/82	49.21	93.71	5.15	5.04		3-1	5.58	3 Jun
				5.40	5.34	5.06	3-2	6.82	4 Jun
				4.88	4.80		3-3	5.68	2 Jun
	5 Jun/83	20.48	64.98				3-1	3.70E	7 Jun
				4.18	3.61		3-2	4.18	5 Jun
							3-3		
IV	3 Jun/80	17.23	65.06						
	12 Jun/81	6.20	55.32	2.53	2.52		4-1	4.05	28 May
							4-2		
	5 Jun/82	49.12	98.22	5.00	5.00E		4-1	5.00E	5 Jun
				5.00	5.00E		4-2	5.00E	5 Jun
	5 Jun/83	12.13	61.23	2.25	2.20		4-1	3.30	8 Jun
				2.20	2.20E		4-2	3.30E	8 Jun
V	5 Jun/80	71.22	98.34						
	1 Jun/81			0.73	0.67		5-1	1.93	1 Jun
VII	12 Jun/81	2.46	38.21	3.02	2.99		7-1	4.85	25 May
	5 Jun/82	60.02	95.77	7.00	7.00E	6.25	7-1	8.00	4 Jun
				5.50	5.50E		7-2	5.74	4 Jun
	5 Jun/83	2.04	37.79	5.74	5.72	5.33	7-1	5.74	5 Jun
				4.94	4.94		7-3	4.94	5 Jun

---

*[1] Net flooding = flooded areas - summer areas.

*[2] Total flooding = flooded areas (all water surface during breakup)

*[3] Date of photography missed flood peak.

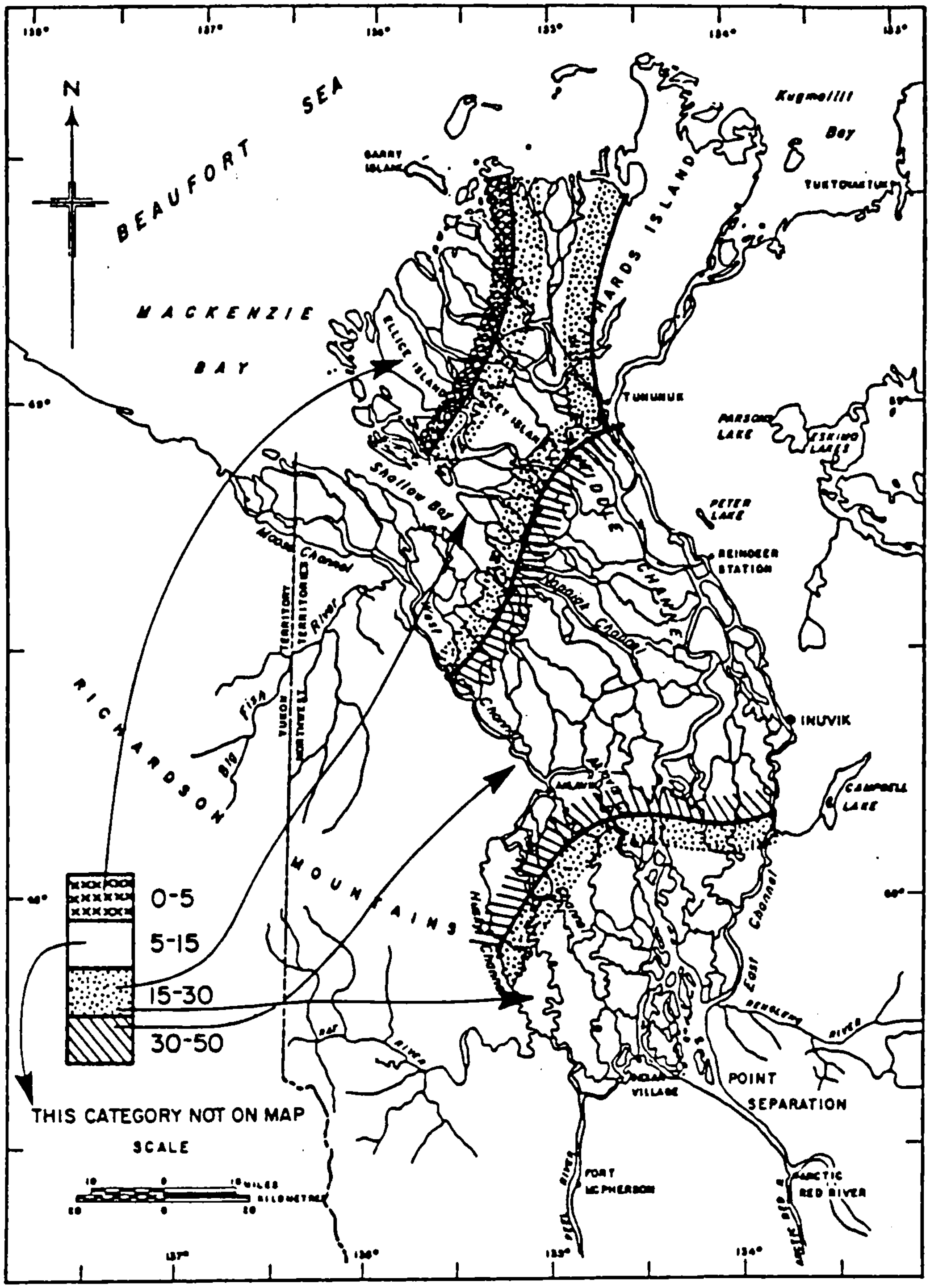
E = Estimated.

(from Blachut et al., 1985)

Station	Date	Peak Water Level (m)	Source of Data
Aklavik	5 June 1933	10.8	Kriwoken, 1983
	3 June 1961	11.2	Kriwoken, 1983
	2 June 1962	10.5	Kriwoken, 1983
	25 May 1963	10.0	Kriwoken, 1983
	29 May 1971	10.2	Kriwoken, 1983
	5 June 1982	10.7	Kriwoken, 1983
	3 June 1982	11.0	Kriwoken, 1983
	1983	9.4	
Inuvik	6 June 1974	8.3	WSC
	3 June 1975	8.6	WSC
	29 May 1976	8.3	WSC
	31 May 1977	8.0	WSC
	9 June 1978	8.0	WSC
	31 May 1979	8.5	WSC
	4 June 1980	7.3	WSC
	24 May 1981	7.6	WSC
	3 June 1982	9.4	WSC
	6 June 1983	8.9	WSC

TABLE 4.2
HISTORICAL FLOODING IN MACKENZIE DELTA
(from Blachut et al., 1985)

List of Figures



PERCENT AREA OF MACKENZIE DELTA IN LAKES AS DETERMINED FROM AERIAL PHOTOGRAPHY
(FROM MACKAY 1963)

FIGURE 2.1

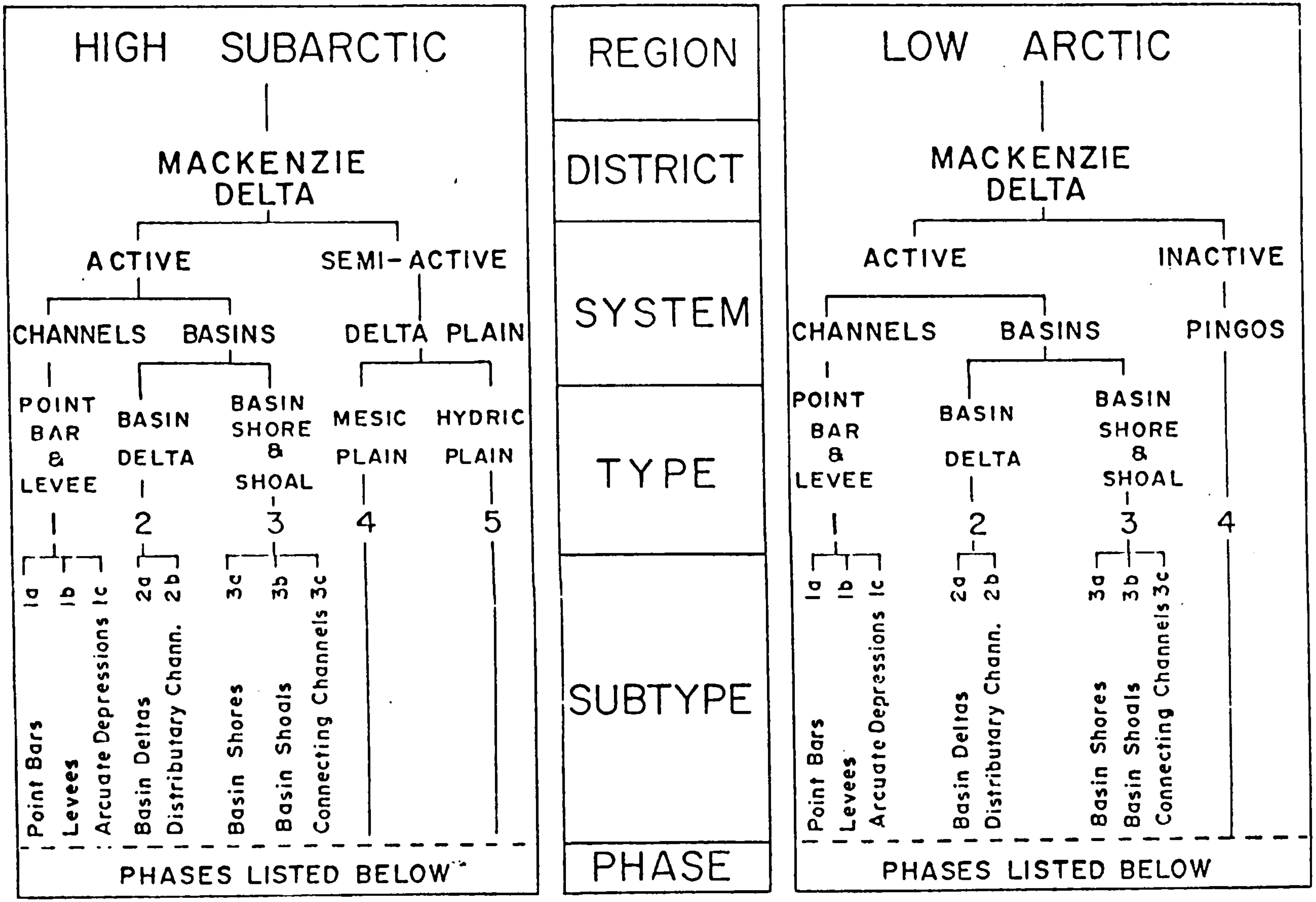


FIGURE 2.2

ECOLOGICAL LAND CLASSIFICATION SYSTEM FOR THE MACKENZIE DELTA

from L.D. Cordes and Associates, 1981

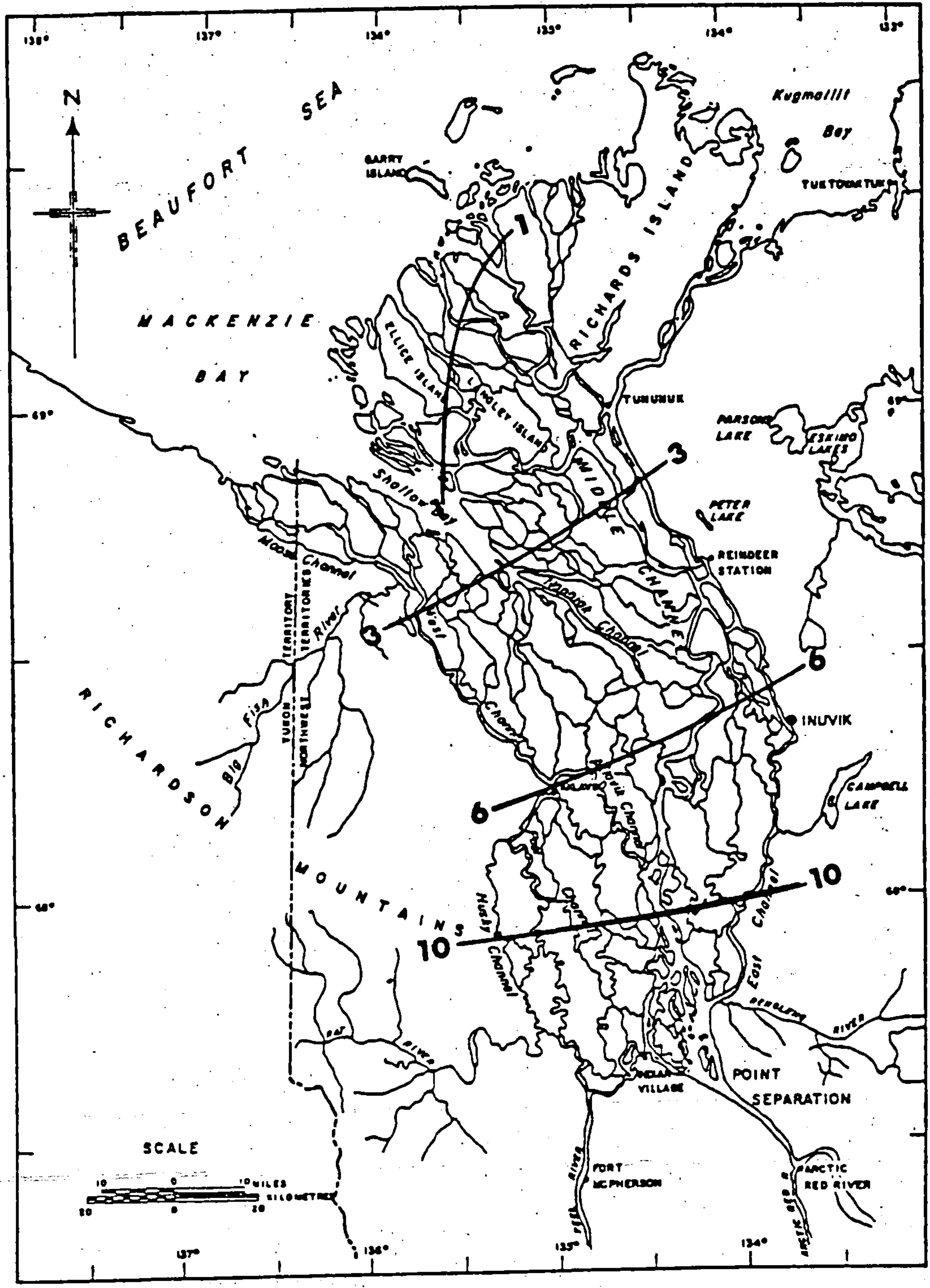


FIGURE 2.3

Estimated Heights (m) of Levees Above Late Summer Low-water Levels (from Mackay, 1963)

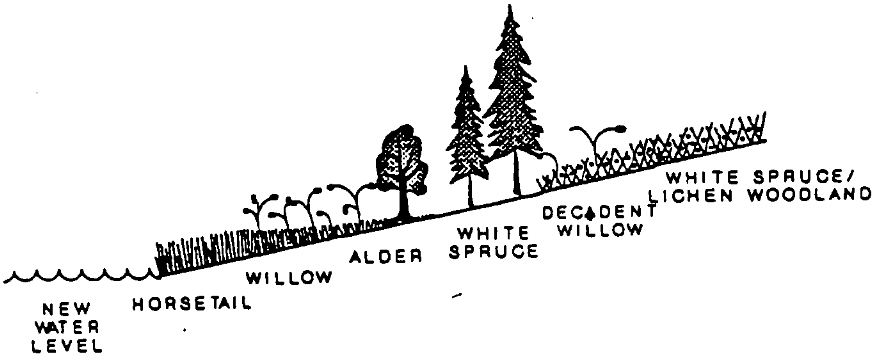


FIGURE 2.4

PLANT COMMUNITIES IN RELATION TO ELEVATION ABOVE CHANNEL WATER LEVEL
(from Boyes, 1991)

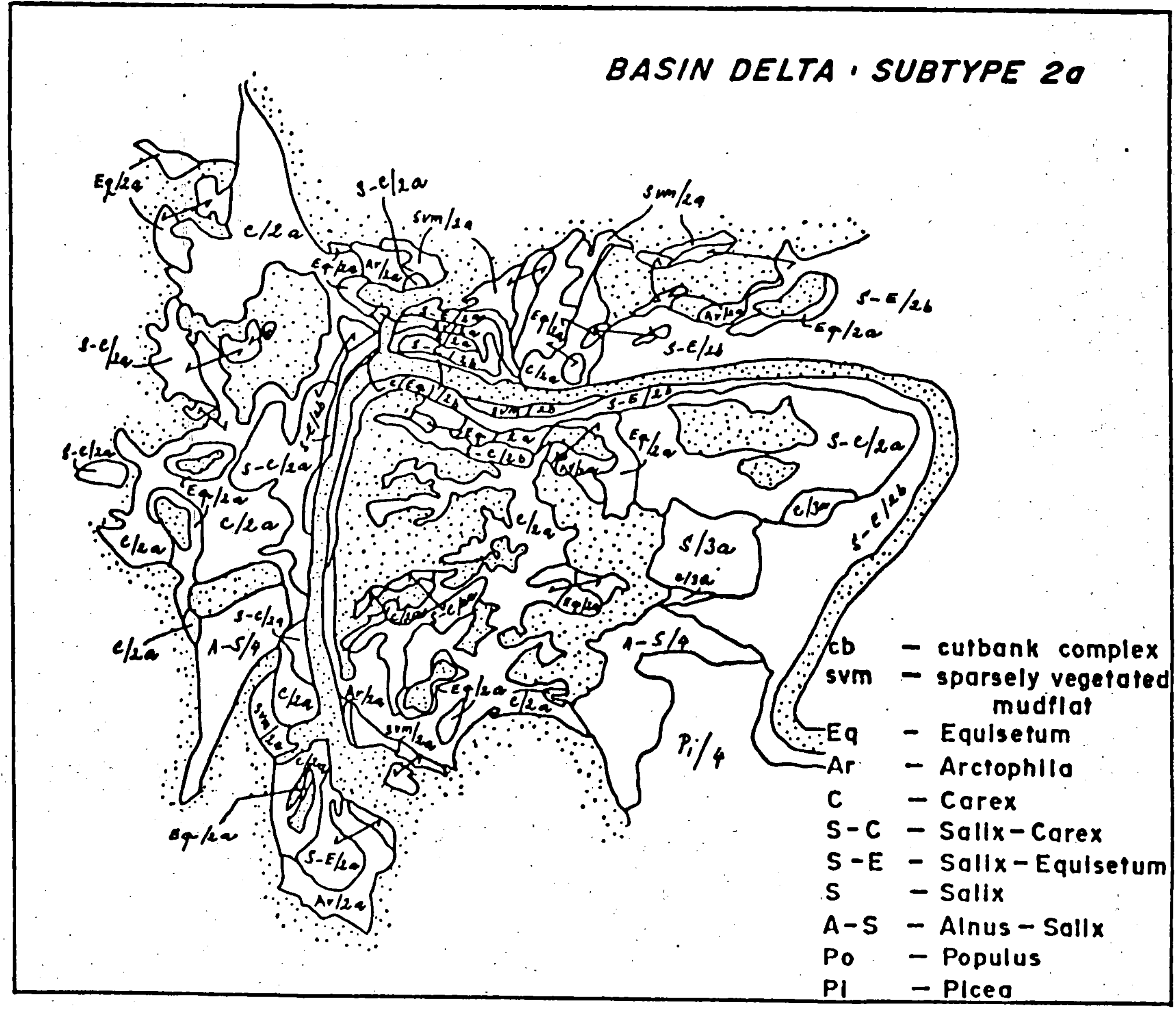


FIGURE 2.5 DISTRIBUTION OF PLANT COMMUNITIES ON TYPICAL LAKE DELTA (from Cordes et al., 1981)

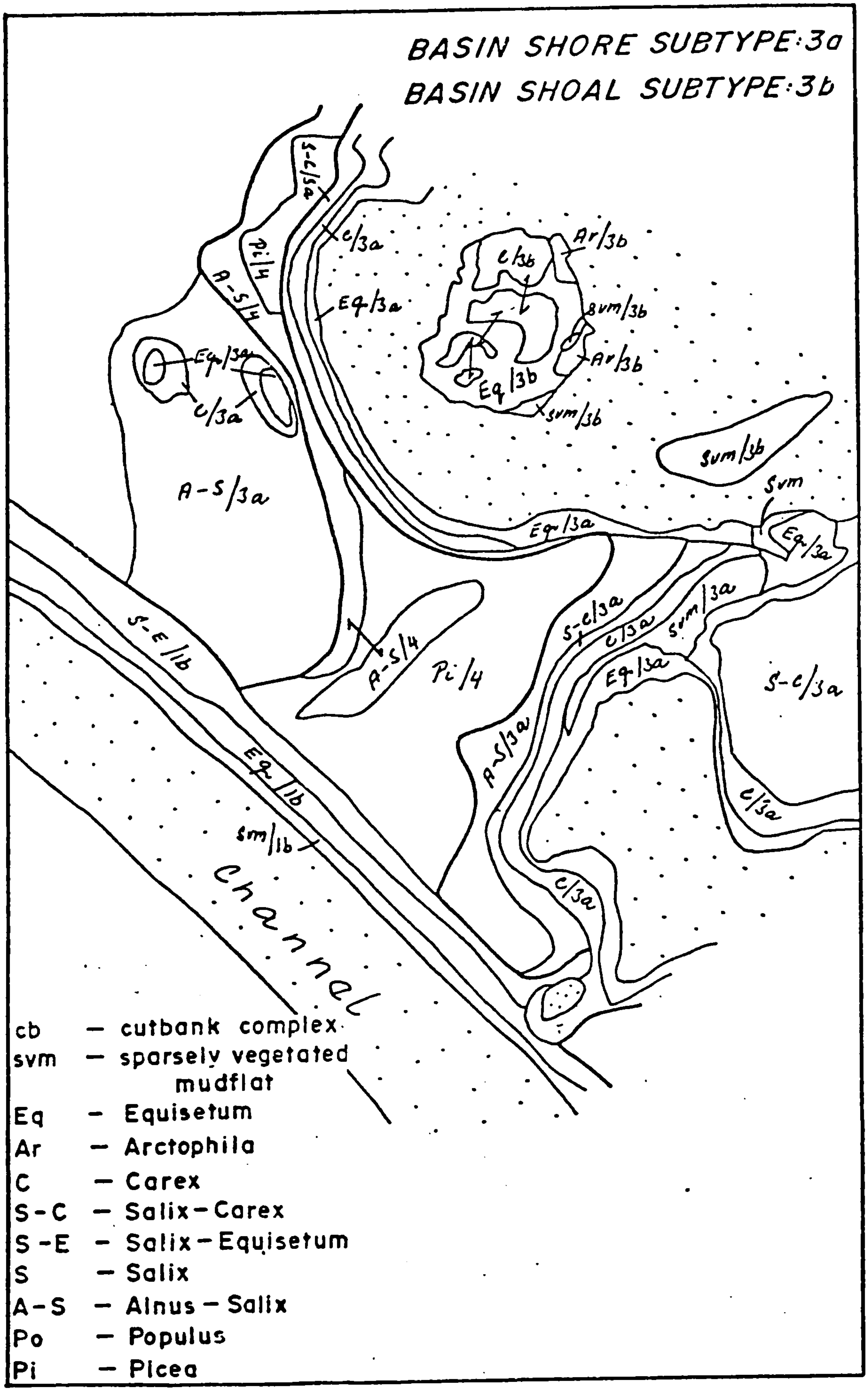
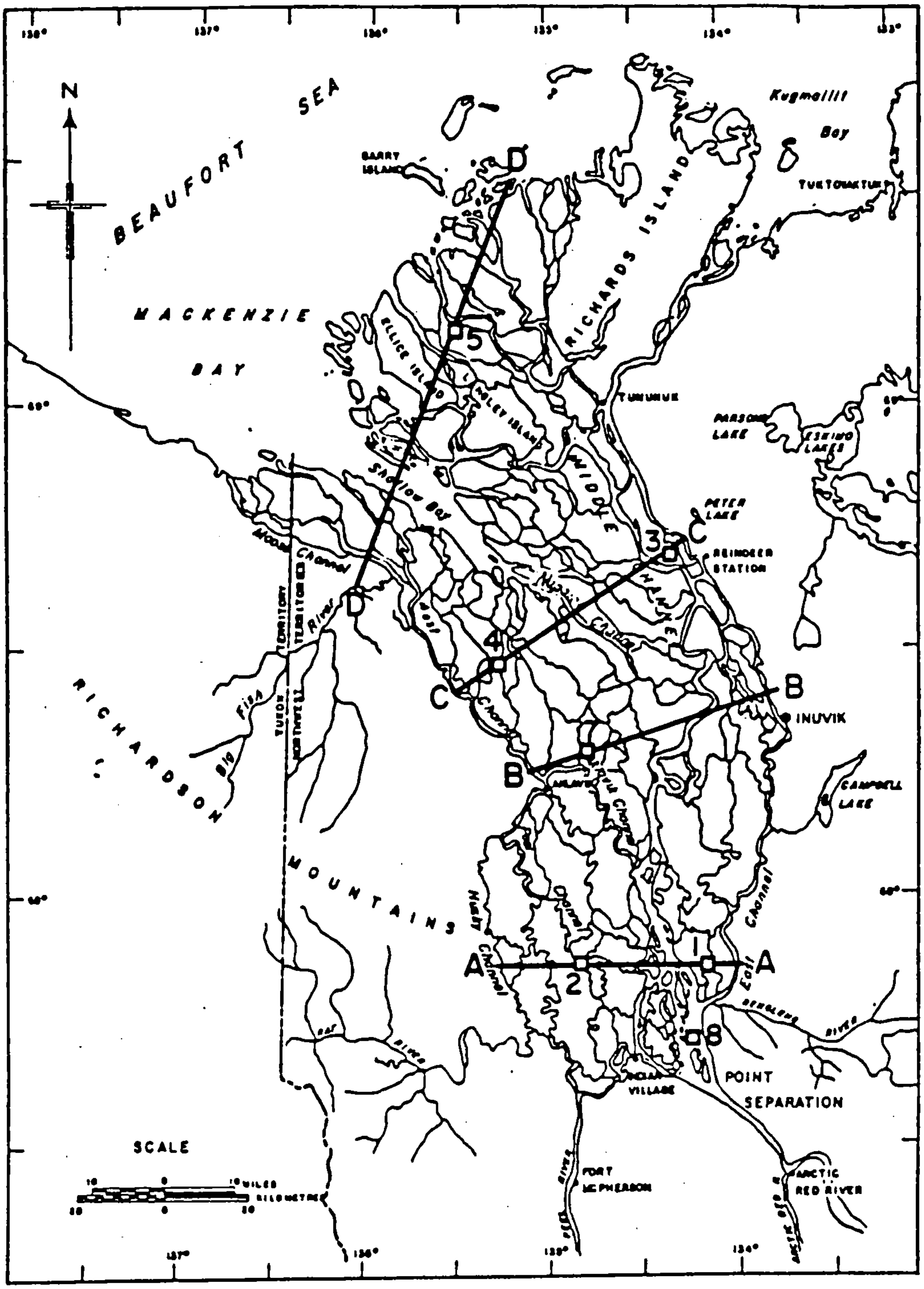


FIGURE 2.6 DIAGRAM OF BASIN SHORE AND BASIN SHOAL SUB-TYPES IN AREA 3 (from Cordes et al., 1981)



B.C. HYDRO STUDY AREAS IN THE MACKENZIE DELTA

Letters Indicate Position of Air Photo Transects

FIGURE 2.7

(from Blachut et al., 1985)

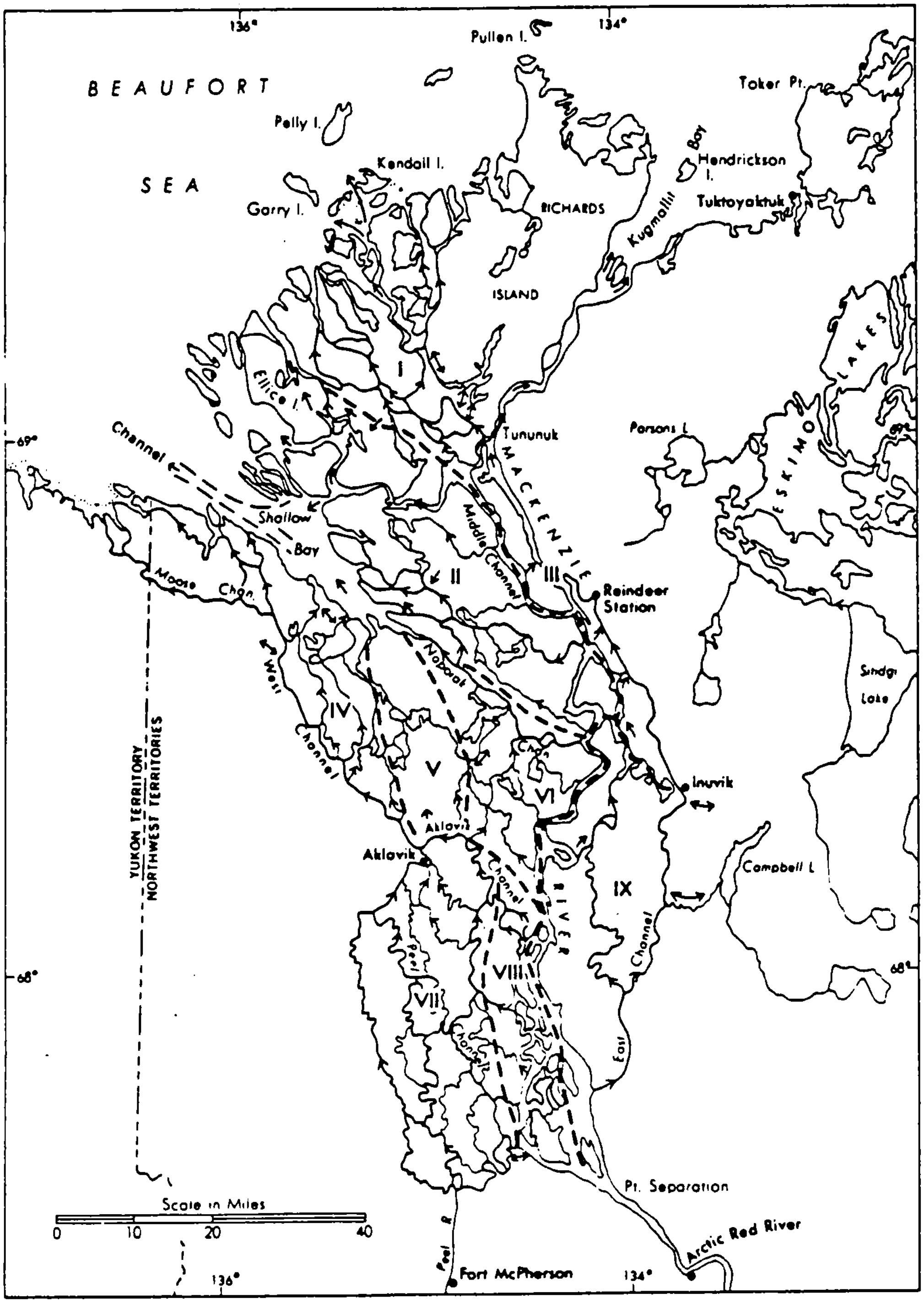


FIGURE 2.8

Major Drainage Areas of the Mackenzie Delta
(after Mackay, 1963)

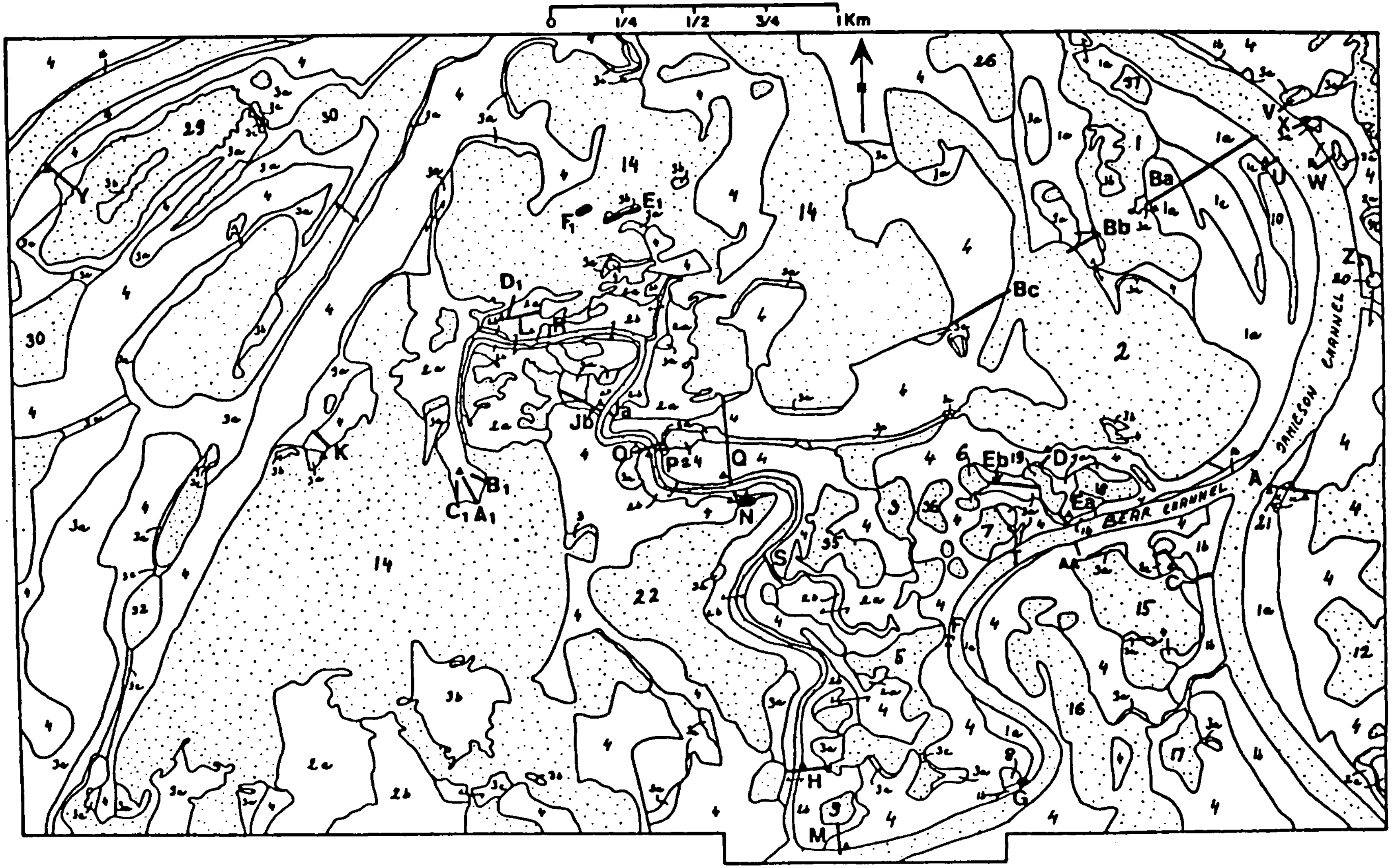


FIGURE 2.9: ECOSITE MAP OF AREA 4 (from Pearce, 1986)

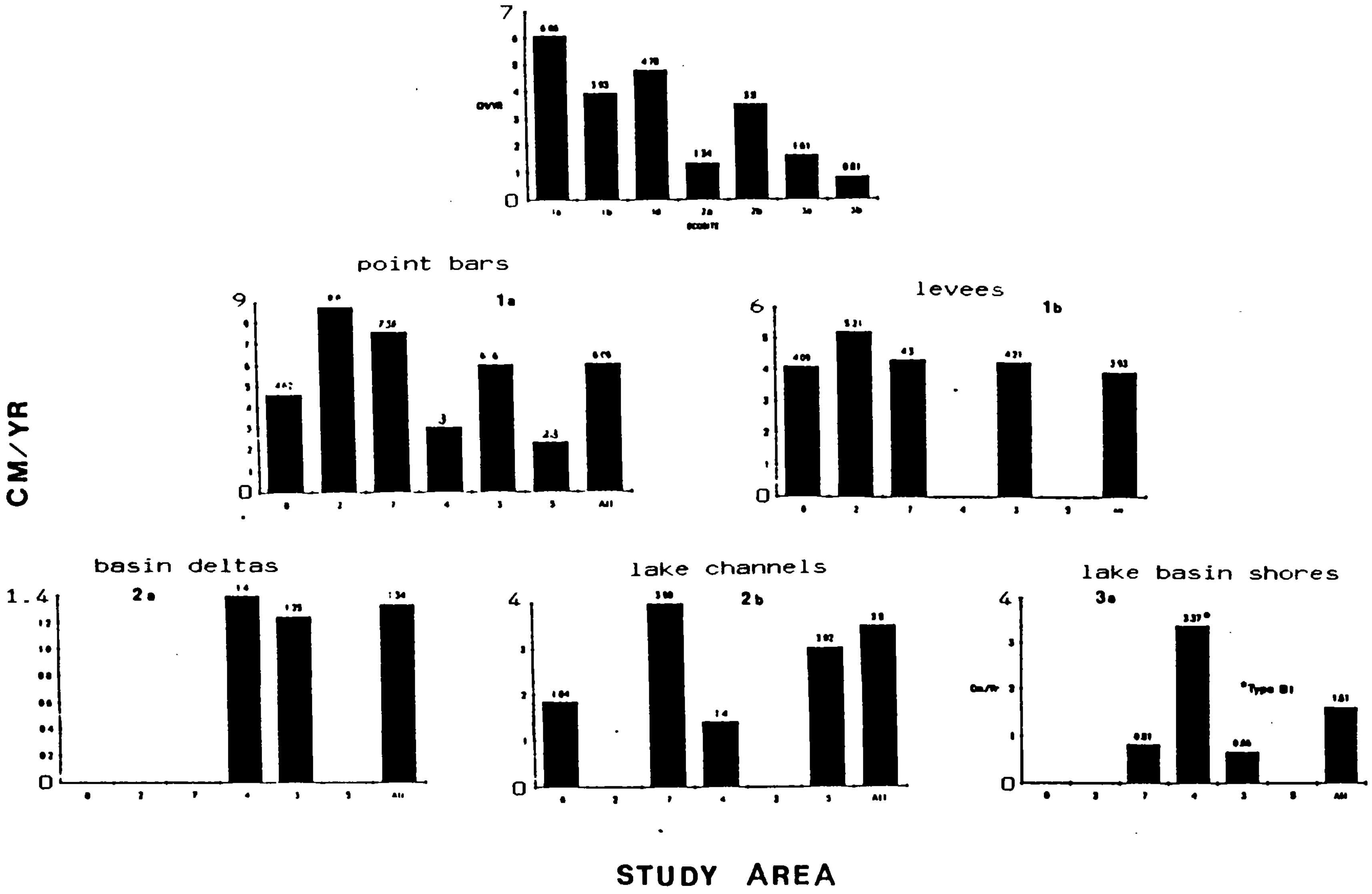


FIGURE 2.10: MEAN ANNUAL AGGRADATION RATES FOR SELECTED ECOSITES ON THE MACKENZIE DELTA BY STUDY AREA. (from Pearce, 1986)

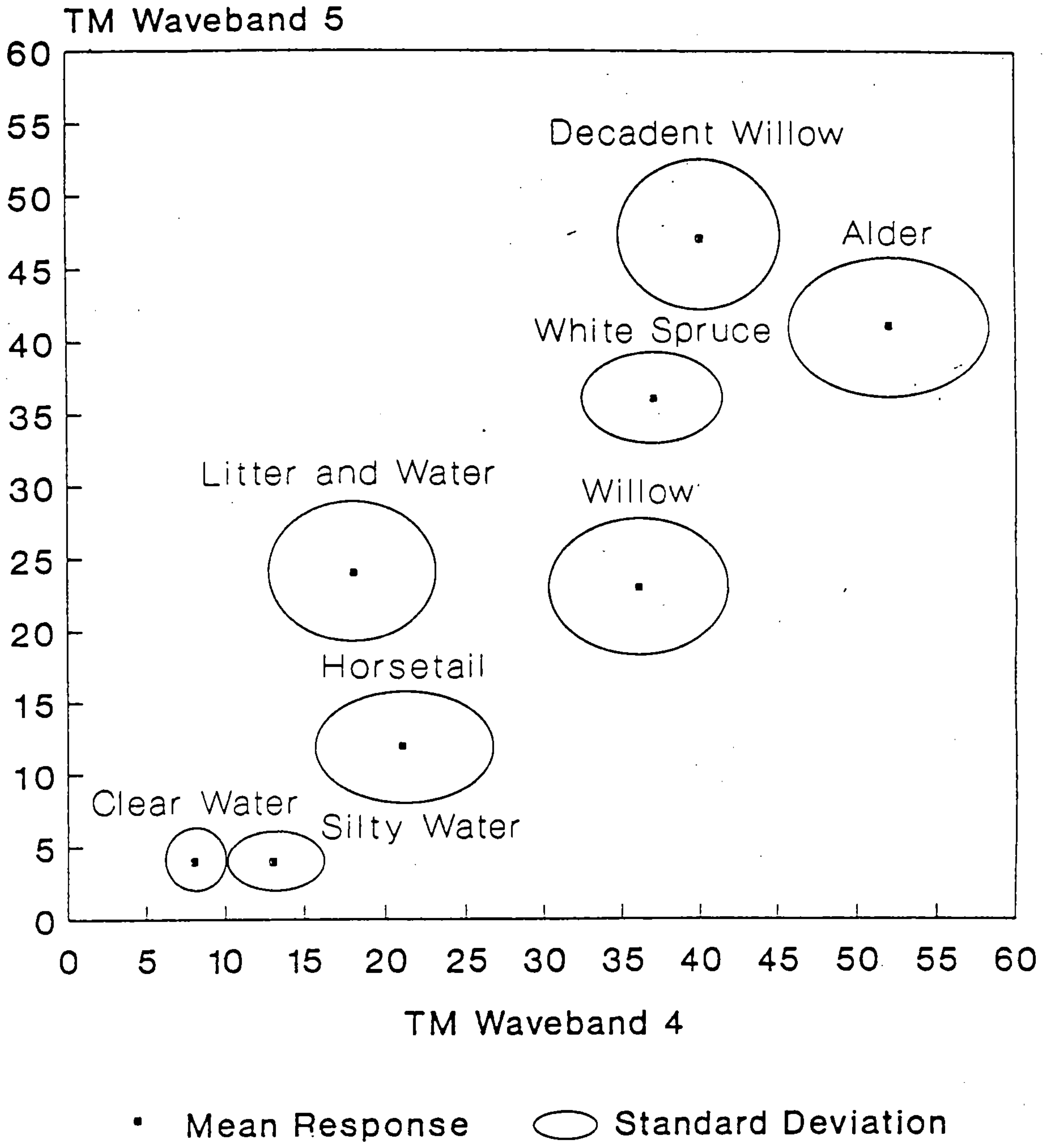


FIGURE 2.11 MEAN AND ONE STANDARD DEVIATION FOR EACH SPECTRAL CLASS IN TWO-DIMENSIONAL FEATURE SPACE FOR TM WAVEBANDS 4 (NEAR INFRARED) AND 5 (MID-INFRARED). (from Boyes, 1991)

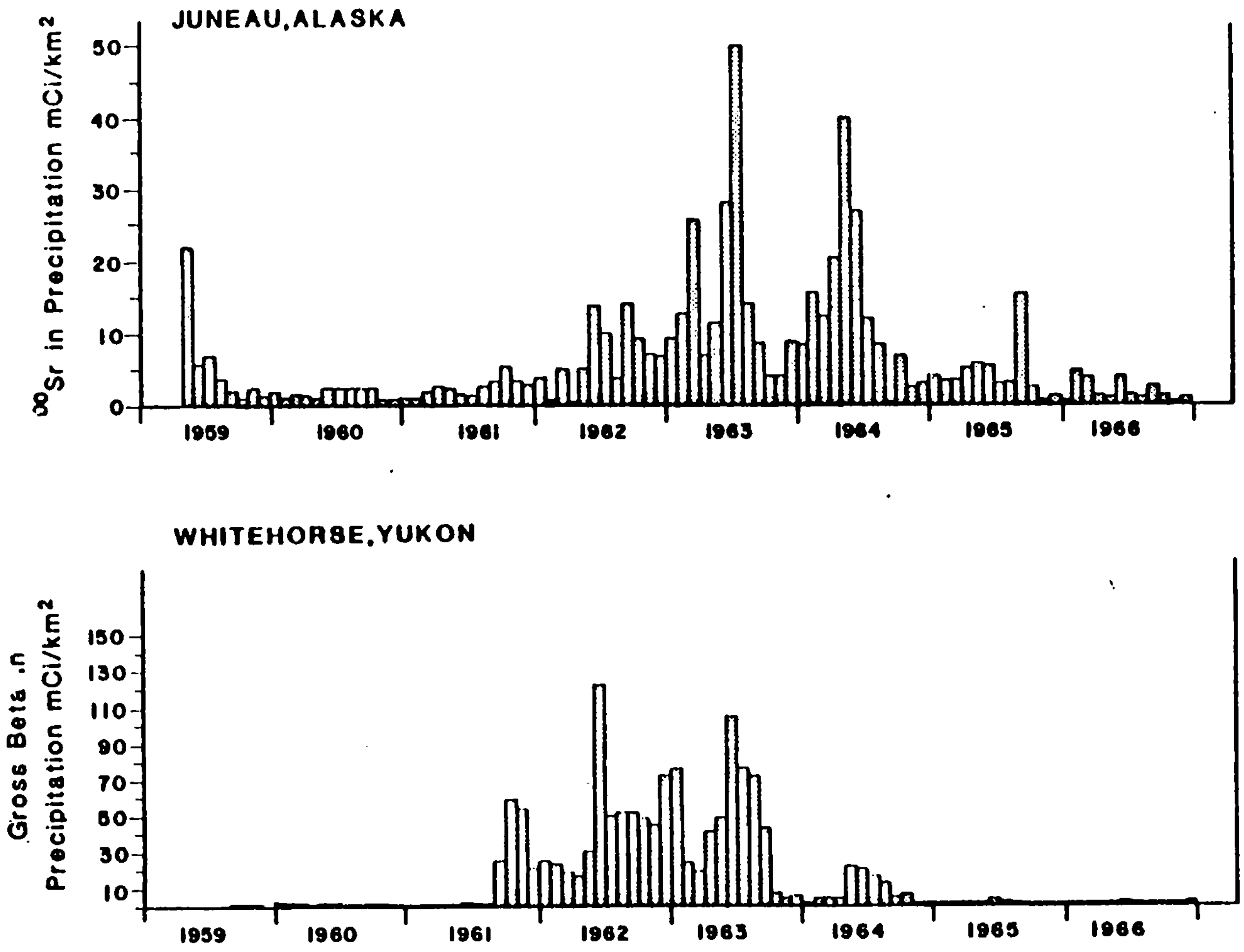


FIGURE 2.12

^{90}Sr in precipitation at Juneau Alaska (Health and Safety Laboratory, U.S. Atomic Energy Committee) and Gross Beta Radiation in precipitation at Whitehorse, Yukon Territories (Radiation Protection Bureau, Health and Welfare Canada).

(from Cordes and McLennan, 1984)

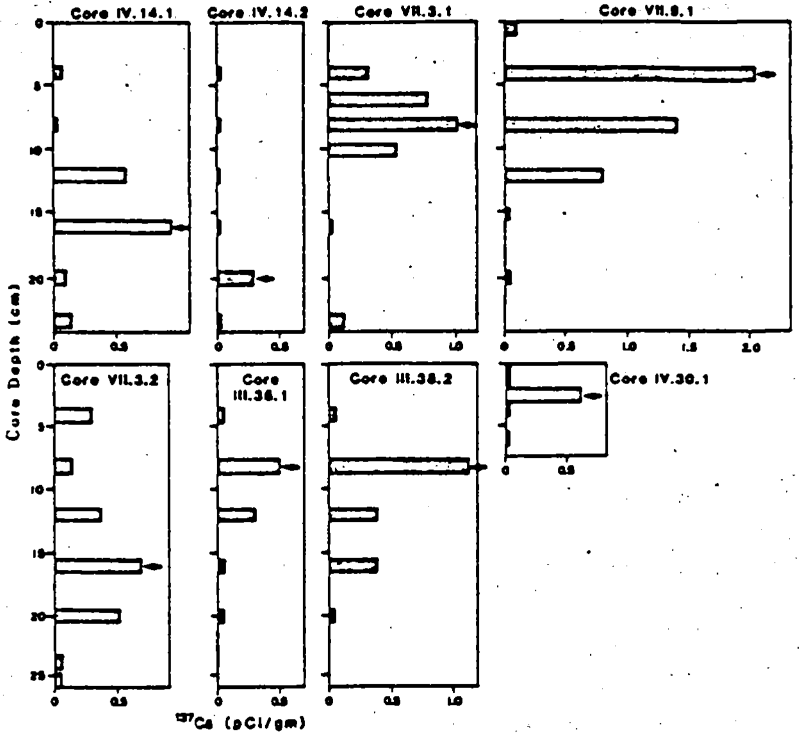


FIGURE 2.13

Patterns of ^{137}Cs activities (pCi/gm) in sediment cores from connected lakes (Type A). Arrows indicate assumed 1962 time-stratigraphic horizons.

(from Cordes and McLennan, 1984)

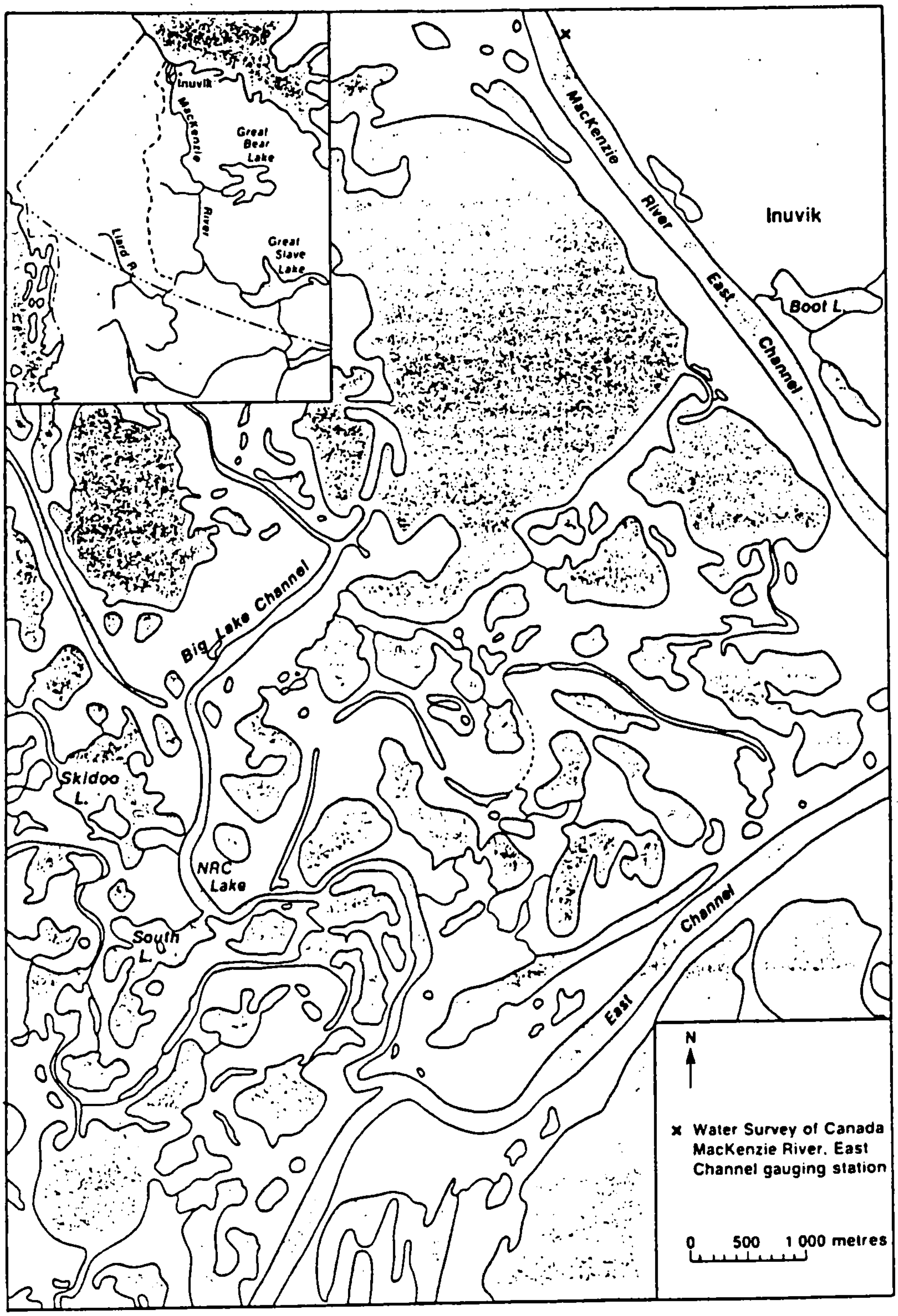


FIGURE 2.14

Location of study lakes near Inuvik, N.W.T. Skidoo Lake, NRC Lake, South Lake and Big Lake Channel are unofficial place names.

(from Ferguson, 1990)

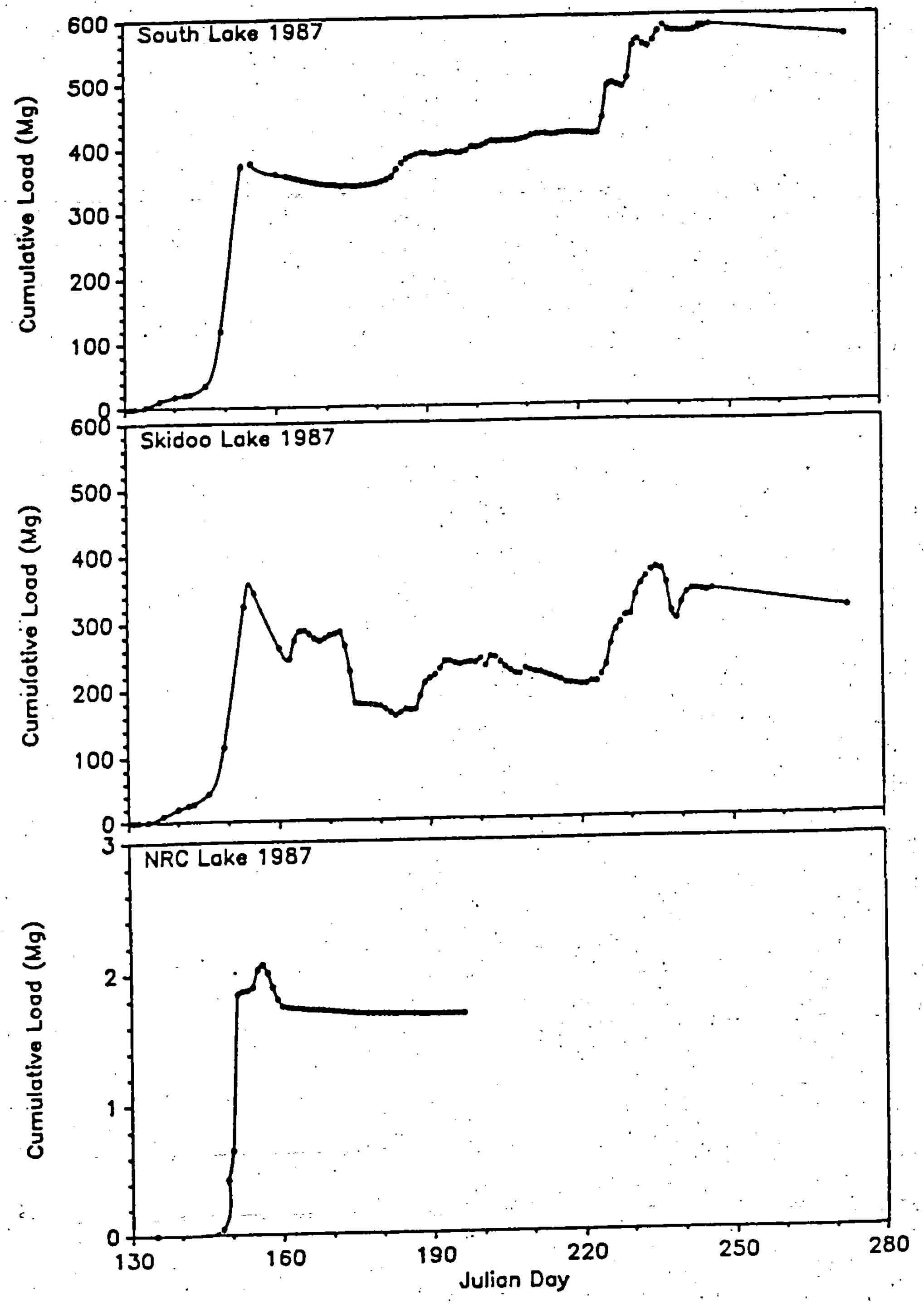


FIGURE 2.15

CUMULATIVE SEDIMENT LOAD FOR EACH OF INUVIK-AREA STUDY LAKES. (from Ferguson, 1990)

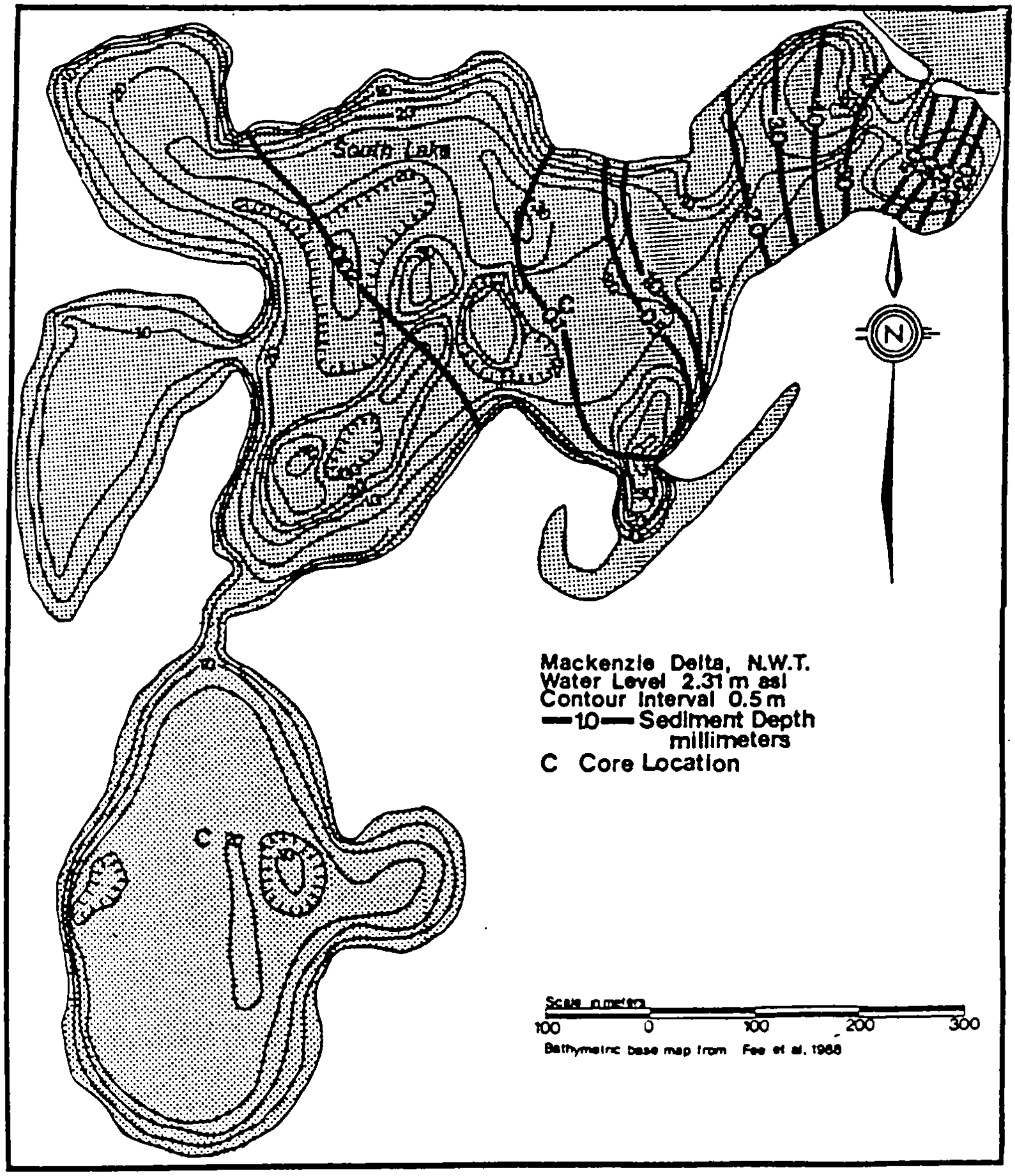


FIGURE 2.16

Sedimentation depths for South Lake determined from the summer sedimentation plates installed June 24 - August 31.

(from Ferguson, 1990)

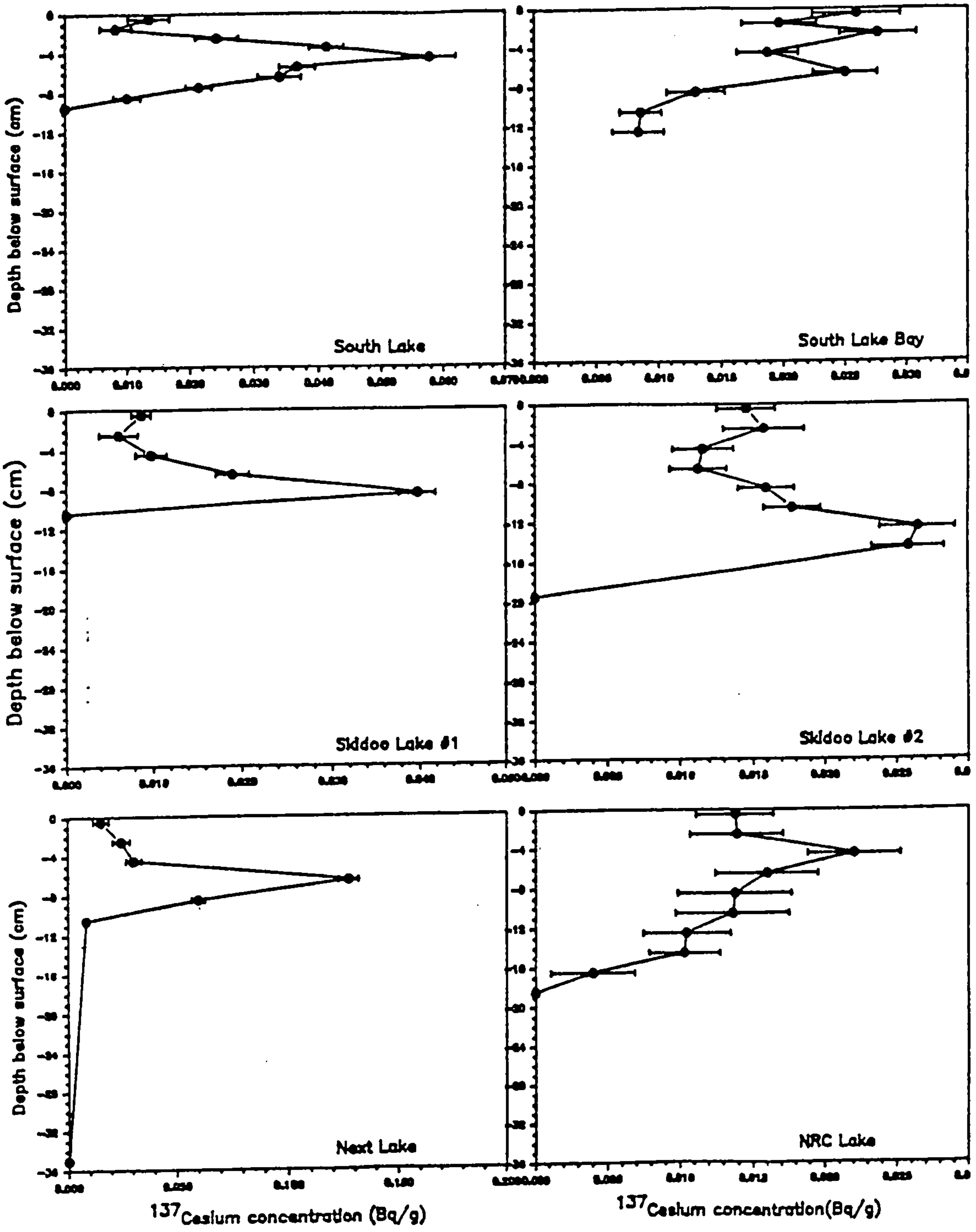


FIGURE 2.17

CESIUM-137 PEAK CONCENTRATIONS IN LAKE SEDIMENTS
(from Ferguson, 1990)

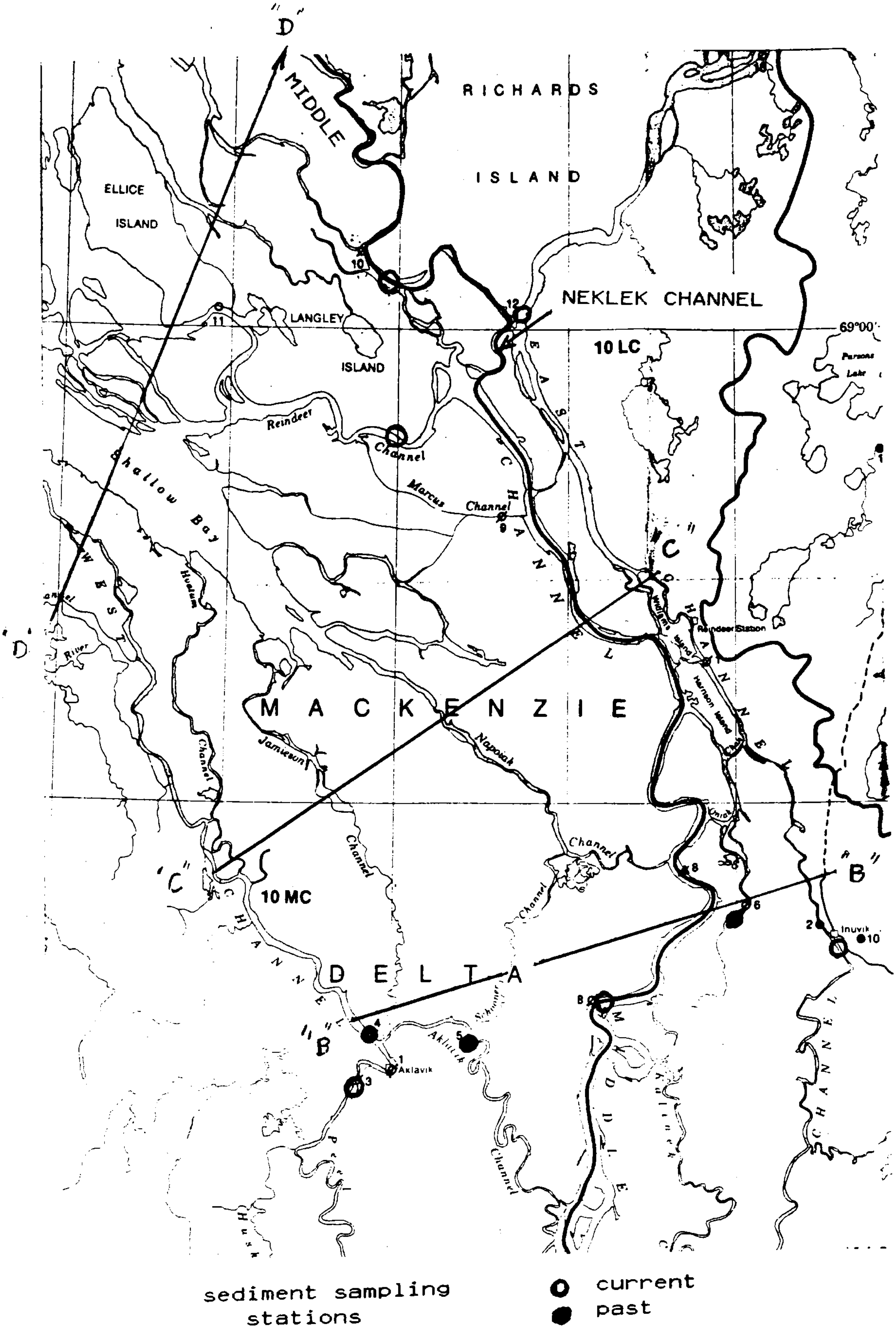


FIGURE 4.1

LOCATION OF BC HYDRO TRANSECTS IN RELATION TO IWD SUSPENDED SEDIMENT STATIONS

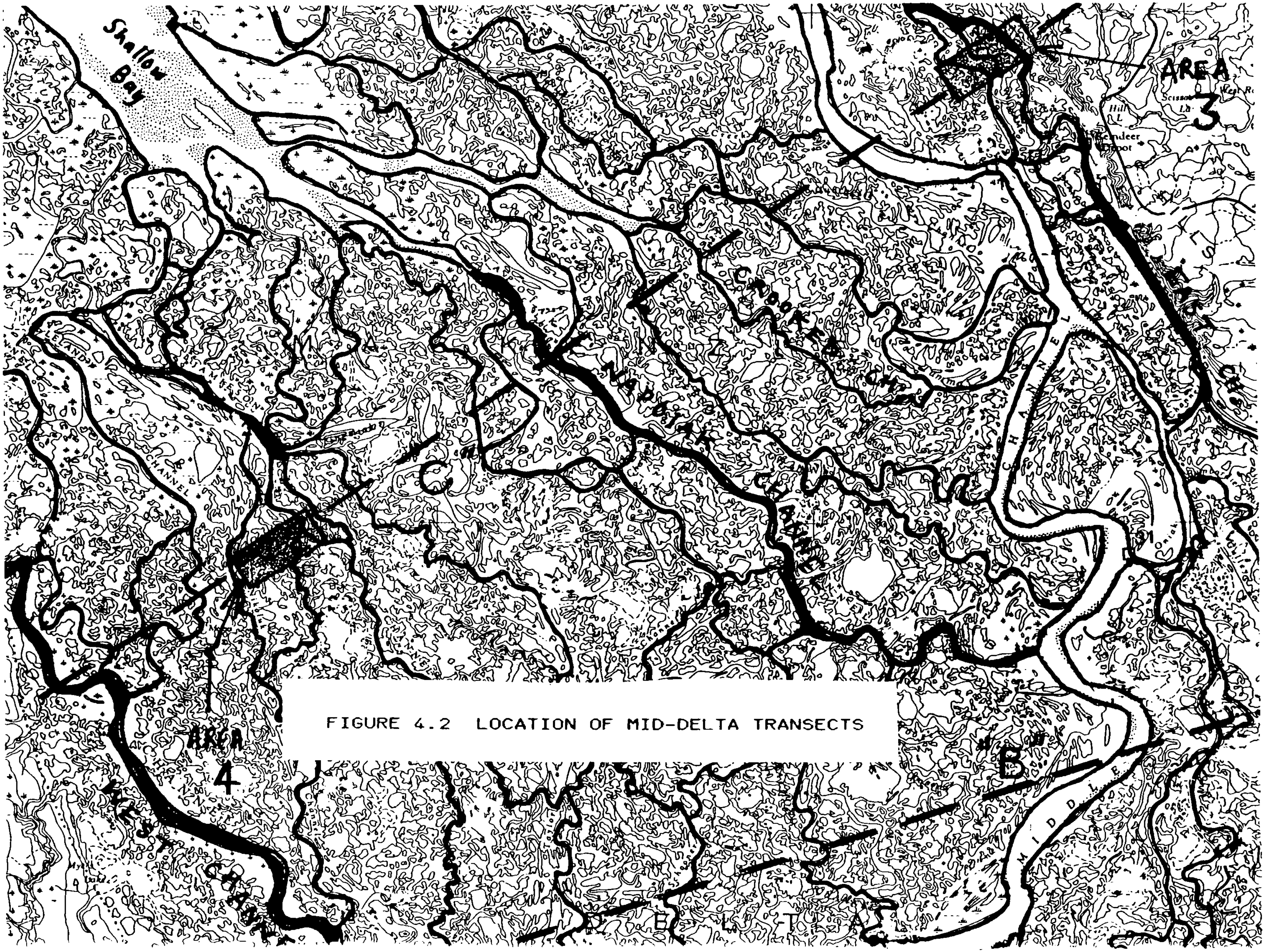


FIGURE 4.2 LOCATION OF MID-DELTA TRANSECTS

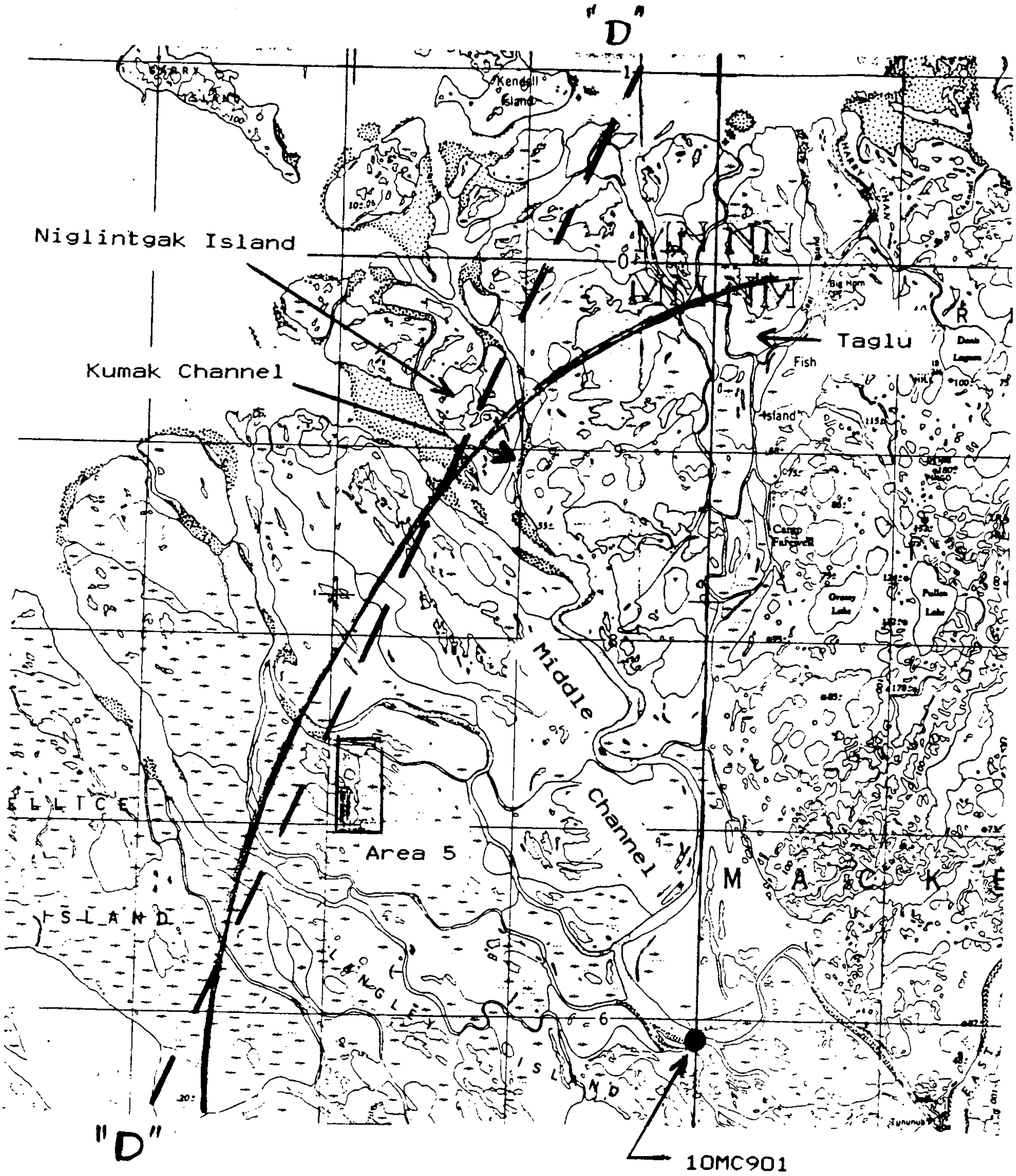


FIGURE 4.3 LOCATION OF BC HYDRO OUTER-DELTA TRANSECT

Solid is possible alternative transect

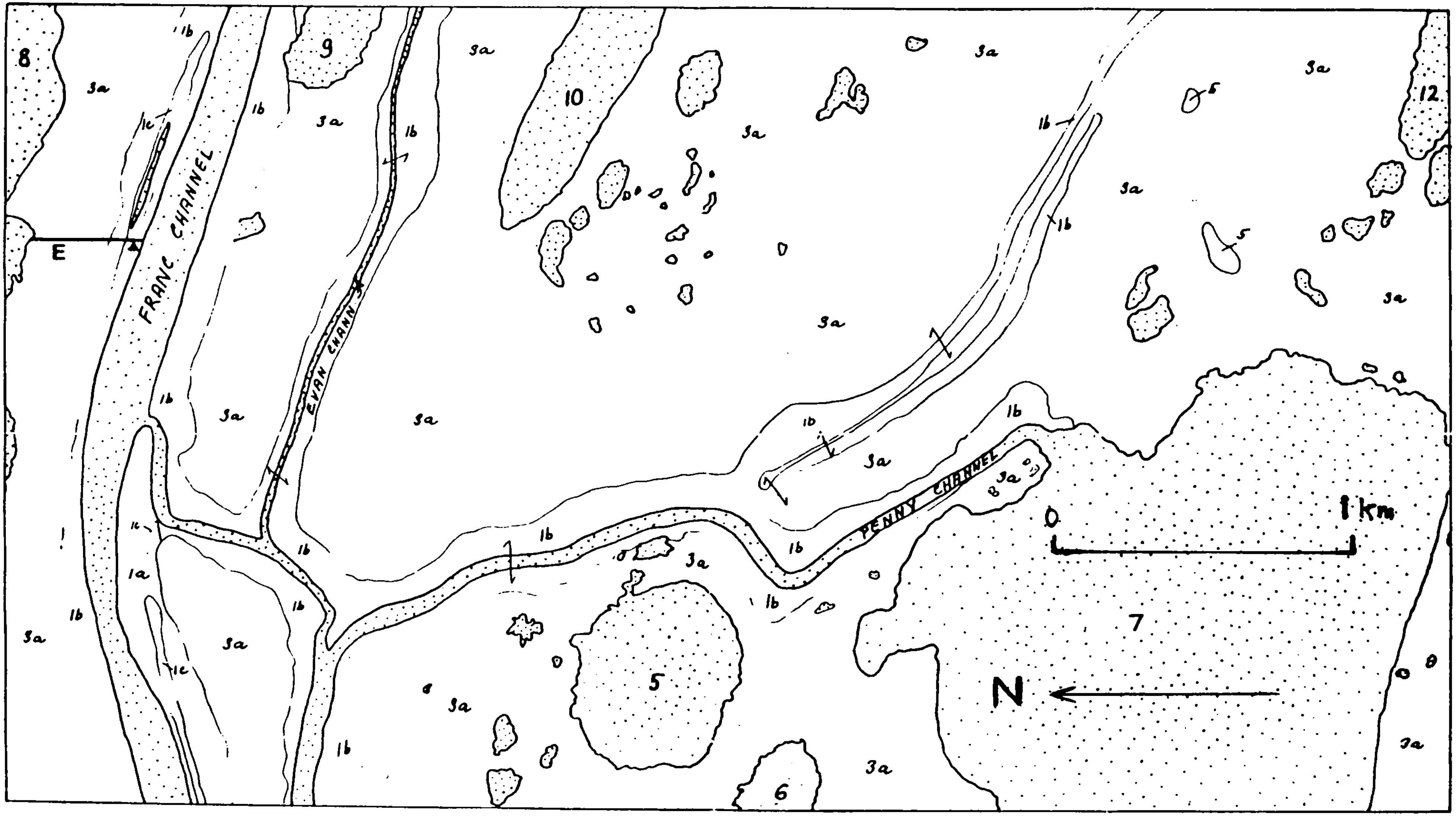


FIGURE 4.4 BC HYDRO STUDY AREA 5

SEDIMENTATION MEASUREMENTS IN THE MACKENZIE DELTA, NORTHWEST TERRITORIES: REVIEW AND RECOMMENDATIONS

by

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for

Inland Waters Directorate
Environment Canada
Yellowknife, NWT

under contract
KE521-1-0085/01-XSG
Supply & Services Canada, Edmonton

December, 1991

Acknowledgments

This report was prepared as one part of Contract KE521-1-0085/01-XSG administered by Supply and Services Canada with F. M. Conly of Inland Waters Directorate, Yellowknife, NWT as Scientific Authority. The assistance provided by Malcolm Conly and Jesse Jasper in the administration of the contract is duly acknowledged.

Phil Marsh of National Hydrology Research Institute and Cheryl Pearce of University of Western Ontario provided copies of various unpublished reports. Malcolm Conly, Henry Hudson and Cheryl Pearce provided thorough reviews of the initial draft of the report. It is also a pleasure to acknowledge, once again, access to the Mackenzie Delta libraries of Peter Lewis and Mike Miles in Victoria.

Executive Summary

1. Inland Waters Directorate (Yellowknife) is considering a program to determine regional variations in medium term (30 years or more) overbank sedimentation along two transects of the Mackenzie Delta: one at mid-delta, and one in the outer delta. This review provides a brief summary of previous work in the delta, and makes recommendations regarding the methodology and sites for the IWD program.

2. A large amount of work has been previously undertaken on sedimentation, especially by consultants working for BC Hydro in five main study areas. The goal of much of this past work was not, however, directly equivalent to that of IWD. Sedimentation cores taken in lakes were used primarily to assess differences in sedimentation rates within lakes and between different kinds of lakes. Sediment accumulation in inter-lake areas was determined primarily to assess the relationship between sedimentation amounts and vegetation type. Nonetheless this previous work provides an important basis for IWD's work:

(a) additional analysis of the BC Hydro data should permit development of a map of sedimentation in each study area and an estimation of the mean rate for each area; this will allow IWD to concentrate its own fieldwork in additional study areas, thus increasing coverage of the delta;

(b) the work provides a tested methodology which can be adapted by IWD in its own program.

3. A major component of the work will be coring. This will provide sediment samples for determination of background (pre-development) levels of contaminants, e.g. hydrocarbons. In addition, it will provide one approach to the estimation of past sedimentation rates. The most suitable method of dating sediment in these cores is probably through Cs-137 determination to locate a time marker for either the onset of Cs presence (1961?) or peak Cs content (1963?). Other methods are also considered.

4. A key issue is determination of the number and location of sites for such coring, given the high variability in sedimentation rates between lakes (due to varying height of sill and location with respect to major channels), within lakes (due to varying proximity to inlet channel) and on land (due to varying elevation and proximity to channels). Examination needs to be made of variance levels in previous studies before numbers of cores can be planned adequately. Existing data from BC Hydro's study areas need to be reanalysed (preferably using GIS methodology) to update

sedimentation rates to the present day, and to assess the suitability of using vegetation as the basis for selection of core sites, and extrapolation of sedimentation rates to unsampled sites in a study area.

5. Installation of permanent stakes (driven into the permafrost) in these study areas, in larger quantities than the number of cores, should allow verification of the sedimentation data at some date in the future. This remains the most cost-effective and most easily interpreted method of assessing sedimentation. On the other hand, on its own it is not likely to yield meaningful data for 5-10 years.

6. The timeframe established for this work is conditioned by the NOGAP funding program: a mid-delta transect in 1992/93 and an outer-delta transect in 1993/94. This is a severe timeframe in which to work. It probably does not provide sufficient time for the appropriate reanalysis of the BC Hydro data. In this case, refinement of the methodology will have to be undertaken concurrently with fieldwork in the new study areas. This is not the most appropriate schedule, and the possibility of adjusting it to mesh with the realities of the project should be examined.

7. It is recommended that the mid-delta transect be made to coincide with BC Hydro's old Transect C, about halfway between the Aklavik-Inuvik line and Shallow Bay. BC Hydro has two study areas on this transect. A minimum of three additional study areas (one near West Channel, one near Napoiak Channel and one near Middle Channel) is suggested.

8. It is recommended that the outer-delta transect be based upon BC Hydro's old Transect D, but restricted to the area northeast of Shallow Bay. The new transect (which would have only one BC Hydro study area) may need to be modified to include previous work undertaken by consultants for the oil and gas companies in the Niglintgak-Taglu areas, as well as more recent vegetation mapping in the outer delta.

1. MACKENZIE DELTA SEDIMENTATION STUDY: INTRODUCTION

1.1 Terms of reference

The background for this report is provided in the program description by IWD Yellowknife for its NOGAP funding proposals for 1991/92 - 1993/94: Project C.11 - Sediment-related aspects of northern hydrocarbon development. The report deals with sub-project C.11-4: Mackenzie Delta Sedimentation Study.

The description of that study reads:

> "A transect of sediment samples will be collected from overbank areas across the middle of the delta in 1992/93 to assess core analysis techniques and tie 1963-92 deposition rates to NHRI delta lake hydrology and sedimentation studies. Cs-137 and other dating techniques will be evaluated for best results. Study areas in the outer delta will be sampled in 1993/94. Sediment samples will be analyzed for hydrocarbon-related contaminants, and archive for future use."

The objective is given as:

> "To measure overbank sediment depths in the Mackenzie Delta, in order to quantify the longterm average sediment deposition component of the delta's sediment budget." An important part of this work is not merely documentation of the magnitude of total overbank sedimentation, but determination of spatial patterns of sedimentation across the delta (Wedel, 1990, p. 5-6). As noted in the description, sediment quality (contaminants) will be investigated as well as sediment quantity: to assess "pre-development" contaminant levels and their variability within the Delta.

1.2 Outline of report

The present report is required by contract to provide "written recommendations on location and methods for sampling and assessing historical sedimentation rates in the Mackenzie Delta".

The report begins by a brief review of the types and locations of sedimentation data previously obtained in the Mackenzie Delta. This is followed by recommendations regarding techniques that could be used and then suggestions regarding locations within the Delta.

2. PREVIOUS STUDIES OF SEDIMENTATION IN THE MACKENZIE DELTA

The major source of information concerning sedimentation rates in the Mackenzie Delta is the work sponsored by BC Hydro, during the early 1980s, as part of its downstream environmental impact assessment of possible hydroelectric generation in the Liard River basin. Detailed work has been undertaken in five main study areas in the delta, in turn by Hardy Associates (1982), Cordes and Associates (1984) and Pearce (1986). Applied Ecology Consultants (1987) have provided an extensive review of this work. In the late 1980s, the National Hydrology Research Institute initiated studies into lake sedimentation in the mid-delta area near Inuvik (Marsh and Ferguson, 1988). Finally, Lewis (1988) has provided a general overview of sedimentation processes in the Mackenzie Delta.

In relation to the proposed NOGAP sedimentation study, Jasper (1991, pers. comm.) commented: "The only criteria generally agreed to at the present time is that the depositional environments must be simple and consistent (overbank areas close to channels rather than in complex lake systems) to eliminate some of the wide variability in delta deposition rates." In the discussion below, both lake and on-land sedimentation are examined. In the mid-delta, 30-50% of the area is actually covered by lakes (Fig. 2.1).

In addition, though the study description refers to "overbank" sedimentation, discussion is provided here of in-channel deposition as well. No sediment budget of the delta can afford to ignore this component, unless it can be shown that sediment accumulation in channels (e.g. on point bars) is balanced by removal of delta sediment through channel scour of bed and banks (e.g. on outer banks of bends).

2.1 Inter-lake sedimentation

2.1.1 Ecological land classification

Overbank sedimentation in the Mackenzie Delta will vary not only according to general location in the delta, but also with elevation of the land surface and proximity to the channel network. Thus some classification of landscape units is needed in order to stratify sedimentation sampling. One, widely-cited classification, was developed by Cordes and Associates (1981), and is given in Fig. 2.2. The system is a hierarchical one: within the Delta, the landscape is subdivided into ecosystems (termed **ecosections** by Pearce, 1986) according to the level of fluvial activity; these are subdivided into ecotypes (termed **ecosites** by Pearce, 1986). These terrain units are, in turn, subdivided into plant associations (**ecophases**).

- **Ecosections and ecosites (terrain units)**

The "active" area of the delta (currently being created by fluvial deposition and flooded annually) is subdivided into the channel ecosection (point bar and levee ecosites) and the inter-channel basin ecosection. The latter is subdivided into the shore and shoal ecosites of basin lakes, on the one hand, and lake deltas, on the other.

The "semi-active" area of the delta (the delta plain ecosection, where elevated surfaces are flooded only infrequently) is subdivided into two ecosites: mesic plains (with good drainage: alder, willow and spruce) and hydric plains (impeded drainage: spruce). These delta plain areas - common in the southern part of the delta - are assumed to represent old inter-levee basins which now occur above modern flood levels either because of gradual aggradation of their surfaces or because of downcutting of adjacent channels.

Mackay (1963, p. 125) noted that levees were much better developed and more common in the northern half of the delta than in the south. This may seem to conflict with his well-known map of levee heights (Fig. 2.3) which shows a systematic decrease towards the north. These "heights", however, are relative to the level of low-water in the channel (which is important from the standpoint of flooding frequency), rather than to the adjacent floodplain (the morphological basis). Data from the Topographical Survey of Canada listed by Mackay (1963) indicate that there is also a progressive decrease in height of floodplain above the low-water datum from south to north, being about 10 m in the south and about 1.5 m near Shallow Bay.

In the low arctic, north of the tree line, restricted areas of "inactive" delta ecosection, typically with pingos and similar hummocks, are also found, being sufficiently high that they are never flooded.

- **Ecophases (plant communities)**

The major ecophases found in the high subarctic coastal plain are listed in Table 2.1, and their location with respect to a gradient of flooding frequency is illustrated in Fig. 2.4. (A listing of common and scientific names for plants is given in Appendix A.) It is generally accepted that within any terrain unit, the pattern of sedimentation rates is largely reflected in the pattern of ecophases. Thus mapping of ecophases and terrain units is one tool in the establishment of mean sedimentation rates in a study area. Typical ecophase maps of a basin delta and basin lakeshore and shoal units are provided in Figs 2.5 and 2.6.

2.1.2 Sedimentation rates and landscape

Studies by Cordes and Associates for BC Hydro involved mapping of these terrain and vegetation units in five areas of the delta (Fig.2.7), together with assessment of longterm sedimentation rates. The study areas, located on four transects, were chosen to correspond to distinct drainage areas of the delta as identified by Mackay (1963) (Fig. 2.8). The numbering system used in the BC Hydro project (unrelated to the numbering of the drainage areas in Fig. 2.8) lacks order and is unfortunately not easy to remember: this is primarily because areas 6 to 8 were added later. Within the initial five units, there is a progression from delta-head (1 and 2) through mid-delta (3 and 4) to outer delta (5).

The percentage area occupied by each subtype, together with lakes and channels, is shown for each area in Table 2.2. The dominance of the mesic delta plain in the two southern areas (1 and 2) is clear. Delta lakes constitute roughly the same percentage of the landscape in the southern (1, 2) areas as in the northern area (5). This is not entirely consistent with Mackay's (1963) map (Fig. 2.1) which shows a marked decrease in the landsurface occupied by lakes in the outer delta. Pearce (1991, pers. comm.) also indicates that the high % lake cover in study area 5 is not typical of the outer delta. The basin lake-shore area is much higher in the low arctic area (5): again this seems to reflect the very large number of small ponds in the study area, but is not typical of the outer delta (Pearce, 1991, pers. comm.). The larger lake area in the mid-delta (area 4) is consistent with Mackay's map.

Much of the Cordes and Associates data on sedimentation rates was for point-bars. These constitute only a small percentage of the delta landscape. In addition, the data do not contribute directly to assessment of overall deltaic sedimentation, because gross accumulation of point bar sediment is probably balanced, to a large extent, by loss of delta sediment through scour of undercut channel banks. In this case, net channel deposition would be small. The issue of whether delta channels are aggrading, degrading or in equilibrium, has not been examined in any detail. Lapointe (1986) considered the issue briefly, and found no conclusive evidence for either aggradation or degradation.

Only limited data were available for the more extensive inter-channel basins. These were summarized by Blachut et al. (1985) and are given in Table 2.3. Comparison between areas is difficult given the large variance within areas.

Sedimentation data collected at the BC Hydro sites during the flooding periods of 1982-83 are summarized more fully in the thesis by Pearce (1986). Attention was again focused on contrasts in sedimentation between different land units within each local area (rather than differences between study areas), the purpose of this being to assess the effects of sedimentation on plant colonization. Vegetation data were collected for 1560 plots on 310 transects normal to shorelines. The number of plots used to monitor sedimentation was not indicated; these were located only on those transects which were surveyed to the camera sites being used to monitor water level changes. As an illustration, the ecosite map of Area 4, with location of transects, is given in Fig. 2.9 (numbers refer to lakes).

Mean aggradation rates (1982-1983) for the different ecosites were as follows (Pearce, 1986):

Channel ecosection:

point bar : 61 mm/yr
levee : 39 mm/yr
alluvial sand plain : 48 mm/yr

Interchannel (basin) ecosection:

basin delta : 13 mm/yr
distributary: 35 mm/yr
lakeshore : 16 mm/yr
lake shoals : 8 mm/yr

Sedimentation amounts within each ecosite, broken down by study area, are given in Table 2.3 (from Blachut et al., 1985) and Fig. 2.10 (Pearce, 1986). The table indicates the large range in amounts even within single ecosite classes. The figure shows larger differences between ecosites than between study areas. There are, nonetheless, differences between study areas, though none of these patterns has been subjected to statistical analysis. Pearce (1986, p. 259) makes the comment:

> "These data (for individual plots) show that there was much variability in deposition rates from site to site, so much so that there was absolutely no point in calculating standard deviation and standard error of the mean to extrapolate the information to unsampled sites."

The logic behind this comment is not clear to the writer. The standard error of the mean, no matter how high, should always be presented. Perhaps what was meant was that there was no point in comparing mean rates between the different study areas. It is unfortunate that standard deviations were not given. Only with this information can some indication be obtained of the number of plots per ecosite needed to estimate sedimentation in a given study area within a specified level of accuracy.

The thrust of the Cordes group approach towards mapping sedimentation is not so much a focus on ecosites, however, as emphasis on the next scale down: the ecophases (vegetation groupings) within ecosites. The basic tenet is that there is a direct relationship between sedimentation rates and the distribution of specific plant communities within the delta, although there is still large variation within individual ecosphases (Table 2.4). The nature of this relationship has still not been quantified accurately, but Table 2.5 lists plant community flood-tolerance groups in a qualitative way. (Note that, though the table indicates grouping by "flooding" tolerance, the key determinant of vegetation is assumed to be sedimentation, not the number of days of submergence.) Boyes (1991), working in a 15 km square area between Inuvik and

Middle Channel, has used Landsat 5 thematic image data to distinguish between these groupings (Fig. 2.11), providing a methodology for the rapid mapping and quantitative analysis of vegetation and inter-lake sedimentation in the delta.

It should be recognized that the high variability in sedimentation rates within a given ecophase refers to short-term rates. These should not be extended to longer term (30 years) rates. For example, while short-term levee sedimentation (Table 2.4, Ecosite 1b) may range 20-180 mm per year in the Carex (sedge) ecophase, this should be not taken to mean that 30-year deposition ranges from 0.6 m to 5.4 m! As sedimentation proceeds, levees are built to higher levels, slowing down the rate of sedimentation in any ecophase. Thus, peak longer term rates for a given ecophase will be less than the maximum short term rates, and the variability will also be less. Indeed, much of the variability in short term rates within a given ecophase is presumably due to different ages of the plant community and thus different land levels.

Determination of longer term rates for a given ecosite (such as levees) is complicated by the fact that some land areas will change from one ecophase to another (e.g. willow to alder) as sedimentation builds up the land level. In other words, quantitative modelling of plant succession is needed to extrapolate short-term sedimentation rates to longer term rates at a given site. Integration of these long-term rates at all sites could then be used to determine a mean for the area under study. This would seem to be a somewhat circuitous, and perhaps speculative, approach to determining long-term mean sedimentation rates over a broad area. Two alternatives might be suggested.

One alternative method is to argue that, while short-to-medium term rates (10 years) <u>at a given site</u> are not necessarily representative of longer term rates at that site, mean short-to-medium term rates <u>in the study area</u> (using the ecological land classification to weight the rates in each ecosite and ecophase) might still be representative of mean longer term rates for the study area. As an example, if 3% of the study area is sedge-covered levee sites, though the long-term sedimentation rate in those sites will decrease as levee height increases and the sedge is replaced, the use of the short-to-medium term data will be valid in the long term if sedge-covered levees continue to occupy 3% of the study area on a long-term basis (through channel migration, new channel routes, etc.).

The other method is to measure long-term sedimentation rates directly, either through coring past sediment accumulation (and dating layers) or through measurement of future deposition. This is pursued in Section 3.3.

2.1.3 Summary

It is evident that a great deal of knowledge is now available on variation in sedimentation rates in inter-lake areas of the delta, on the controls on this pattern, and on the methodology for mapping and analyzing it.

There are still issues to be resolved: the most important is providing the actual calibration between vegetation and sedimentation. This may prove somewhat more difficult than anticipated because it is still not clear whether these vegetation associations are controlled by flooding, or by sedimentation, given the fact that the relationship between the two may vary throughout the delta. Nonetheless, sufficient background and expertise are available to address the topic of inter-lake sedimentation.

2.2 Lake sedimentation

2.2.1 Cs-137 studies in the BC Hydro study areas

The post-1963 rates of sediment accumulation in 19 lakes in the BC Hydro study areas were investigated by Cordes and McLennan (1984) based on Cs-137 dating of lake cores.

The rationale of the Cs-137 approach is as follows. Atmospheric testing of nuclear weapons in the 1950s and 1960s produced fallout of radioactive nuclide such as cesium. As indicated in Fig. 2.12, the fallout of radioactive nuclide in the subArctic (as elsewhere) peaked in 1962-64. On settling to the earth's surface, the cesium quickly (and strongly) bonds to fine silicates. Thus Cs-137 will be found in lake sediments because of both direct fallout onto lake surfaces in the testing period, and because of transport into lakes (in the post-testing period) of soil that had been contaminated prior to erosion. Sediment laid down in lakes in 1963 should thus show markedly higher levels of Cs radioactivity than sediment layers from earlier years, providing a stratigraphic marker for measuring subsequent sedimentation.

The Cs-137 profiles might be expected to increase abruptly in 1961, peak in 1963 and decrease gradually since that time. The actual Cs-137 profiles (Fig. 2.13) do not entirely match expectations: in some cases (e.g. Core VII.9.1) there is a gradual increase in Cs-137 upwards towards the peak with a more abrupt decline from the peak towards the surface of the sediment. It is not clear why these departures from the expected pattern occur. It must be recognized, however, that 1961 was the year of a major flood throughout the delta. In many high-level lakes, remote from channels, it is possible that virtually no sedimentation had taken place since then prior to the coring program. All cores were taken in the deepest parts of lakes: bathymetric maps were provided for each lake showing core locations.

Lakes were chosen primarily to assess differences between lake type (proximity to sediment-carrying channels and height of lake sill) rather than to determine mean rates for each study area. The data are summarized in Table 2.6 according to lake type:

Type A lakes are "no closure" lakes, i.e. connected directly to the river network by a channel;

Type B and C lakes are "lakes with closure", i.e. lakes where connection with the river network is lost when flood levels subside below the sill level of the lake basin: Type B lakes are "low closure" and are flooded annually; Type C lakes are "high closure" and are not flooded annually.

The percentage of each study area occupied by the three lake types is indicated in Table 2.7 High-closure lakes are unimportant in the middle-delta and outer-delta areas.

The suffix in each lake type denotes proximity of the lake to the distributary network: "1" denotes lakes that are close to the channel network and therefore subjected to high rates of sedimentation; "2" denotes lakes further from channels. There is usually a strong contrast in morphology between the two types of lake: "2" tend to be steep-sided, reflecting thermokarst processes; "1" have become more infilled with sediment and have gently sloping shorelines colonized by emergent vegetation.

Average rates of sedimentation in the Type 2 lakes are remarkably similar: 1.7 mm/yr in Type A; 1.3 mm/yr in Type B; and 1.2 mm/yr in Type C. Individual Type 2 lakes do show more variability: from almost nothing (0.3 mm/yr) to 3.2 mm/yr. Type 1 lakes show higher rates, as expected, averaging 6.7 mm/yr in Type A and 2.6 mm/yr in Type C. No cores were taken in Type B1 lakes. The data of Table 2.6 are inadequate to make any comment about regional variability because of the small number of lakes (often none) in each lake type class in each study area.

2.2.2 NHRI's Inuvik area study

Sedimentation rates in three small lakes southwest of Inuvik were monitored in 1987 by the National Hydrology Research Institute (NHRI) (Marsh and Ferguson, 1988; Ferguson, 1990).

The lakes receive sediment and water from a distributary (named Big Lake Channel) off East Channel (Fig. 2.14). South Lake has a low sill elevation and is connected directly to Big Lake Channel. Skidoo Lake also has a low sill elevation and is part of a complex lake system through which sediment and water pass from Big Lake Channel. NRC lake has no connecting channel and depends on overbank flooding for renewal.

Sedimentation rates were determined by three methods: sediment budget; sedimentation plates; and Cs-137 dating of cores of lake bed material. The results are summarized in Table 2.8.

The sediment budget approach involved determination of daily discharges and sediment concentrations at the lake inlet: depth-integrated sampling was done every second day after breakup (Fig. 2.15). The results (for the period May 12 - Sept. 3) indicated 1.3 mm sedimentation in South Lake, somewhat less in Skidoo Lake (0.5 mm) and only 0.2 mm in NRC Lake. These figures assume a bulk density of 1210 kg/m3, based on sediment cores extracted from the lake (Marsh and Ferguson, 1988, p.24)

Direct measurement of sedimentation on plates set at representative sites on the lake bed was difficult because of (a) loss of plates (inserted in winter) during ice breakup, and (b) large variability in rates within the lake according to distance from the inlet (Fig. 2.16). The inferred mean lake sedimentation rates for the summer period agreed well with the sediment budget calculations for the same period on South and Skidoo Lakes. A relatively large discrepancy occurred for NRC Lake (1.1 mm) because only two plates were recovered.

Using the Cs-137 method (Fig. 2.17), the post-1963 mean annual sedimentation was determined as: South Lake (2.0 mm), Skidoo Lake (3.7 mm) and NRC Lake (2.0 mm). These post-1963 data give appreciably higher sedimentation than the 1987 sediment budget, even though the cores were taken from the deepest part of the lake. The South Lake core with 2.0 mm mean annual rate was taken where the inferred local 1987 sedimentation was only 0.1 mm (Fig. 2.16). The Skidoo Lake cores (3.7 mm) were located at sites where the 1987 sedimentation was only 0.1-0.5 mm.

This order-of-magnitude difference between the two data sets should not be considered surprising. The sediment flux in 1987 along East Channel is likely to have been appreciably smaller than the average for the post-1963 period. The WSC hydrometric data for East Channel at Inuvik show the peak daily discharge in 1987 (June 11) to have been only 546 m3/s. This was the lowest on record (since 1974). The June mean flow was only 379 m3/s (compared to the mean since 1974 of 481 m3/s) and the July (234 m3/s) and August (216 m3/s) flows were also less than the longterm means.

No annual sediment load data are available for East Channel, but annual loads on the Mackenzie at Arctic Red River in 1974-1986 ranged between 141 Mt (1974) to 54 Mt (1980), averaging 98 Mt (Carson, 1988). The low flow year of 1980 thus still had about half of the mean annual load. However, it would be expected that sediment input to lakes in low-flow years would be a much smaller percentage of the mean longterm input.

2.3 Lake shrinkage: comparison of aerial photographs

In a comparison of 1950 and 1981 aerial photographs of the delta (for the purposes of determining rates of channel shifting), Lapointe (1984, p. 41) made the comment that: "on a regular basis, small and isolated lakes that are approached by shifting channels become completely filled with sediments".

Though Lapointe provided no maps nor data for lake infilling, his casual observation nonetheless suggests that aerial photograph comparisons could be an important tool in the mapping of longterm lake sedimentation. Some control is obviously required on lake water levels at the time of the photography, and some information is needed on the pre-infilling bathymetry of the lakes. The latter problem may be limiting. Nonetheless, on a qualitative basis, inspection of aerial photographs may provide at least some indication of lakes which have infilled fairly quickly.

At the same time, it should be noted that the process of sedimentation in the lakes noted by Lapointe is not clear. The maximum longterm rate of lake sedimentation noted in the BC Hydro studies (Table 2.6) was 10 mm per year. Thus lake-filling in a period of 30 years indicates either much higher rates than previously documented or very shallow lakes or sediment accumulation by other processes (such as lake delta and shoreline progradation: Figs 2.5 and 2.6). This does not, however, detract from the potential of the method in assessing rates of lake sedimentation. Indeed, comparative aerial photography would seem to be the most logical approach to determining short-to-medium term shoreline progradation.

It is recommended that consideration be given to this approach in the IWD study, given the high cost of Cs-137 work (noted in the next chapter).

2.4 Sedimentation rates and clastic sediment flux

IWD's concern with sedimentation in the Mackenzie Delta arises, in part, from the role of out-of-channel deposition of sediment in the overall fluvial sediment budget of the delta. In that context, assuming that the riverine sediment is essentially inorganic, some relationship is ultimately needed between sediment thickness and the mass of clastic (inorganic) sediment per unit volume. Two points are noted here:

- not all deltaic sediment is clastic, some is biogenic;

- the bulk density of deltaic sediment is affected not only by conditions of sediment deposition, but also by post-depositional consolidation and decomposition of organic material.

It is beyond the scope of this report to pursue these points in depth, but some comment is required.

2.4.1 Organic sediment

Much of the biogenic material in the delta lakes appears to be macroalgal remains (that form a carpet on the bottom of lakes) into which settling fine-grained clastic sediment becomes incorporated (Gordes and McLennan, 1984, p. 47). Analysis of the BC Hydro lake cores indicated a consistently low amount of organic material, typically 5-7% by weight (ignition loss at 550°C). Expressed in terms of the volumetric composition of sediment, the figures would be somewhat higher.

A similar statement applies to inter-lake (subaerial) parts of the delta. Lewis (1988, Chap. 6) reported measured carbon contents of less than 15%. He added: "Given the essential role of organic material in the rapid infilling of lake basins in temperate and tropical deltas, it seems reasonable to hypothesize that a significant, even the most significant, factor in the continued survival of lakes in arctic/subarctic deltas like the Mackenzie is the existence of a pronounced decrease in the relative importance of organic accumulation in deltas in cold climate zones."

Notwithstanding these findings, organic material (especially peat) accounts for as much as 25% of the total volume of sediment in some cutbanks of the delta (Lewis, 1988, Chap. 6), so that any attempt to incorporate overbank sediments in the delta's clastic sediment budget cannot ignore the organic component completely.

2.4.2 Post-deposition consolidation

The importance of consolidation of deltaic sediment in temperate deltas (such as the Mississippi), and its role in the creation of lake basins (particularly in the vicinity of levees), was discussed by Lewis (1988, Chap. 6). The role of differential deltaic subsidence in moulding basin topography is not directly relevant here, but it is important to emphasize that the thickness of sedimentary strata, at depth, is a function not only of initial rates of sedimentation, but also subsequent rates of compression due to consolidation and decay of organic material.

In inter-lake areas of the delta, it seems likely that consolidation will be significantly less than in temperate areas because of permafrost strength (Lewis, 1988). Nonetheless, in coring sediments in the vicinity of large water bodies, it should be anticipated that deeper sediments may well have been compressed more than surface strata. Thus interpretation of deep cores based on C-14 dating may give an apparent rate of long-term sedimentation that is affected by compression, and not strictly comparable with medium term (post-1963) rates.

The impediment to consolidation (and organic matter decay) provided by permafrost certainly does not apply beneath many of the delta lakes. In this situation, marked changes in apparent sedimentation rate with depth would be expected to occur because of compression. Cordes and McLennan (1984, p. 36) speculated that compression of organic sediment occurred in one lake at depths only slightly greater than 10 cm. Again, therefore, use of deep cores to estimate long-term sedimentation may give misleading information.

These observations provide one reason for the emphasis given in Chapter 3 to short-to-medium term sedimentation measurements. On the other hand, in the context of longterm accumulation of sediment in the delta, these shorter-term rates will need to be adjusted by reference to rates of compression.

3. RECOMMENDED PROCEDURES FOR SEDIMENTATION STUDY

3.1 Choice of timescale

One of the key features of sedimentation in the Mackenzie Delta is variability from year to year. This is well recognized by previous studies in the delta. Pearce (1991), who has worked extensively in the delta on this topic, notes: "One-time, very short-term, studies are almost useless in dynamic ecosystems such as the Mackenzie Delta." The same conclusion is evident in the findings of the NHRI work on lake sedimentation near Inuvik: 1987 sedimentation rates were an order of magnitude less than post-1963 rates as noted in the previous chapter.

This observation, therefore, must determine the main thrust of the sedimentation program. Sampling of sedimentation rates in 1992 (mid-delta) and 1993 (outer-delta) will not be worthwhile unless they can be tied into medium-term sedimentation patterns. Given the cost of determining medium-term patterns (see below), it would seem logical to restrict the sedimentation study to this topic. In the case of non-lake sediments, however, it may be necessary to use short-term rates to assist in computation of longterm rates, for reasons given in Section 3.3.

There are essentially two approaches possible for the determination of medium-term (decades) sedimentation rates:

(a) installing reference stakes (steel bars driven into the permafrost) and returning to measure burial of the stakes after perhaps 5 and 10 years have elapsed;

(b) extraction of cores and dating of surfaces interbedded within the cores. Dating by adventitious roots and burial of litter horizons, techniques employed by Pearce (1986) in some shoreline areas, could be considered examples of the latter. Radioactive isotope (C-14) has been used for deep cores reaching sediments laid down more than 200, generally thousands, of years ago.

Though the first of these approaches is certainly sound, a 5 or 10 year time lag may be difficult to justify to a funding agency anxious to acquire conclusions in the near future. The method could therefore not be recommended as the sole approach to adopt. On the other hand the method is extremely cost-effective, and provides unambiguous data, and is a logical supplement to the coring approach which is discussed more fully below. The advantages of the coring approach are that (a) it provides an immediate database on sedimentation, and (b) it provides sediment samples for laboratory analysis of contaminants. Dating of lake sediments is considered first.

3.2 Lake sedimentation

In the case of lake sedimentation, it is suggested that work be restricted to the collecting of cores for Cs-137 analysis, though the cost of Cs-137 analysis is not small. Marsh (1991, pers. comm.) notes that determination of Cs-137 content at one level in a core was about $40 (based on 1987 dollars). As can be seen from the core profiles obtained in the NHRI study (Fig. 2.17), about eight Cs-137 determinations are required to accurately locate the level of peak Cs content (and hence the assumed 1963 marker level). The laboratory analysis for one core would therefore be about $350.

Attempting to locate the peak Cs-137 stratum may not be, however, the most reliable or the most cost-effective approach to obtaining a time marker in lake sediment cores. Hudson (1991, pers. comm.) advocates using the onset of Cs-137 presence in the sediment (assumed to be 1961) rather than peak Cs-137 as the most appropriate marker layer. He notes that: (1) peak Cs-137 concentration in the sediment may not necessarily be equivalent to the year of peak Cs-137 fallout (1963), depending on the Cs-level of sediment deposited in lakes after 1963; and (2) detection of the onset of Cs-137 presence is likely to involve fewer Cs determinations per core (and shorter count periods), and therefore be less expensive per core.

The points raised by Hudson are important ones, though there is likely to be some debate as to whether onset of Cs-137 or peak levels is the better marker of a given year in all lakes. It is beyond the scope of this review to pursue these points further, but they should be considered carefully by those charged with the conduct of the research. Re-examination of existing Cs-137 profiles, measured on previously extracted cores, would be a useful starting point. The data from the cores of Cordes and McLennan (1984) are given in Appendix B.

The number of cores required would depend on (a) internal variability within a lake; (b) variability between lakes in a local area; and (c) number of local areas to be sampled on a cross-delta transect.

To some extent, the number will also depend on the purpose of the sampling. In the NHRI study, attention was focused on the pattern of sedimentation within lakes and the contrast in rates between lakes of different types. This is not the raison d'etre of the IWD study: the goal is, rather, the accurate determination of mean sedimentation rates within local areas. Thus it might be possible, for example, to have a good estimate of mean lake sedimentation in an area based on one core in each of ten lakes, even though that sampling program would shed little light on patterns of sedimentation within individual lakes.

The exact sampling program within a local area must be left to the research agency responsible for the work. Several points might be noted here though.

- The NHRI studies showed appreciable variation in short-term sedimentation within a lake, due to the fact that most settling occurred near the lake inlet. This pattern may not be representative of the longer term, however, if ice-shove and other processes were to redistribute sediment from the lake inlet area to the main lake basin. In other words, the within-lake variation in medium-term sedimentation rates may well be less than the variance in short-term rates.

- The NHRI study showed marked differences in short-term rates between lakes, but much less difference in the long-term rates. This is not surprising if long-term rates are basically controlled by years of widespread (high) flooding. Again, it suggests that between-lake variance in the context of the present study may not be as severe a constraint on the sampling as suggested by the NHRI short-term data.

The assumption is made here that ten lake cores will provide an acceptable level of accuracy in the determination of mean sedimentation rate in a local area. (The actual level of accuracy will, of course, depend on the standard deviation of the values which will not be known until the data have been collected.) Using the peak-Cs approach, the resultant cost of laboratory work of Cs-137 levels would thus be about $3500 per local area. This means that a program of five local areas along a delta transect would cost about $17,500 in Cs-137 work alone (out of a total NOGAP budget for the project of about $35,000 in both years). Use of Cs-onset as a time marker would presumably lower this cost.

In view of the high cost of Cs-137 analysis per core, the possibility of using other time markers in the cores should also be examined. Unfortunately, although Cordes and McLennan (1984) did note lithologic variations (layering) within cores, they were not able to identify varve, as might be expected given the shallowness of the lakes and the small thickness of deposits in individual floods.

Some cores examined by Cordes and McLennan (1984) did show evidence of rhythmic sedimentation (one with distinct bands of clastic material in a matrix of black organic sediment), but few provided definite evidence for discrete floods (p. 35-36). The stratigraphy of these cores is presented in Appendix C. It might be noted that the core with best development of rhythmitic banding (II.16.2) was in a closed lake, not flooded annually, with peak Cs-137 concentration in the top 1 cm.

3.3 Inter-lake sedimentation

The problems of determining medium-term sedimentation in inter-lake areas are probably even more severe. In part, this is because inter-core variability is likely to be greater than in lakes, thus requiring more cores for the same level of accuracy. In part, it arises from the fact that no single technique appears to have been successfully applied to dating inter-lake cores in all the different types of ecosites. Two possible approaches are discussed below: (a) identification of a Cs-137 time marker; (b) dating of organic debris by C-14.

3.3.1 Use of a Cs-137 marker

The use of a Cs-137 time marker (whether through peak or onset of presence: Section 3.2) for dating sedimentation in land cores would ensure comparability in terms of time period with the lake component.

Determination of Cs-137 levels has certainly been undertaken before in stream sediments (e.g. Hudson and Askin (1987) in the Oldman River basin) and in surface soils (e.g de Jong et al., 1982) in Saskatchewan. Profiles of Cs-137 have also been used in non-lake sedimentation cores to determine the level of the 1963 stratum in the same way as used in lake sediments (Ritchie and McHenry, 1990, p. 218-221).

Actual concentrations of Cs-137 in these other studies appear comparable with those noted by Ferguson (1990) in Inuvik lakes. In the Oldman basin, stream bed sediments ranged 0.67 - 12.7 Bq (Becquerels of radioactivity) per kg of sediment; in Saskatchewan soils, Cs-137 levels averaged about 20 Bq/kg in 1966 soils, decreasing to less than 2 Bq/kg at the present time in badly eroded fields. The peak levels in the Inuvik cores were slightly higher, typically about 30 Bq/kg, possibly reflecting the smaller particle size (and hence larger specific area) of the sediment in lake basins.

It would certainly seem as though Cs-137 profiling of non-lake sediments is possible. Cores will probably have to be longer (given the higher sedimentation rates); and given the likelihood of stratigraphic variations in texture (which may affect Cs-137 adsorption), greater attention would have to be directed to the location of Cs-137 readings within cores. The key issue is likely to be cost, bearing in mind the huge spatial variability in sediment rates documented by Pearce (1986). On the other hand, this variability may not necessitate large numbers of cores. Pearce (1986, p. 259) cites Dahlskog's (1966) work on a Lappland delta showing that, though sedimentation rates varied appreciably (both spatially in a given year, and over time at a given point), the actual sedimentation patterns on sites flooded annually did not vary much from year to year. Pearce (1986) commented that this conclusion was applicable to the Mackenzie Delta.

This has important implications for the experimental design of any longterm sedimentation study. Assuming that the spatial pattern of sedimentation can be established in any one year, then strategic coring for Cs-137 profiles within that pattern could be used to calibrate the mean sedimentation for a single year to an estimate for the post-1963 mean. This seems to be the only route available to tackling this problem if Cs-137 analysis is to be used, given the high point-to-point variability and the high cost of analysis.

The key task then becomes the experimental design for the single-year sediment pattern. The logical route here is surely to extend the approach of the BC Hydro study: subdivide the non-lake landscape by ecosection, ecosite and vegetation assemblage; and sample to determine single-year sediment within each of these units; then extrapolate the information to the full study area on the basis of percentage area occupied by each unit.

The question remains as to the most appropriate approach to actually determine the single-year at-a-point sediment rates. The NOGAP program assumes that fieldwork for the sedimentation component will be completed in the mid-delta area within 1992/93 and in the outer-delta within 1993/94. It is therefore already too late to install stakes to use as a reference datum for sediment accumulation in 1992 in the mid-delta. Two methods appear to have been used before in this situation (Pearce, 1986, p. 64-5): (a) by digging trenches down to the previous year's autumn leaf litter layer; (b) insertion of a narrow probe until an abrupt increase in resistance is encountered. The latter method is unfortunately somewhat subjective (varying with the type of sediment) and needs to be undertaken fairly soon after retreat of floodwater. The former method is probably more accurate, but does require availability of sufficient annual leaf litter. Pearce (1986) used the former method, but did not indicate what percentage of plots yielded a satisfactory datum.

The problems involved in assessing the medium-term mean sedimentation rate in the inter-lake portions of a study area need to be clearly recognized. Assuming that:

- a suitable method of monitoring 1992 (mid-delta) and 1993 (outer delta) sedimentation is found;
- the single years of 1992 and 1993 are representative in terms of spatial pattern;
- a satisfactory landform-vegetation unit map can be produced from aerial photographs or imagery prior to the field season;
- and that calibration of the medium-term sedimentation record by Cs-137 core profiling is successful;

then the investigation may produce acceptable results. However, the first of these issues remains unresolved, and satisfying the second assumption might be largely a matter of luck.

Again, it seems likely that about ten Cs-137 cores per region would be necessary, and up to eight Cs counts per core (depending upon whether the peak or onset of Cs is sought). The cost of the Cs-137 work in interlake areas would thus be up to $3500 per study area, as with the lake coring program.

3.3.2 Use of core stratigraphy and dating by C-14

The standard approach to determination of sedimentation rates is through searches for a datable marker, frequently organic debris that can be dated by C-14 analysis. On the other hand this implies a longer time period, because reliable C-14 dating requires deposits at least several centuries old (Pollach, 1977; Stuiver, 1982).

As an example of this problem, Carson and MacLean (1986) used C-14 dating of three pieces of wood to assess dune movement in the Athabasca dunefields: dates in radiocarbon years before present were typically 200 ± 100, the uncertainties being two standard deviations of the derived DC-14 value (done by GSC, Ottawa). Added to this is the problem of past variation in the production of atmospheric C-14 which produces marked non-linearity in the relationship between actual and radiocarbon years. The estimated calendar age for the three samples in this study were 470 to 70 years ago, 440 to 70 years ago, and in the case of the youngest sample an upper limit of 310 years and an undefinable lower limit.

Such imprecision in the case of the present program would mean that, for a core with a layer dated at about 200 C-14 years, the actual range in sedimentation rates would be 6- to 7-fold. The relative imprecision would decrease in the case of older organic layers.

The method also hinges on success is finding datable organic material. On some levee sites, organic material of minimum datable age might be buried anywhere from 0.3 m to 2 m, or even deeper. Unlike the Cs-137 approach, the same time marker will not be located in each core; thus sedimentation rates will refer to different periods in different cores. This may be a problem during interpretation for various reasons, including those given in Section 2.4.

Notwithstanding the uncertainties involved with this method, it would seem sensible to at least explore its use. A major cost of the project will be field travel. Once at a site, if a core is already being obtained for Cs-137 work, it might be little extra effort to extend the depth of the core sufficiently (perhaps 3 m) to obtain sediment in the hope of obtaining datable organic material at depth. The extra cost of C-14 analysis should also be considered. One reliable C-14 dating of material in a core is likely to be far more expensive than Cs-137 profiling.

The approach above implicitly assumes that the sampling locations chosen for Cs-137 cores are the most appropriate for C-14 dating also. This assumption may not be valid: the fluvial setting of a study area may have changed appreciably over, say, five hundred years. This criticism would probably be true of any sampling design for C-14 cores: knowing where in a study area to sample for C-14 age determination, and knowing how to extrapolate that information over the study area is no small task. Indeed, what is currently inter-lake area may have been a site of lake sedimentation in the recent past. In this respect the method may not be as good as the Cs-137 approach.

3.3.3 Point bar data

Careful attention needs to be directed to what parts of the landscape are appropriate for sampling in the context of the IWD study. As noted previously, much of BC Hydro's work was done on point bars; but data for point bars serve little, if any, purpose in the assessment of overall in-delta sediment accumulation, unless they are supplemented with data on channel bank scour. Net channel deposition equals gross in-channel deposition minus channel scour.

Lapointe (1984, 1986) has mapped bank scour throughout the delta (based on 1950-81 aerial photographs) and, in principle, his data - in each of BC Hydro's study areas -could be compared with point bar data. In practice, Lapointe's data are not really suitable for this purpose, however, because they usually refer to peak erosion rates on channel bends (Lapointe, 1984, p. 16): these would lead to overestimates for channel bank scour and hence underestimates for net channel sedimentation. The aerial photographs used by Lapointe could, of course, be reanalysed for channel bank scour over the full length of channel in each study area. It would seem worthwhile to undertake this task in at least some of BC Hydro's study areas (e.g. areas 3 and 4 on transect C: see Chapter 4) prior to the 1992 field season in order to assess how important net in-channel sedimentation really is. Simple measurement of gross in-channel sedimentation, alone, is of no value in the proposed study. If bank scour is not determined, all sedimentation measurements should be restricted to overbank areas.

3.4 Summary

A possible program for the determination of mean sedimentation rates in a given study area has been outlined based on the following:

1.) determination of % area occupied by lakes and interlake areas, both groups in turn being subdivided into subcategories (different lake types, levels and location; different land-unit types, elevations and location); this information is required prior to the start of the field season; determination of lake levels might require new springtime aerial photography;

2.) a summer program in inter-lake areas involving determination of sediment accumulation in the previous spring, together with extraction of cores for Cs-137 and possible C-14 analysis;

3.) a late winter period of sediment coring in selected lakes to obtain sediment cores for Cs-137 profiles.

The time constraints on the program are huge, and the difficulties are not small: this must be clearly recognized. The program will certainly require careful planning well in advance. Without this, the program will need modification (Section 4.3.3).

The use of markers for determining future sedimentation is certainly a simpler program (and one more likely to succeed) than determination of past sedimentation on the basis of cores. Installation of stakes for this purpose might be combined with the summer coring program. On the other hand it is unlikely to yield meaningful data for about 10 years. The analysis of sedimentation rates based on markers inserted by Pearce in 1980 is likely to provide the most immediate unequivocal data. On the other hand, the study areas used by Pearce (BC Hydro areas) are, on their own, insufficient to provide adequate coverage on the delta (see below).

The issues related to number, size and locations of study areas are dealt with in the next section.

4. SELECTION OF STUDY AREAS

The limited budget for the sedimentation program, together with the high costs of both field and laboratory work, suggest that, as far as possible, the planned program should be coordinated with previous work done in the delta. The obvious approach is to link it with BC Hydro's studies in the 1980s. Notwithstanding the limited scope of the results of these studies, the work actually done in them represents a considerable investment. In addition, though detailed work was restricted to only five local areas, these areas were viewed as part of four cross-delta transects (Fig. 2.7).

4.1 Availability of existing aerial photography

Each of the four transects was flown for colour aerial photography during spring breakup in each of the four years in the 1980-1983 period (the first two years by BC Hydro; the last two by NHRI) at a height of 4500 m with a scale of 1:30,000. The negatives for the first two years are stored at BC Hydro; the photography for the last two is stored at National Air Photo Library in Ottawa. The extent of spring flooding was determined by comparison with additional areal photography taken in August 1980.

The dates of the photography vary slightly according to the transect but are summarized below, together with peak daily discharges for the Mackenzie River at Arctic Red River (IWD, 1989):

1980 May 27 - June 5 Q = 26,400 m3/s (May 29)
1981 June 11 - 12 Q = 28,300 m3/s (May 24)
1982 May 29 - June 6 Q = 28,800 m3/s (June 4)
1983 June 3 - 10 Q = 29,000 m3/s (June 2)

For comparison, peak Q during the year of the 1987 NHRI survey was 21,600 m3/s (June 9). Flooding was far more extensive during the photography of 1982, approximately double that in the other three years (Blachut et al., 1985, p. 5-38), reaching over 90% in four of BC Hydro's study areas. The flood inundated most of Aklavik for the first time since the large flood of 1961. A summary of the flooding in the five study areas is given in Table 4.1. Historical flooding data for Aklavik and Inuvik are provided in Table 4.2.

The term "Total" area of flooding is the total water surface area during breakup; "net" area of flooding is the total area minus the area still occupied by lakes during the autumn 1980 photography. "Net" thus refers to the transient extent of flooding during spring. Local water level on the days of aerial photography are compared with peak water levels in each area and year in the table.

Blachut et al. (1985, p. 5-38) make the following comments regarding the outer delta: "Extent of flooding for area V was only mapped in 1980 as the date of photography in other years missed the peak of flooding, or Mackenzie River floodwater was indistinguishable from in-situ snowmelt. By the time it reaches the outer delta, river flood water appears to have a lower turbidity, and the non-forested, flat-lying, outer delta experiences rapid in-situ snowmelt."

They go on to add: "The problem of accurately timing the aerial photography to catch the maximum extent of flooding was encountered in other areas, particularly in 1981, when poor weather delayed photography until 12 June." These comments suggest that, in order to avoid scheduling problems associated with such failure, the IWD sedimentation field programs in 1992 and 1993 should probably be based on existing imagery, rather than attempting to collect its own.

In summary, existing aerial photography exists which would allow mapping of land-vegetation units prior to the fieldwork for the inter-lake component. This work would simply be a repeat of methods already used in BC Hydro's own study areas. The four-year coverage of spring flooding should also be sufficient to guide selection of lakes for the lake sedimentation component.

4.2 Availability of existing data

The use of one of BC Hydro's transects also has the advantage that considerable data have already been collected in one or two study areas on each transect. This information will certainly require further processing to compute mean inter-lake and lake sedimentation (and standard errors), but access to it would add one or two additional sets of data to the transect without (hopefully) additional fieldwork (except for extra lake cores).

There is, of course, the problem that BC Hydro's sedimentation rates refer to periods that are different from the data to be collected in the IWD study. BC Hydro's lake coring (Cordes and McLennan, 1984) was done between April 23 and May 1, 1982: sedimentation rates thus refer to 1963-1981. IWD's will refer to 1963-1992(93), and will include sediment from the widespread 1982 flood, unlike BC Hydro's data. The relevant dates for BC Hydro's inter-lake sites are unclear. Pearce (1986) appears to present data that are largely 1982-83 averages (but some are longer term, being based on the depth of the first adventitious root above the root stock) which would imply that BC Hydro's inter-lake sedimentation rates are probably not directly comparable with the longer term CS-137 lake rates.

Some method will be required to adjust all data to a common 1963-1992 time frame. The obvious approach is to utilize existing BC Hydro transects where sedimentation has been measured each (or almost each) year. Pearce (1991) writes: "I have permanent transects all over the delta that I put in in 1980. These transects run from within the water (channels or lakes) to the highest elevation of land adjacent to the water. I sampled these transects for 3-4 years (and some again between 1987 and 1990) to analyze .... the amount and texture of sediment deposited annually and over a longer time period ...". It may be possible to use these data to derive a relative (but quantitative) index of sedimentation for individual years, at least for the period 1980-1992, if these shoreline transects (at least those on the selected cross-delta transects) are resurveyed in 1992. It may be possible to then extend this information back to 1963 by deriving a relationship between the sedimentation index and peak annual stage in the delta.

4.3 Choice of appropriate transects

The goals of the IWD sedimentation transects are essentially threefold:

(i) to depict the geographic pattern of sediment transfer through the delta, and of sedimentation within the delta, in both the mid-delta and outer delta areas;

(ii) to provide an estimate of the magnitude of out-of-channel sedimentation on a representative cross-delta transect in the two delta areas, so that these can then be compared with sediment influx to and outflow from those areas;

(iii) to acquire sediment samples to allow determination of "pre-development" contaminant (especially hydrocarbon) levels.

Transect A is at the delta head (Fig. 2.7) and not really appropriate in the context of the stated goals of the IWD work.
Transects B and C can both be considered as candidates for the mid-delta program. Transect D is a logical transect for the outer delta.

4.3.1 Mid-delta transect

Transect B, between Inuvik and Aklavik, would, initially, seem to be the obvious transect to use in the mid-delta from a logistical standpoint. In addition, existing and past suspended sediment sampling stations are located close to the transect on Peel Channel, West Channel, Aklavik Channel, Middle Channel, North Kalinek Channel and East Channel (Fig. 4.1). And yet, from other perspectives, Transect C is a far better choice, for three main reasons.

(i) The major drainage lines in the vicinity of Transect B are not normal to the transect line (Figs. 4.1, 4.2). Aklavik Channel flows essentially parallel to the line between Schooner Channel and Peel Channel. Middle Channel also flows parallel to the line downstream of Raymond Channel and then crosses the transect at a very gentle angle. Bearing in mind that (for any given land unit or lake type) sedimentation rates are likely to decrease away from the main channels, this orientation of sediment pathways in the vicinity of Transect B is not a good one for documenting the cross-delta variability in sedimentation rates. Transect C is far superior in this respect, with almost all flow normal to the transect. The one disadvantage of Transect C is that Middle Channel crosses it at the far right of the transect where it may swamp the sedimentation associated with East Channel.

(ii) Transect C is about half way between the Inuvik-Aklavik suspended sediment sampling line and the head of Shallow Bay (Fig. 4.1). As just noted, one of the stated purposes of the sedimentation transects is to quantify the longterm out-of-channel component of the delta's sediment budget. The goal of the delta suspended sediment program is to determine the flux to the delta at the delta head, the flux at mid-delta and the flux at the outer delta. The difference, for example, between the east-delta flux at the mid-delta (Middle, Kalinek and East channels) and the outer delta suspended sediment flux (Reindeer, Middle and East channels) will be an indication of the net deposition in the region between the mid-delta line and the outer delta stations. (The budget is more complicated than this: there will be losses down unsampled rivers, e.g. Napoiak Channel, as well as gains from bank scour.) The best field verification of that deposition (though a gross not a net figure) will be on a line about midway between the two areas of suspended sediment sampling, not on a transect that is virtually coincident with the mid-delta suspended sediment sampling line. (It is acknowledged that there will be no similar verification of the computed deposition between the delta head and mid-delta suspended sediment transects, but this would, in any case, not be afforded by a sedimentation transect between Aklavik and Inuvik.)

(iii) Transect B has only one BC Hydro study area, Transect C has two such study areas. Thus more additional information is available along Transect C. It is true that NHRI's work on lake sedimentation is available near Transect B, but there has been no corresponding work on inter-lake sedimentation in the area.

Transect C corresponds roughly with a levee height (relative to low water datum) of about 4.5 m. It extends slightly more than 60 km across the delta from Peel Channel to East Channel. Study area 3 is centred on East Channel. Study area 4 is at the confluence of Jamieson and Bear channels on the other side of the delta, though still about 20 km from West Channel. Additional study areas are recommended as follows:

on both sides of Middle Channel;
one centred on Crooked Channel;
one centred on Napoiak Channel;
one centred on West Channel.

Using the cost estimates given in Section 3, the Cs-137 work for these five sites would total $35,000. Fieldwork costs are extra. Assuming that labour costs are minimal (based on personnel with existing salaries), the project is still only feasible if additional funding is obtained from other sources. Without this funding, it is suggested that, rather than decreasing intensity of work within study areas, one or more study areas be deleted (or postponed). One Middle Channel site, and the Napoiak and West Channel sites are seen as being essential to the program.

4.3.2 Outer-delta transect

Transect D extends 100 km, on a line SW-NE (rather than W-E) from just southwest of West Channel near Shallow Bay to the delta front near Kendall Island (Figs. 4.1, 4.3). Though the orientation of the line differs appreciably from the mid-delta transect, it is reasonably consistent with the fluvial landscape. The main channels flow more or less at right angles to the transect. The 1 m levee line on Mackay's (1963) map shows a similar orientation and is roughly coincident with the transect on the north side of Shallow Bay.

The area northeast of Shallow Bay is shown in more detail in Fig. 4.3. Middle Channel flows directly towards the transect in the vicinity of IWD's suspended sediment station 10MC901, then turns northeast to flow parallel to the transect (about 20 km away from it) towards Richards Island. It then turns to the northwest again (where Harry Channel leaves it) to cross the transect more or less at right angles. Several distributaries leave Middle Channel in the reach between the suspended sediment station and Harry Channel, and also flow across the transect roughly normal to it. Study area 5 is located on a large unnamed island bounded by two such channels (Fig. 4.4).

The transect crosses Middle Channel and continues northeast across Niglintgak Island (Fig. 4.3). Kumak Channel, the likely site of pipeline crossings from gas fields on Niglintgak Island towards Richards Island, leaves Middle Channel upstream of the transect and crosses it about 7 km east of Middle Channel. A study area in this part of the transect would therefore be useful in the context of nearby hydrocarbon development. Slaney (1974) has examined the relationship between vegetation and topography in the Niglintgak and Taglu areas, and the connecting corridor, and these data may be useful in the sedimentation work proposed by IWD for 1993/94. A shallow coring program has also been undertaken by Terrain Sciences Division of Geological Survey of Canada (Dallimore, 1991, pers. comm.): the possibility of obtaining C-14 dates on any organic material in these cores should be examined.

A second new study area on the northeast side of Shallow Bay at the mouth of Reindeer Channel (Fig. 4.1), and a third one on the other side of Shallow Bay where West Channel crosses the transect would seem to be necessary to afford a reasonably comprehensive coverage of the transect, but to a large extent this would depend on the exact purpose of the outer-delta sedimentation transect.

The goals of the outer delta sedimentation study need to be defined more clearly. Sedimentation in the outer delta is supposed to be seen in the context of the two outer-delta suspended sediment stations on the southwest side of Richards Island: Middle Channel near Langley Island, and Reindeer Channel below Lewis Channel (above Marcus Ch.). It seems inappropriate, then, to include a sedimentation site in the West Channel area of Transect D. The nearest suspended sediment station upstream is on Peel Channel (above Aklavik: Fig. 4.1). Transect D can hardly be considered representative of sedimentation downstream of this station; on the contrary, Transect C is being used for this purpose (Fig. 4.1). In addition, sedimentation around the margins of, and within, Shallow Bay will be affected not only by riverine sediment inputs, but also by the rapid shoreline erosion along the southwest side of the bay. It is therefore suggested that sedimentation measurements on Transect D be restricted to that part of the line northeast of Shallow Bay.

Such a focus for the outer delta sedimentation study would permit estimation of how much of the suspended sediment flux is deposited on the outer delta (assuming that the transect is representative of the entire landward delta downstream of the two suspended sediment stations), and thereby provide a better estimate of the flux to the Beaufort Sea. In addition, it would focus core-sampling in those parts of the delta that are most likely to be affected by hydrocarbon development.

Three new study areas would involve, using the same estimates as before, about $21,000 in Cs-137 analysis. In fact, lakes occupy a much smaller percentage of the landscape in the outer delta (Fig. 2.1), so that the lake component could probably be reduced. The actual number and location of study areas on the outer-delta transect should probably be deferred until autumn-winter 1992, however, and assessed in the light of experience and results from the mid-delta transect. Pearce (1991, pers. comm.) indicates that she has added about 20 new sites (additional to study area 5) across the entire outer delta. It may be useful to incorporate some or all of these sites in the outer delta program.

4.3.3 Sequence of work

The main recommendation of this report is that the IWD sedimentation project be built upon the framework previously established by BC Hydro. Three of the five BC Hydro study areas are located on the two transects recommended for the IWD work. The data collected in those three areas can thus be used to supplement the data collected by IWD.

The other advantage of building upon the BC Hydro work is that a definite methodology has been established, at least for inter-lake sedimentation, based on its ecological land classification. The report recommends following the same approach in IWD's study areas.

It should be recognized, however, that BC Hydro has apparently not taken its own work to the stage required by IWD, namely the mapping of sedimentation throughout the full study area and the determination of a mean sedimentation rate. Ideally, therefore, the first stage of IWD's work would be to extend BC Hydro's analysis in the three BC Hydro study areas. This would provide an appropriate level of experience for planning IWD's work in its own field areas.

This recommendation raises serious problems in the scheduling of IWD's fieldwork. It is improbable that this preliminary data analysis and GIS work would be complete before the summer of 1992, currently scheduled for the mid-delta transect.

The schedule proposed by IWD is dictated by the three-year NOGAP program which ends with fiscal 1993/94. Three possible avenues are suggested for circumventing the restrictions of this timeframe:

- Seek an extension (six to nine months) beyond the end of fiscal 1993. This would allow (a) completion of analysis of BC Hydro data and detailed formulation of work schedule for IWD field program during 1992; (b) undertaking fieldwork for the mid-delta transect in the spring (lake coring) and summer (land sediments) of 1993; (c) undertaking fieldwork for the outer delta in 1994.

- Abandon IWD's field program in the mid-delta transect and concentrate on the outer delta program. The 1992 program could follow that outlined in (a) above, and the 1993 program would follow (c) above. Though this would not meet the full program goals of the IWD proposal, it would provide a much more manageable schedule, and provide the basis for adding to BC Hydro's study areas in the mid-delta at some future date.

- Use summer of 1992 as a period for review of BC Hydro data and development of appropriate methodology for determination of mean sedimentation rate in an area, assessment of sampling and analytical procedures, and preparation of experimental design. Limited field program might include installation of stakes for 1993 spring flood sedimentation and some preliminary cores, especially to assess usefulness of Cs-137 in levee areas where coarser grain size might affect profiles. Even limited field program will need careful planning. Use summer of 1993 for field work in both mid-delta and outer-delta transects.

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LIST OF TABLES

		74	75	76	77	87	88	89	90	91
Outer delta stations										
10MC902	Reindeer Ch					1	9			13
10MC901	Middle Ch					1	9			13
10LC901	East Channel					1	9			13
Mid-delta stations										
10MC3	Peel Channel	9	6							14
10MC4	West Channel	7	5							
10MC5	Aklavik Ch	9	6							
10MC6	Middle Channel	8	8							
10MC8	Middle Channel									14
10LC6	N. Kalinek Ch	8	5							
10LC2	East Channel	15	5	*	*					16

* denotes data available but not seen

only initial 1991 sampling examined in this report

TABLE 1.1

NUMBER OF DAYS SAMPLED AT DELTA SEDIMENT STATIONS
1974 - 1991

Sediment Sampling Program Summary[1]

Location	Timing of Full Measurements				SV's[2]
	J	J	A	S	(per wk)
Delta Inputs					
- Mackenzie River above Arctic Red	X X	X	X	X	1-2
- Peel River at Fort McPherson	X X	X	X	X	1-2
Mid Delta					
- East Channel at Inuvik	X	X	X	X	1
- Middle Channel below Raymond Chl (7000[3])	X	X	X	X	1
- Peel Channel above Aklavik (1040)	X	X	X	X	1
Outer Delta					
- Middle Channel at Tununuk Point (5670?)	X	X	X	X	1
- East Channel below Tununuk Point (3970)	X	X	X	X	1
- Reindeer Channel below Middle Chl (5410)	X	X	X	X	1

Notes:

1. X = full sediment measurement at a site, consisting of a suspended - top/bottom sample from each of 5 verticals (to be preceeded by a flow measurement), and a bed material sample from each of the 5 verticals in spring, mid-summer, and fall. Other measurements do not include bed material samples and particle size analyses.

2. SV = single vertical samples to be taken 1 to 3 times weekly (preference for vertical 2,3, or 4 of full measurement site in small channels, vertical 1 or 5 on larger channels, talweg side of channel; more frequent sampling for periods of high flows)

3. (7000) = 1-D model site location node (see Figure 1)

TABLE 1.2

PRELIMINARY SEDIMENT SAMPLING PROGRAM
1990s NOGAP MACKENZIE DELTA STUDY

	June	July	August	Sept.
West		1.4	3.2	0.3
		1	4	2
Aklavik	1.0	1.0	1.6	0.1
	1	2	4	2
Peel	2.0	1.0	1.5	0.1
	1	2	4	2
Middle		43.7	64.0	6.2
		2	3	2
N. Kalinek		1.4	1.4	0.0
		1	3	2
East	0.5	0.4	0.8	0.0
	2	5	6	2

First row denotes monthly load in Mt
Second row denotes number of sample days

TABLE 2.1

MID-DELTA SUSPENDED SEDIMENT LOADS, 1974
(from Davies, 1975)

	June	July	August	Sept.
West		209	238-831	34-81
Aklavik	182	138-395	234-1310	48-120
Peel	222	71-536	107-749	33-99
Middle		249-636	387-1350	81-192
N. Kalinek		99-1110	171-741	33-51
East	244-404	112-1940	222-1130	44-64

TABLE 2.2

SEDIMENT CONCENTRATIONS (MG/L) AT MID-DELTA SITES IN 1974
(from Davies, 1975)

Peel Channel 10MC3

Year	Month	Day	Type	m3/s	mg/L
74	6	12	M	1883	222
74	7	12	S	668	536
74	7	18	M	833	71
74	8	1	M	1116	349
74	8	8	S	1000	107
74	8	15	S	1289	749
74	8	29	S	1065	193
74	9	9	S	765	99
74	9	18	S	549	33
75	6	17	S	1500	597
75	6	23	S	1210	317
75	7	17	M	864	153
75	8	13	M	733	71
75	8	20	M	742	82
75	9	11	M	575	39
91	6	12	M		126

M denotes multiple vertical; S single vertical

All 1974 data are daily mean values.
1975 sediment concentrations are instantaneous values;
1975 discharge data are daily means.

Sediment rating: log (mg/L) versus log (m3/s):

Constant	-3.46848
Std Err of Y Est	0.320781
R Squared	0.472315
No. of Observations	15
Degrees of Freedom	13

X Coefficient(s)	1.909695
Std Err of Coef.	0.559838

TABLE 2.3

West Channel below Aklavik 10MC4

Year	Month	Day	Type	m3/s	mg/L
74	7	12	*	1750	209
74	8	1	M	1841	691
74	8	8	*	1592	238
74	8	15	S	2183	831
74	8	25	*	2373	490
74	9	9	*	1303	81
74	9	18	*	937	34
75	6	17	S	2830	460
75	6	23	M	2180	235
75	8	12	M	1220	82
75	8	20	M	1230	197
75	9	11	M	932	38

S denotes single vertical; M is multiple;
* indicates verticals not known.

All 1974 data are daily mean values.
1975 sediment concentrations are instantaneous;
1975 discharges are daily mean values.

```
                 Regression Output:
Constant                              -5.97758
Std Err of Y Est                      0.233057
R Squared                             0.771669
No. of Observations                         12
Degrees of Freedom                          10

X Coefficient(s)   2.578585
Std Err of Coef.   0.443555
```

TABLE 2.4

Aklavik Channel 10MC5

Year	Month	Day	Type	m3/s	mg/L
74	6	12	*	875	182
74	7	12	S	711	395
74	7	18	*	612	136
74	8	2	M	725	1310
74	8	8	*	640	416
74	8	15	S	867	887
74	8	29	S	736	234
74	9	9	*	513	120
74	9	18	*	371	48
75	6	17	S	1040	378
75	6	23	S	827	263
75	7	17	M	685	474
75	8	12	M	586	115
75	8	20	M	589	304
75	9	11	M	428	36

M denotes multiple vertical; S single vertical;
* = unknown

All 1974 values are daily means.
1975 sediment concentrations instantaneous;
1975 discharges are daily means.

Sediment rating: log (mg/L) versus log (m3/s):

```
          Regression Output:
Constant                          -4.92594
Std Err of Y Est                  0.304704
R Squared                         0.525236
No. of Observations                     15
Degrees of Freedom                      13

X Coefficient(s)  2.589620
Std Err of Coef.  0.682849
```

TABLE 2.5

Middle Channel 10MC6 and 10MC8

Year	Month	Day	Type	m3/s	mg/L
74	7	11	*	18000	638
74	7	19	*	15800	249
74	7	31	M	19000	2320
74	8	8	*	16800	1100
74	8	14	S	21700	1390
74	8	29	S	16700	387
74	9	9	*	15700	192
74	9	19	*	12600	81
75	6	13	*	24800	904
75	6	17	*	21800	741
75	6	23	S	16500	365
75	7	18	M	13900	492
75	8	12	M	13200	164
75	8	20	S	12700	617
75	9	5	M	11000	204
75	9	11	M	10000	91
91	6	12	M		214

All 1974 values are daily means.
1975 sediment concentrations instantaneous;
1975 discharges are daily means.

Sediment rating: log (mg/L) versus log (m3/s):

```
Constant                        -9.37695
Std Err of Y Est                0.286749
R Squared                       0.560957
No. of Observations                   16
Degrees of Freedom                    14

X Coefficient(s)   2.857053
Std Err of Coef.   0.675526
```

TABLE 2.6

East Channel at Inuvik 10LC2

Year	Month	Day	Type	m3/s	mg/L
74	6	10	*	674	244
74	6	25	*	369	404
74	7	19	*	297	112
74	7	26	*	343	209
74	7	27	*	374	540
74	7	30	M	425	1500
74	7	31	*	416	1940
74	8	9	*	362	633
74	8	12	S	447	1350
74	8	14	S	467	1130
74	8	16	S	453	892
74	8	22	S	504	791
74	8	29	S	340	222
74	9	10	*	218	64
74	9	16	*	168	44
75	6	12	M	660	425
75	6	17	S	510	269
75	6	24	S	379	134
75	7	7	S	413	246
75	7	9	S	436	227
75	7	17	S	314	466
75	7	28	*	276	173
75	7	30	*	276	161
75	8	5	*	223	82
75	8	7	*	201	100
75	8	11	*	155	76
75	8	13	*	212	76
75	8	14	*	238	73
75	8	19	*	256	261
75	8	21	*	230	232
75	8	22	*	219	254
75	8	25	*	187	134
75	8	28	*	181	97
75	8	29	*	181	76
75	9	3	*	183	43
75	9	5	*	177	33
75	9	9	*	164	36
75	9	10	*	154	53
75	9	24	*	123	37
75	10	7	*	88	21
77	7	6	*	374	153
77	7	25	*	227	50
77	8	5	*	254	282
77	8	18	*	169	50
77	8	31	*	186	40
91	5	27	S		266
91	6	6	M		157

TABLE 2.8 (continued over)

All 1974-75 values are daily means.
1975 values from Sediment Survey printout.
1977 concentration values are instantaneous.
1977 discharge values are daily means.
All 1977 data from IWD (1988).

Sediment rating: log (mg/L) versus log (m3/s)

```
         Regression Output:
Constant                          -2.73784
Std Err of Y Est                  0.293298
R Squared                         0.660000
No. of Observations                     45
Degrees of Freedom                      43

X Coefficient(s)  2.037271
Std Err of Coef.  0.222988
```

TABLE 2.8 (continued from previous page)

SUMMARY OF SEDIMENT DATA FOR EAST
CHANNEL AT INUVIK 10LC2

	SEE	r2	n	b	SE(b)
Peel	0.32	0.47	15	1.91	0.56
West	0.23	0.77	12	2.58	0.44
Aklavik	0.30	0.52	15	2.59	0.68
Middle	0.29	0.56	16	2.86	0.68
N Kalinek	0.32	0.61	13	2.01	0.50
East	0.29	0.66	45	2.04	0.22
Mackenzie at A. Red	0.23	0.66	361	2.21	0.08

SEE	standard error of estimate
r2	percentage prediction
n	sample size
b	regression coefficient (slope)
SE(b	standard error of (b)

TABLE 2.9

SEDIMENT RATING STATISTICS FOR MID-DELTA SITES

Extreme positive residuals

1974	July	11	Kalinek
		12	Peel
		30	East
		31	East, Middle, Kalinek
	Aug.	1	West
		2	Aklavik
		8	Middle
		12	East
		14	East
		15	West
1975	Aug.	20	Middle

Extreme negative residuals

1974	June	10	East
		12	Aklavik, Peel
	July	17	Kalinek*
1975	June	12	East, Kalinek
		17	Aklavik

TABLE 2.10

DATES OF EXTREME RESIDUALS IN SEDIMENT CONCENTRATIONS,
MID-DELTA STATIONS, 1974-1975

Reindeer Channel below Lewis Channel 10MC902

Year	Month	Day	Type	m3/s	mg/L
87	8	25	M		*378
88	6	14	D		769
88	6	27	S		416
88	7	26	S		860
88	7	29	S		1223
88	7	30	S		1022
88	7	31	S		690
88	8	1	S		651
88	8	5	S		678
88	9	16	S		410
91	6	20	M		*358

D denotes dip sample
M denotes multiple vertical sampling
S denotes single vertical sample

* simple (unweighted) mean concentration

All concentrations are instantaneous

TABLE 3.1

Middle Channel (Langley Is.) 10MC901

Year	Month	Day	Type	m3/s	mg/L
87	8	25	M		313
88	6	14	D		716
88	6	27	S		422
88	7	26	S		989
88	7	29	S		957
88	7	30	S		840
88	7	31	S		813
88	8	1	S		515
88	8	5	S		484
88	8	13	S		273
91	6	20	M		*171

M denotes multiple vertical sampling
S denotes single vertical sampling
D denotes dip sample

* simple (unweighted) mean concentration

All concentrations are instantaneous

TABLE 3.2

East Channel below Tununuk Point 10LC901

Year	Month	Day	Type	m3/s	mg/L
87	9	1	M		*82
88	6	14	D		617
88	6	27	S		715
88	7	26	S		700
88	7	29	S		625
88	7	30	S		686
88	7	31	S		717
88	8	1	S		687
88	8	5	S		718
88	9	13	S		566
91	6	13	M		*144

D denotes dip sample
M denotes multiple vertical sampling
S denotes single vertical sample

* simple (unweighted) mean concentration

All concentrations are instantaneous

TABLE 3.3

LIST OF FIGURES

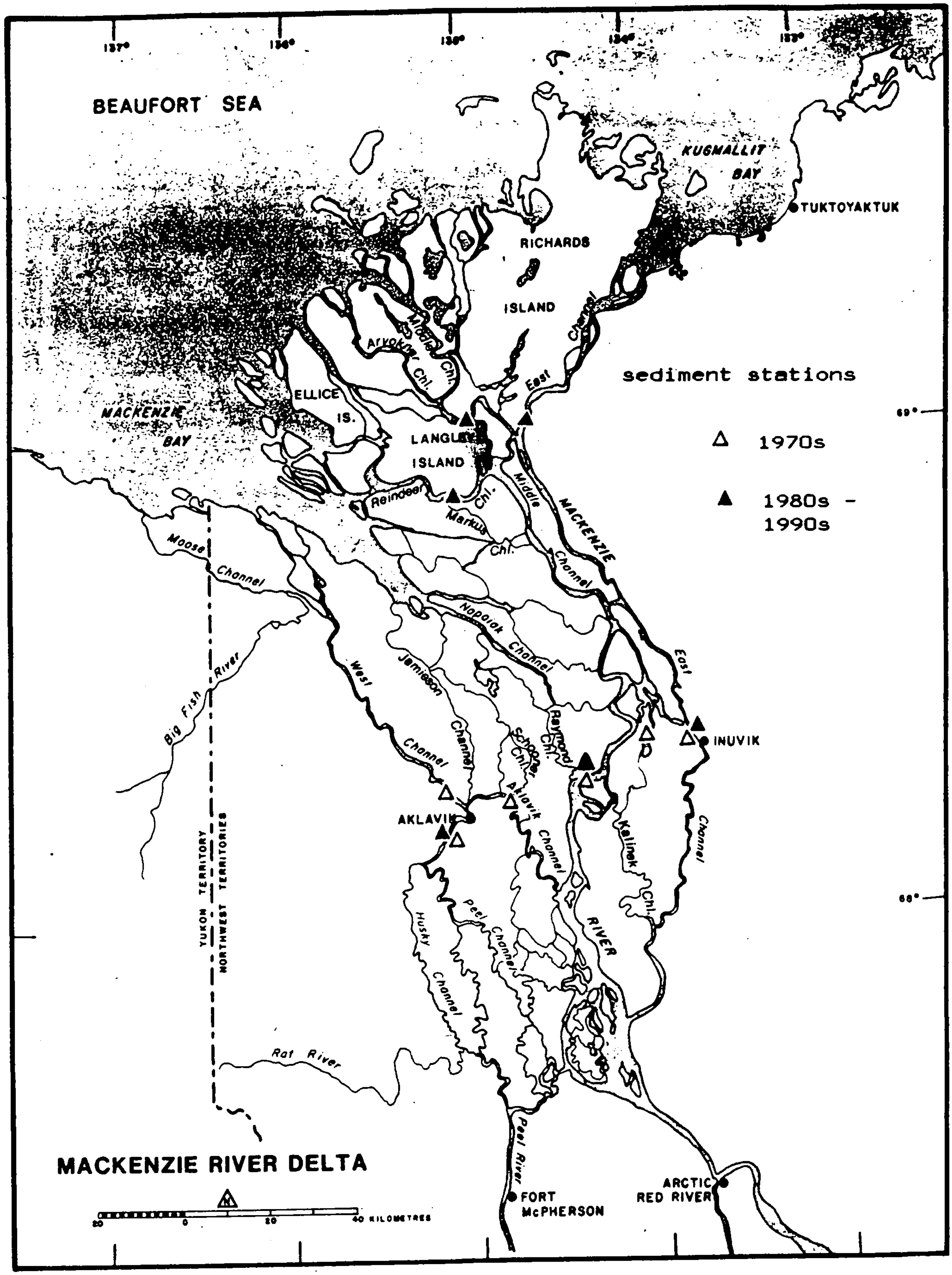


FIGURE 1.1

SUSPENDED SEDIMENT SAMPLING STATIONS, MACKENZIE DELTA, NWT

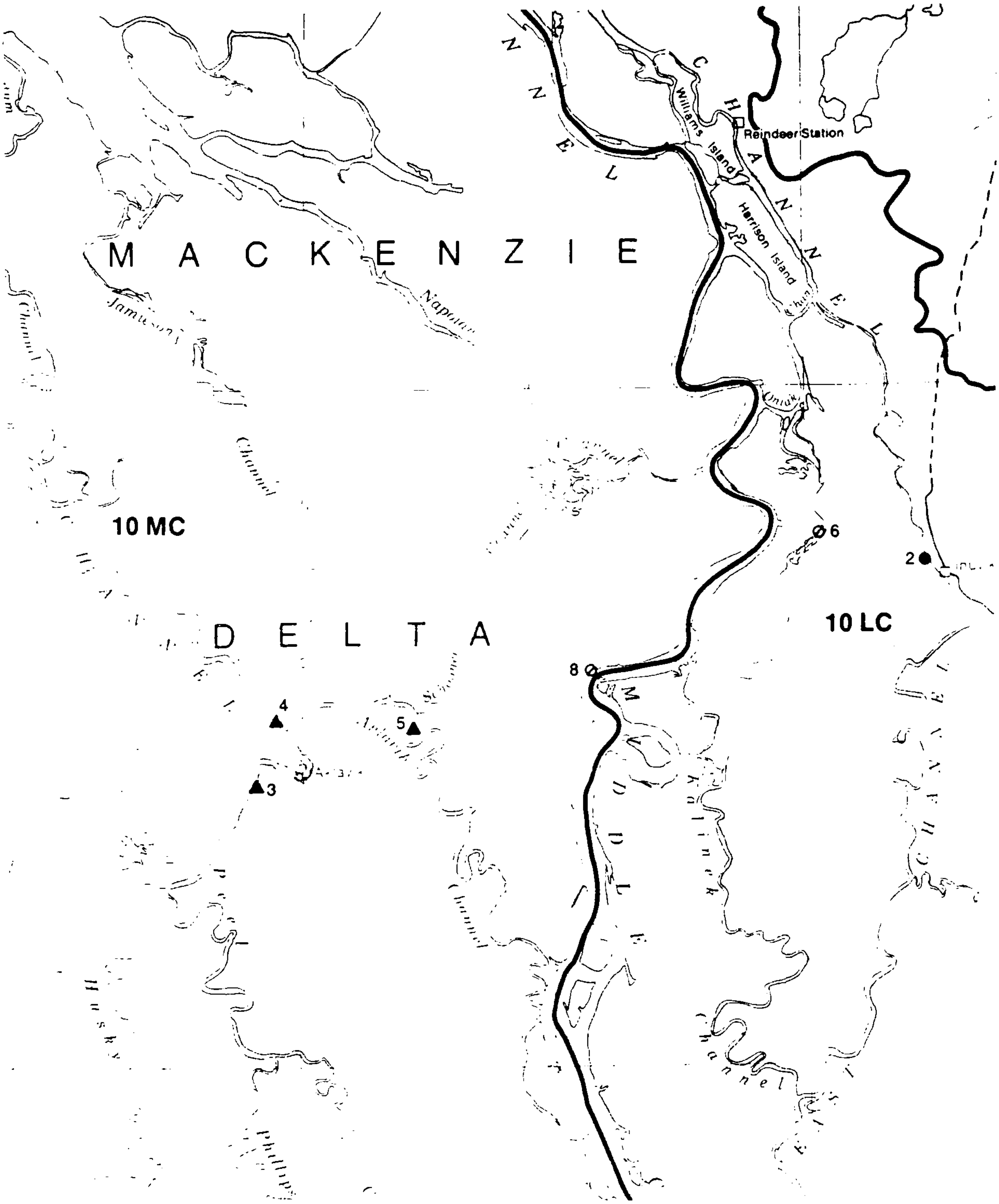


FIGURE 2.1

MID-DELTA SAMPLING TRANSECT, 1974-75

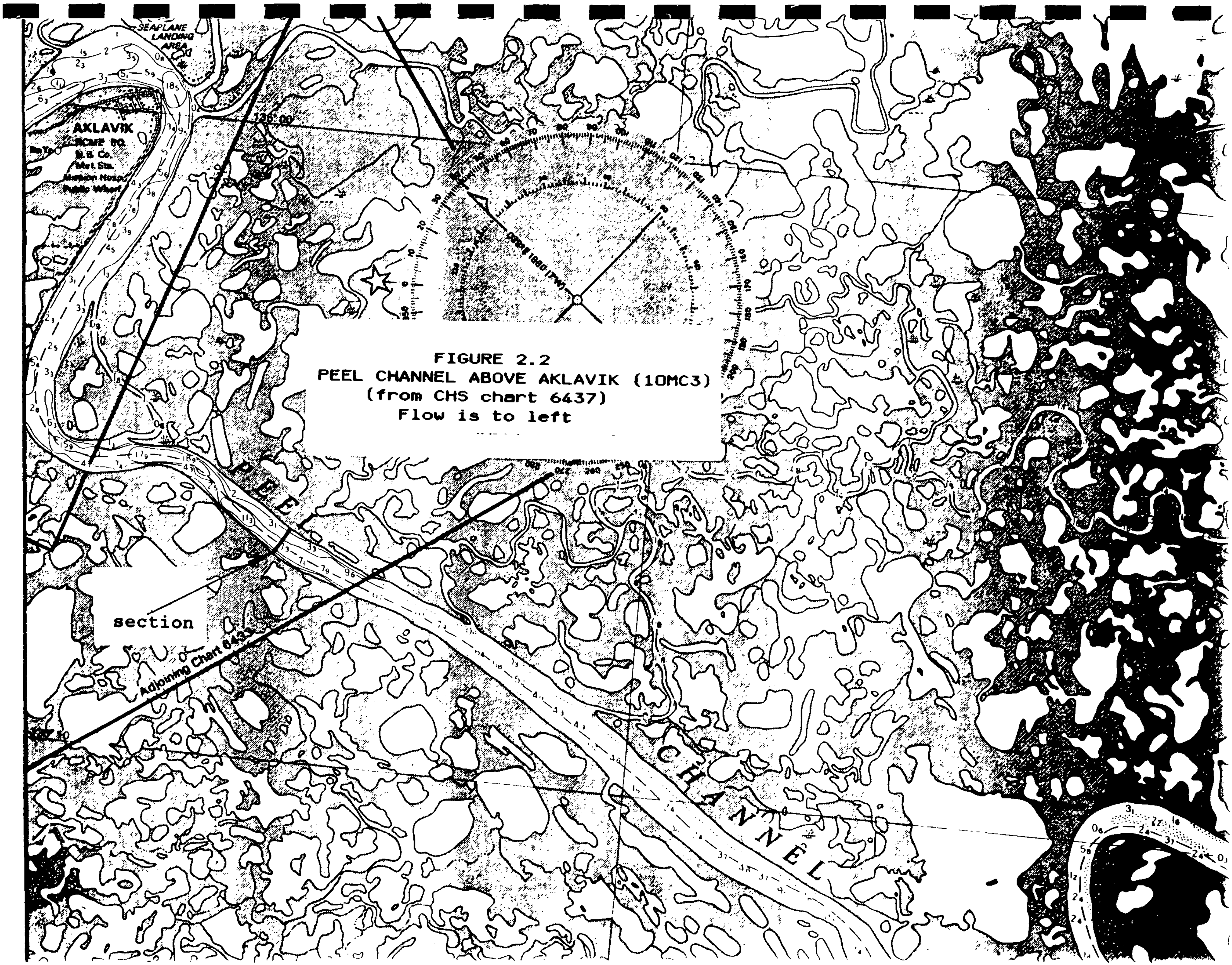
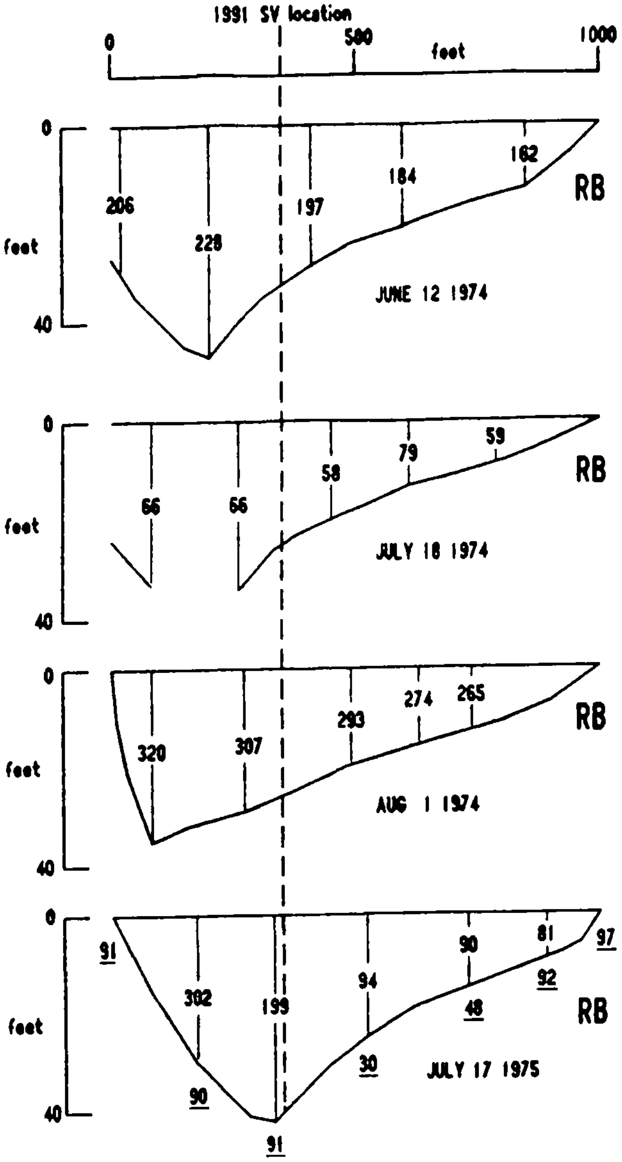


FIGURE 2.2
PEEL CHANNEL ABOVE AKLAVIK (10MC3)
(from CHS chart 6437)
Flow is to left



concentrations in mg/L;
underlined values are % silt-clay of bed material;
location of 1974 right bank position is assumed.

FIGURE 2.3

PEEL CHANNEL ABOVE AKLAVIK CHANNEL:
1974-75 MV SAMPLINGS

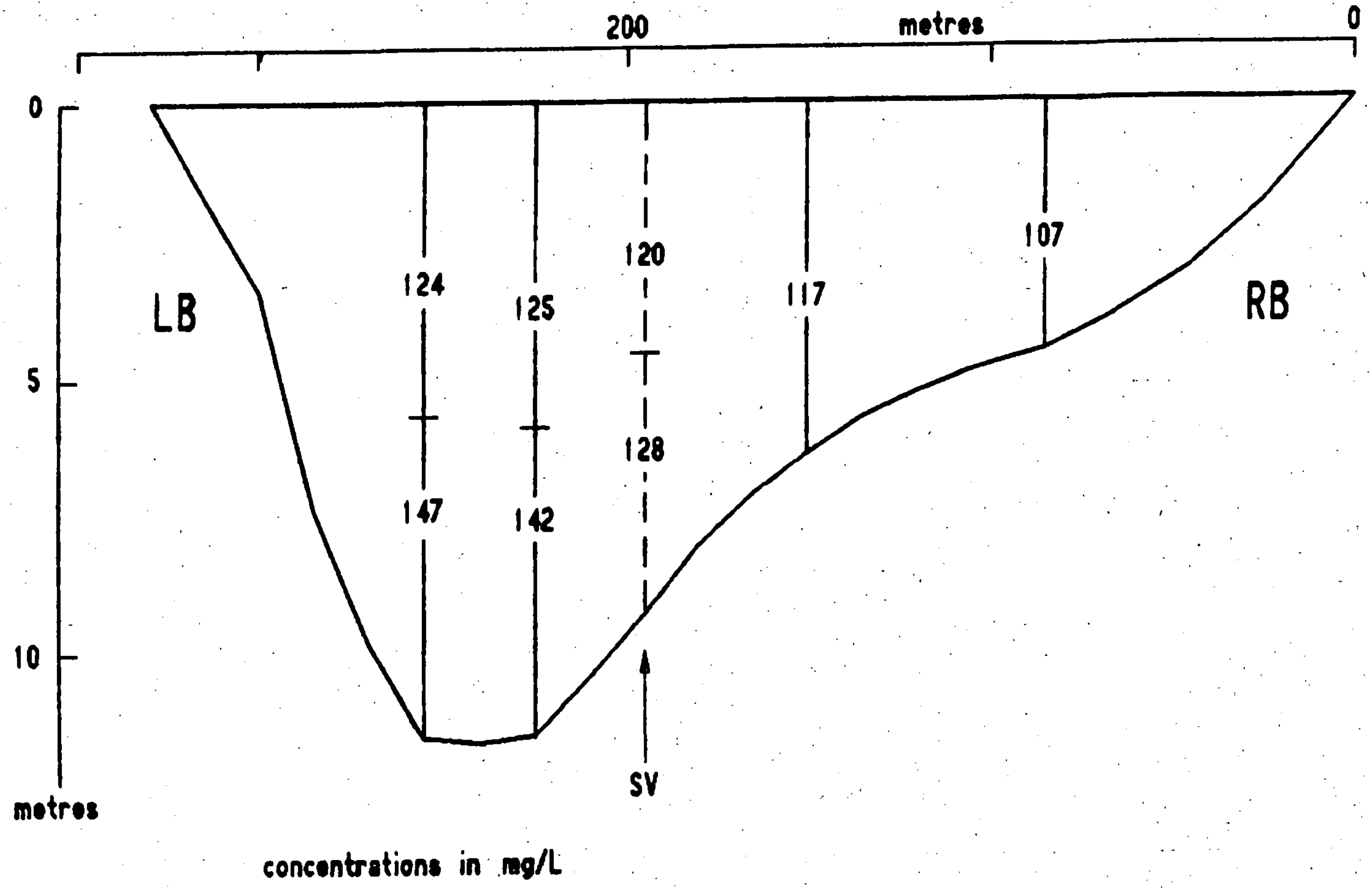


FIGURE 2.4

PEEL CHANNEL ABOVE AKLAVIK CHANNEL:
1991 JUNE 12 MV SAMPLING

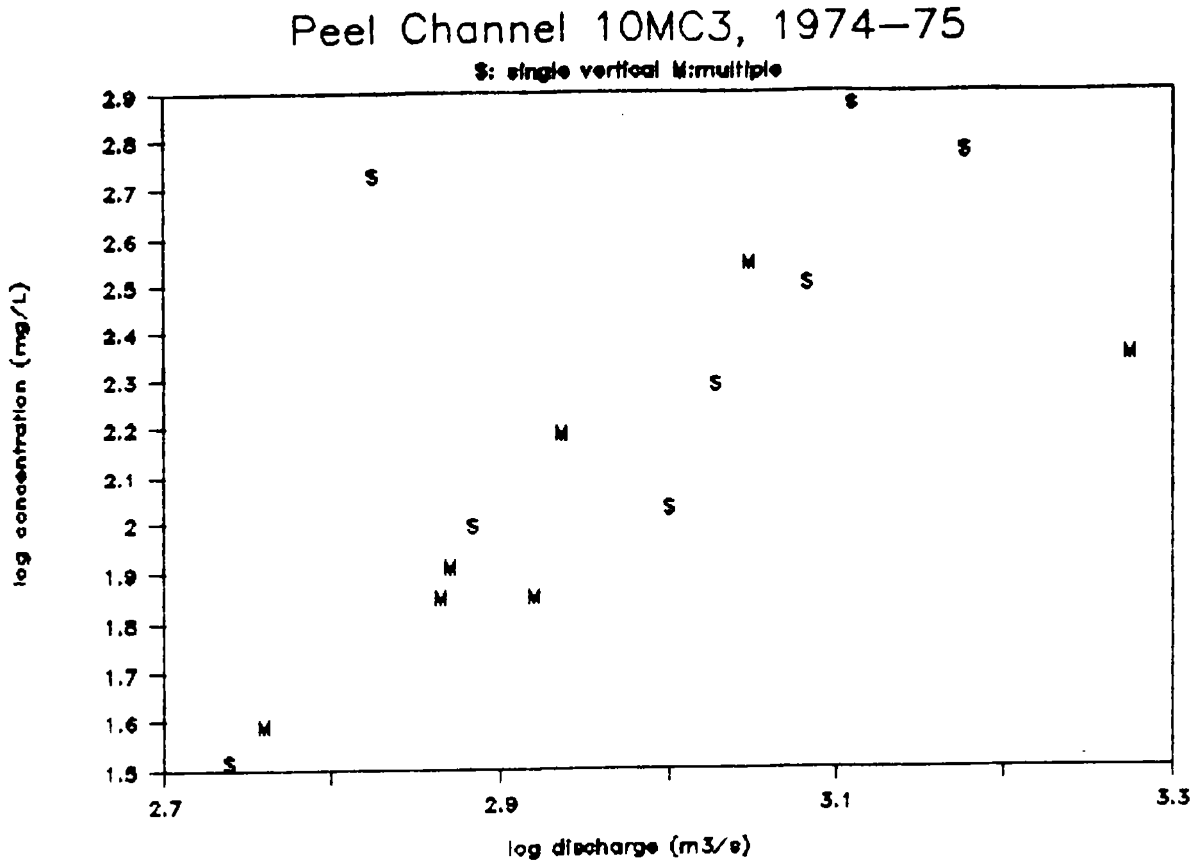
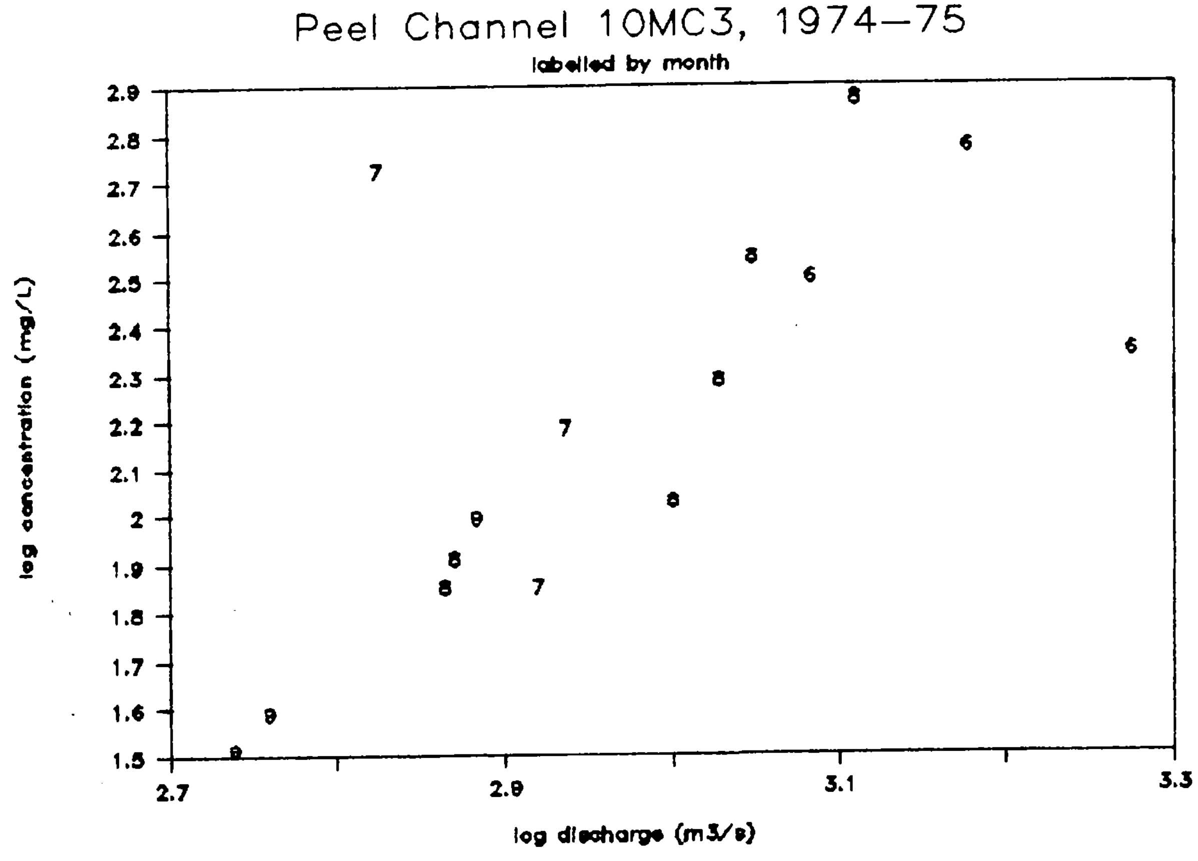

Peel Channel 10MC3, 1974–75
S: single vertical M:multiple
log concentration (mg/L)
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
2.7
2.9
3.1
3.3
log discharge (m3/s)

FIGURE 2.5


Peel Channel 10MC3, 1974–75
labelled by month
log concentration (mg/L)
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
2.7
2.9
3.1
3.3
log discharge (m3/s)

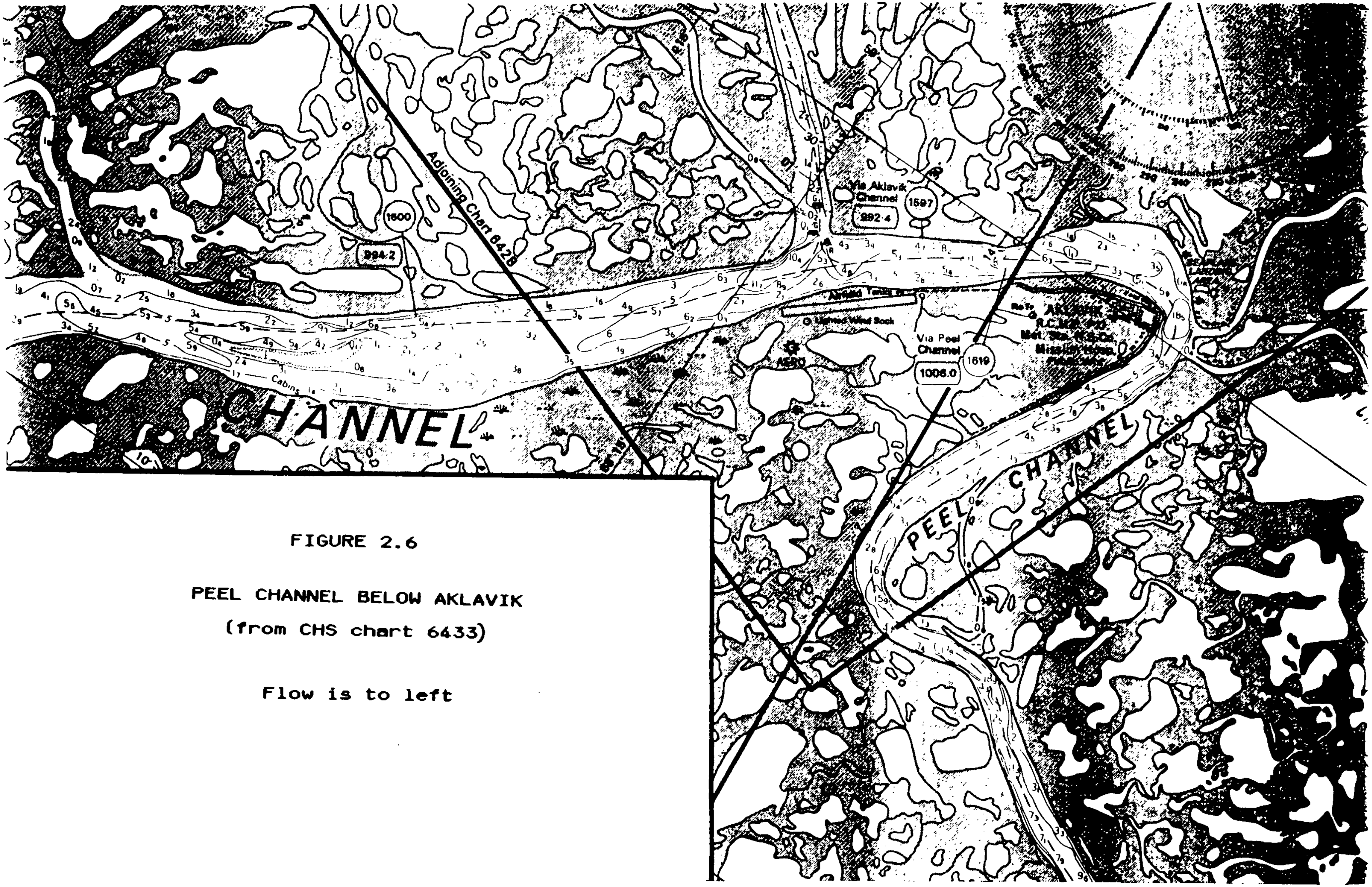


FIGURE 2.6

PEEL CHANNEL BELOW AKLAVIK

(from CHS chart 6433)

Flow is to left

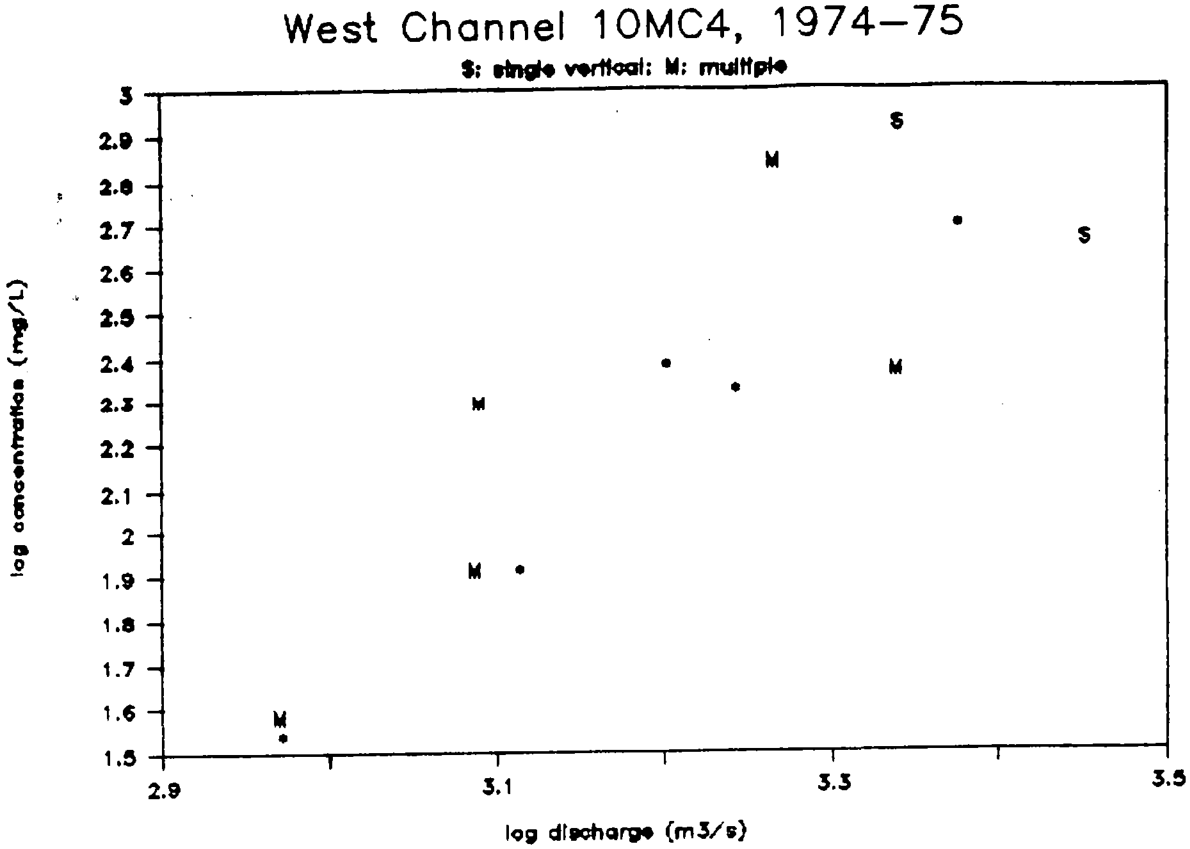
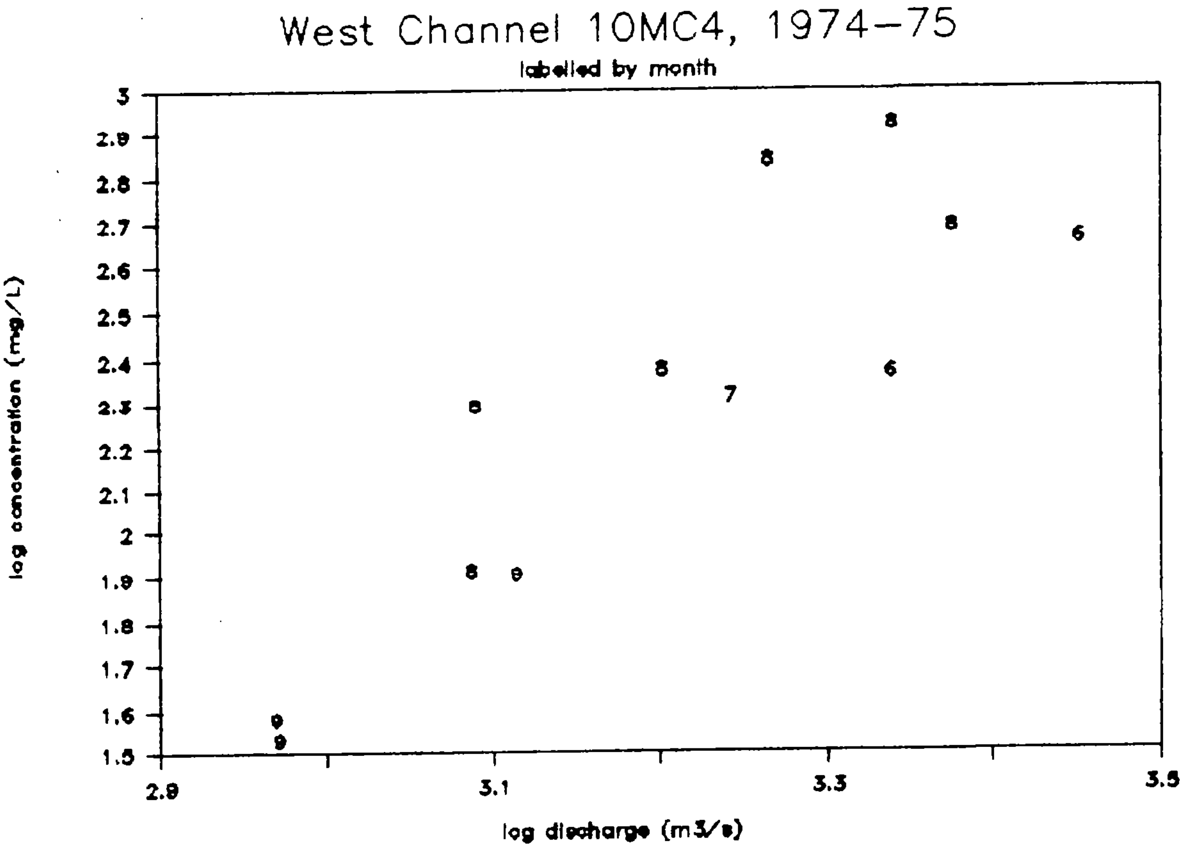

West Channel 10MC4, 1974–75
S: single vertical; M: multiple
log concentration (mg/L)
log discharge (m3/s)
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
2.9
3.1
3.3
3.5
S
M
S
M
M
M
M

FIGURE 2.7


West Channel 10MC4, 1974–75
labelled by month
log concentration (mg/L)
log discharge (m3/s)
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
2.9
3.1
3.3
3.5
8
8
8
6
8
7
6
8
8
9
9
9

flow is towards

bottom of page

FIGURE 2.8

AKLAVIK CHANNEL UPSTREAM OF SCHOONER CHANNEL

(from CHS chart 6428)

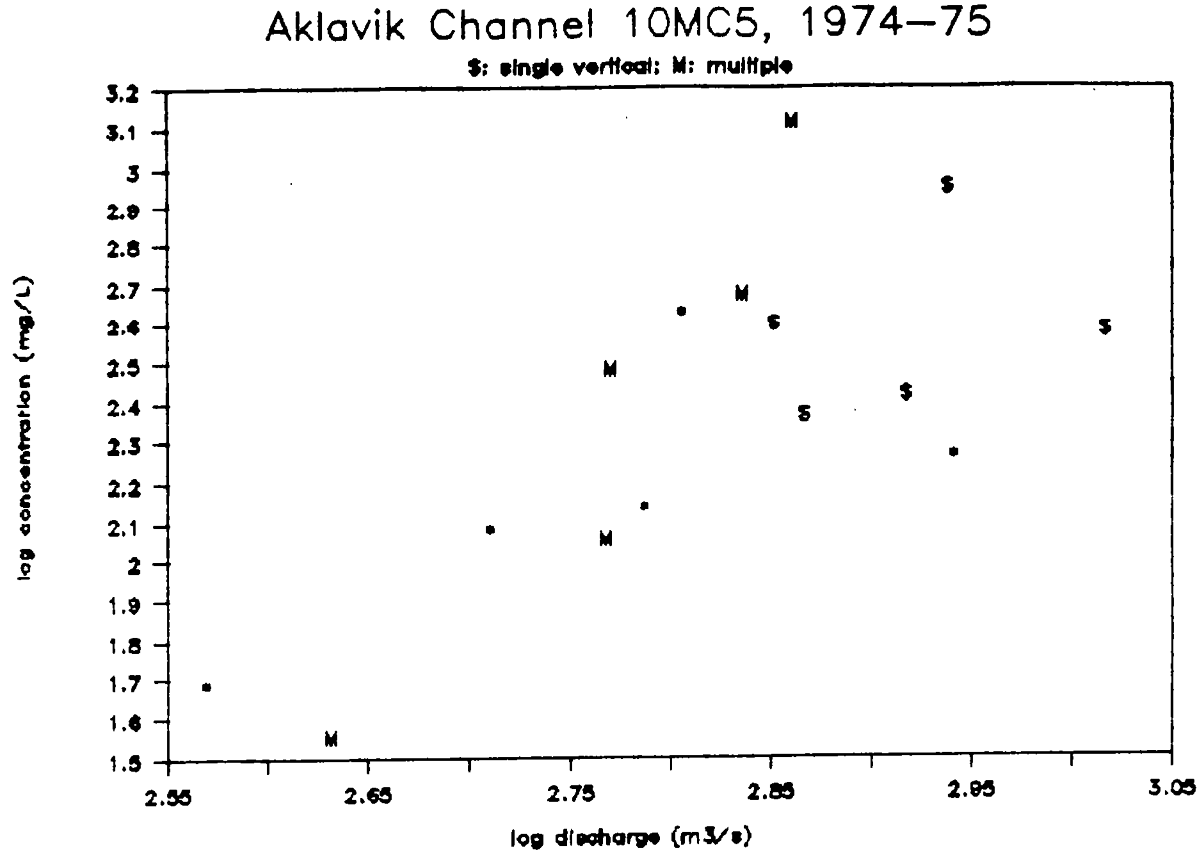
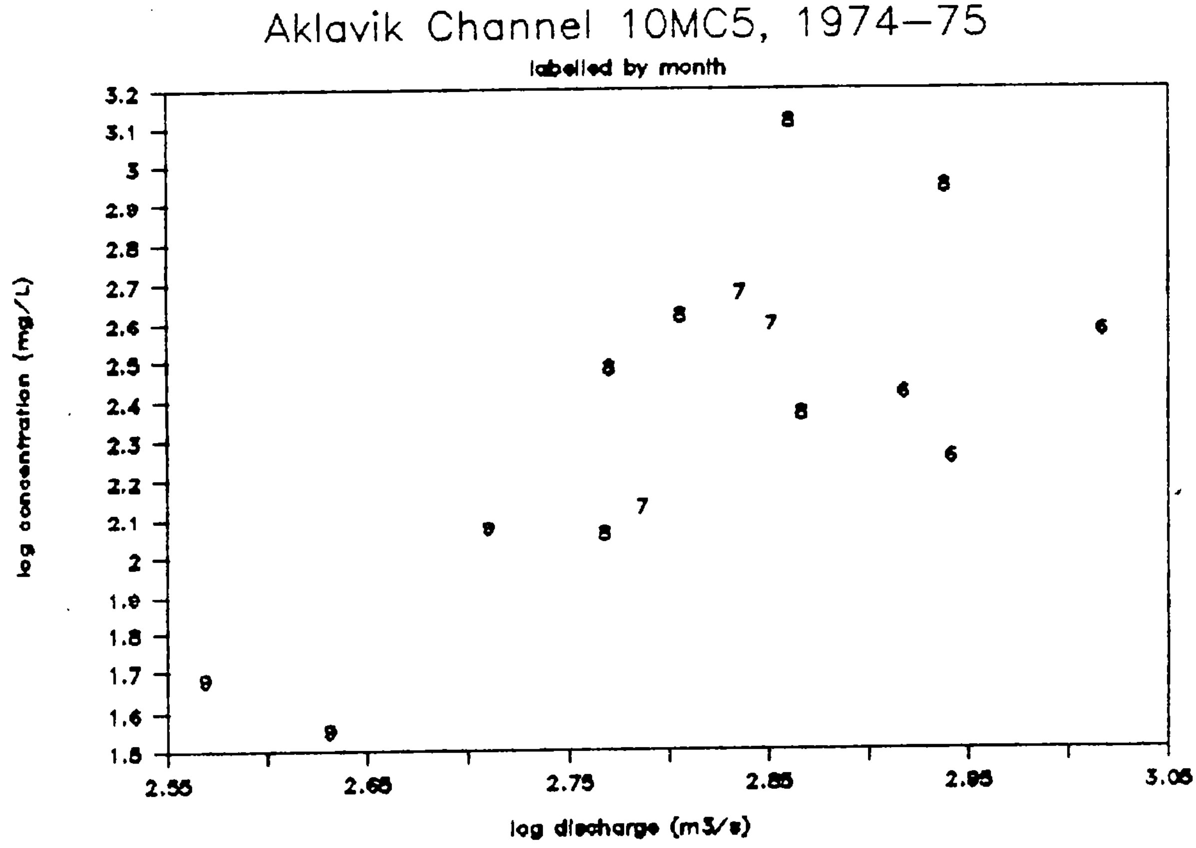

Aklavik Channel 10MC5, 1974–75
S: single vertical; M: multiple
log concentration (mg/L)
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
2.55
2.65
2.75
2.85
2.95
3.05
log discharge (m3/s)
M
S
M
S
S
S
M
S
M
S
M
M

FIGURE 2.9


Aklavik Channel 10MC5, 1974–75
labelled by month
log concentration (mg/L)
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
2.55
2.65
2.75
2.85
2.95
3.05
log discharge (m3/s)
8
8
7
8
7
6
8
6
8
6
7
9
8
9
9

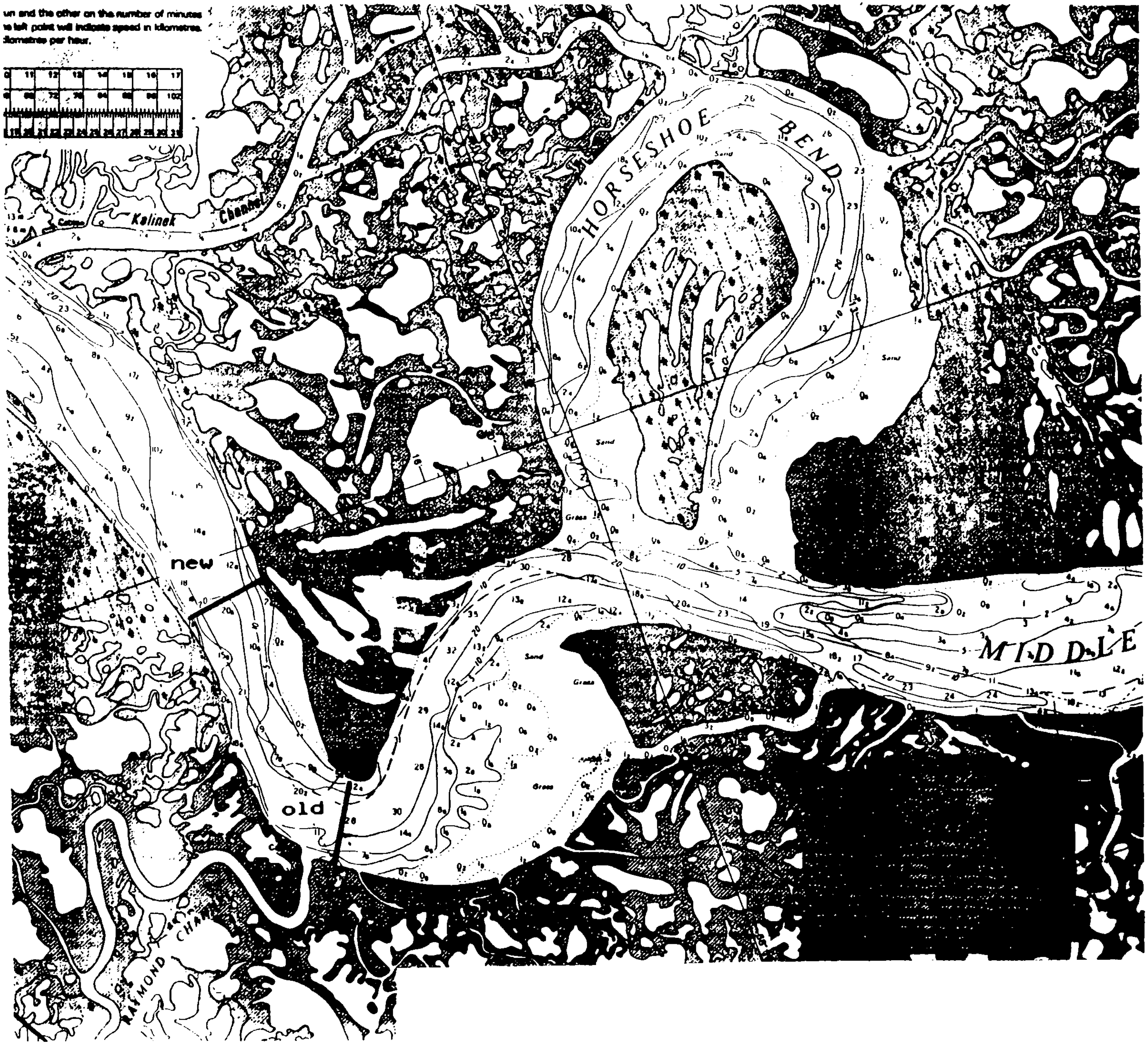


FIGURE 2.10

MIDDLE CHANNEL
BELOW
RAYMOND CHANNEL

(from CHS chart 6428)

Flow is to left

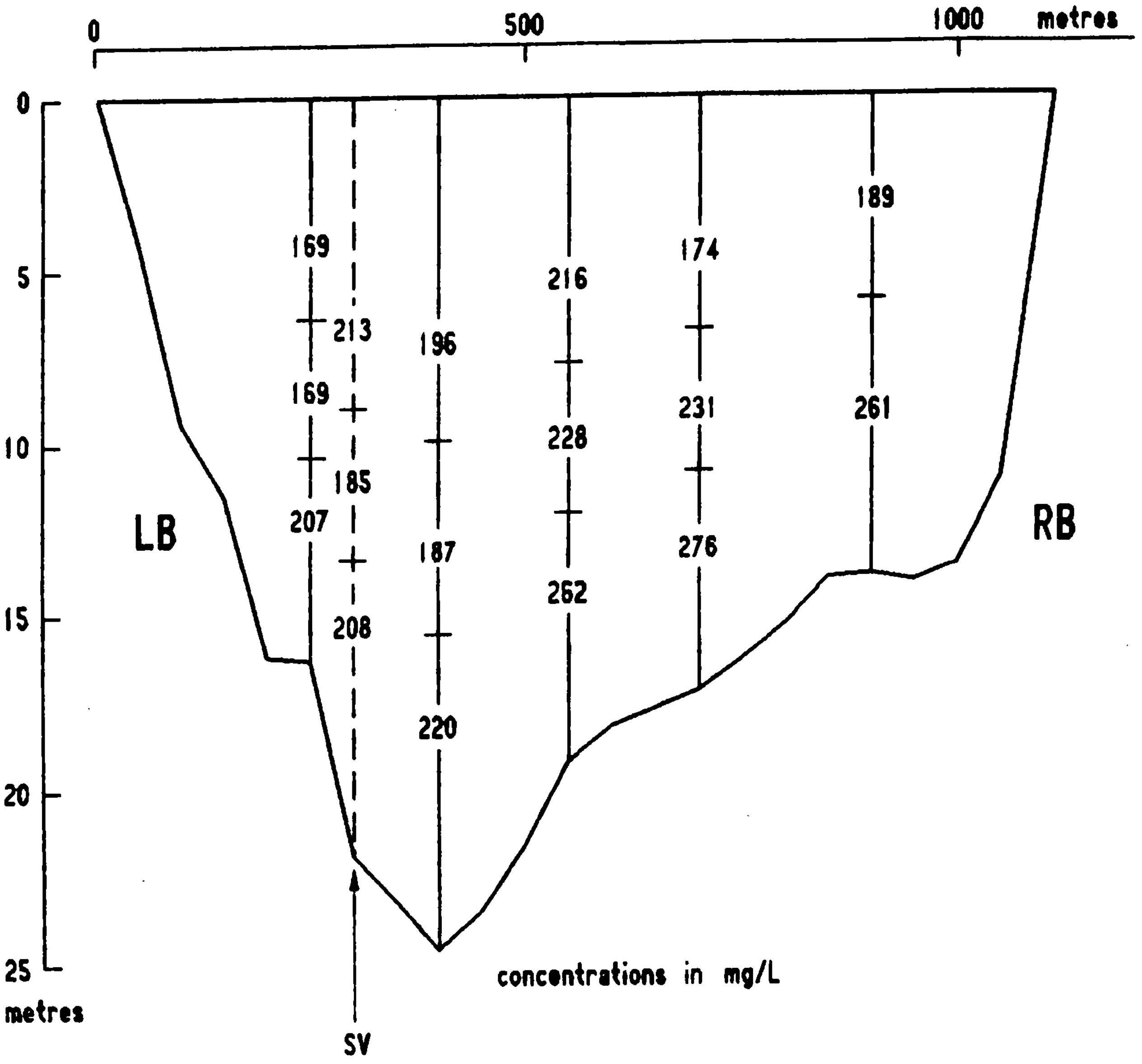


FIGURE 2.11

MIDDLE CHANNEL BELOW RAYMOND CHANNEL:
1991 JUNE 12 MV SAMPLING

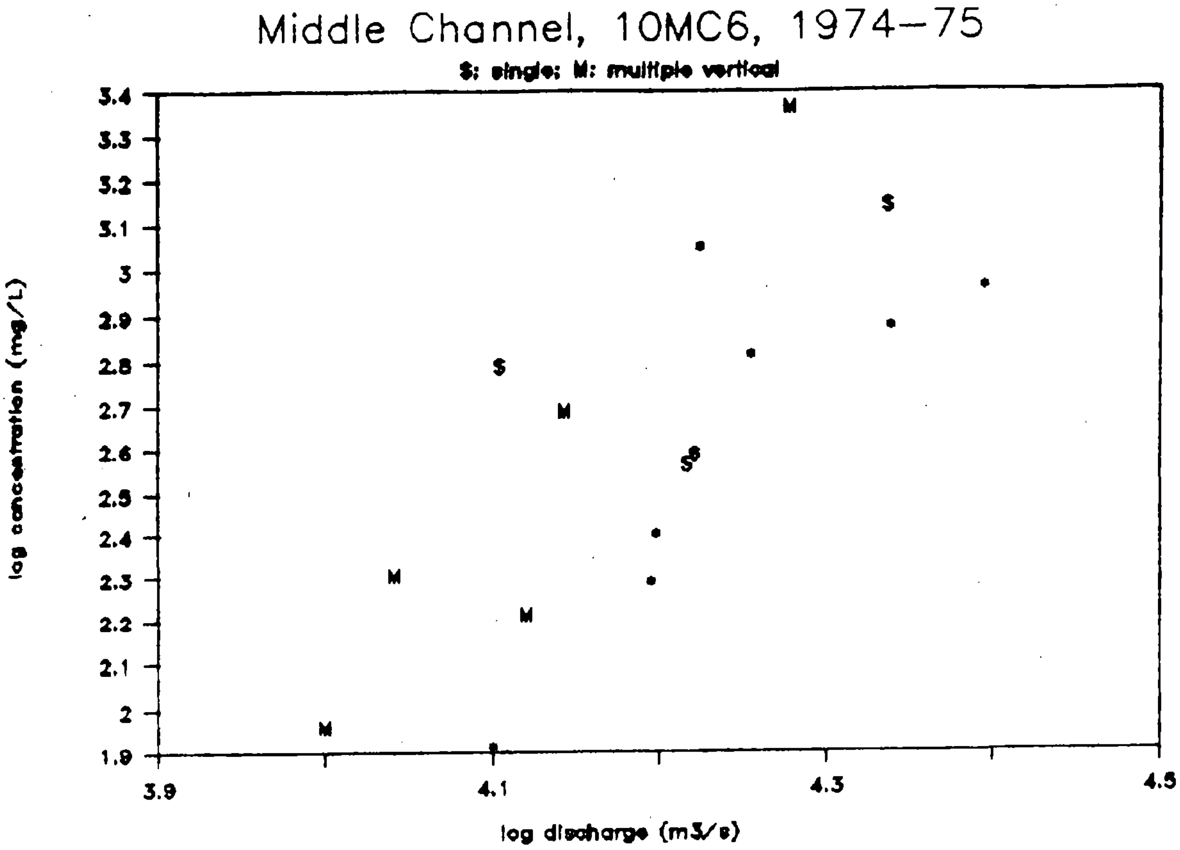
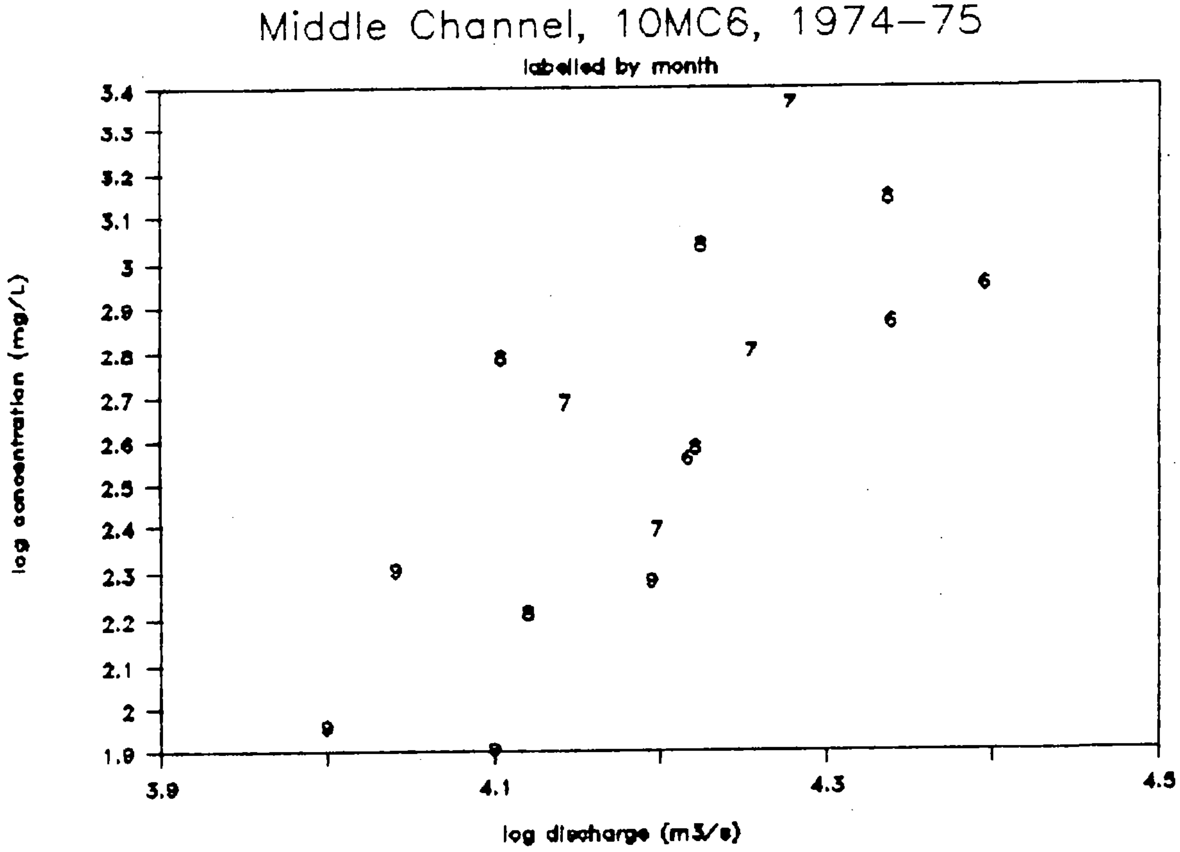

Middle Channel, 10MC6, 1974–75
S: single; M: multiple vertical
log concentration (mg/L)
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
3.9
4.1
4.3
4.5
log discharge (m3/s)

FIGURE 2.12


Middle Channel, 10MC6, 1974–75
labelled by month
log concentration (mg/L)
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
3.9
4.1
4.3
4.5
log discharge (m3/s)

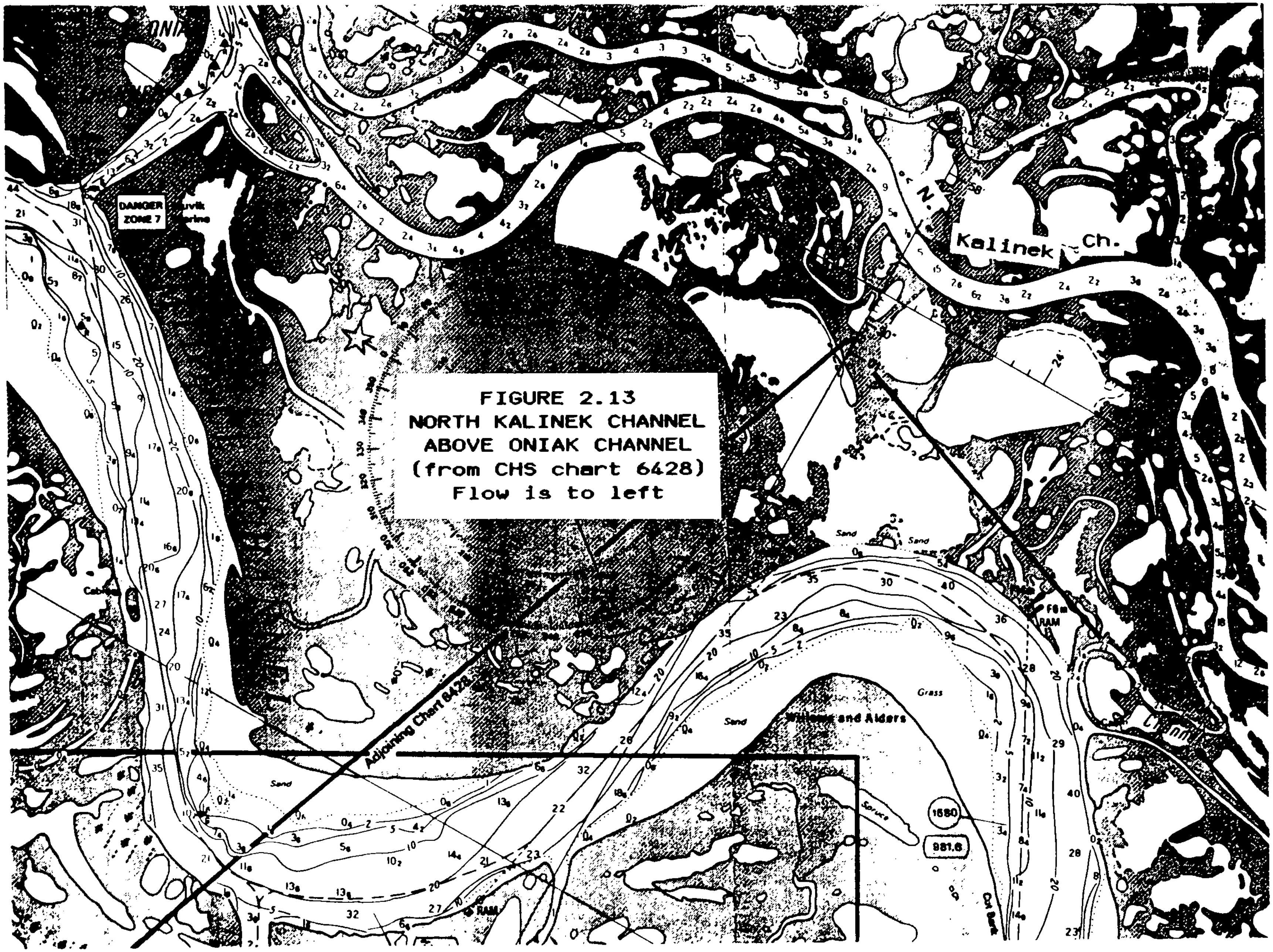


FIGURE 2.13
NORTH KALINEK CHANNEL
ABOVE ONIAK CHANNEL
(from CHS chart 6428)
Flow is to left

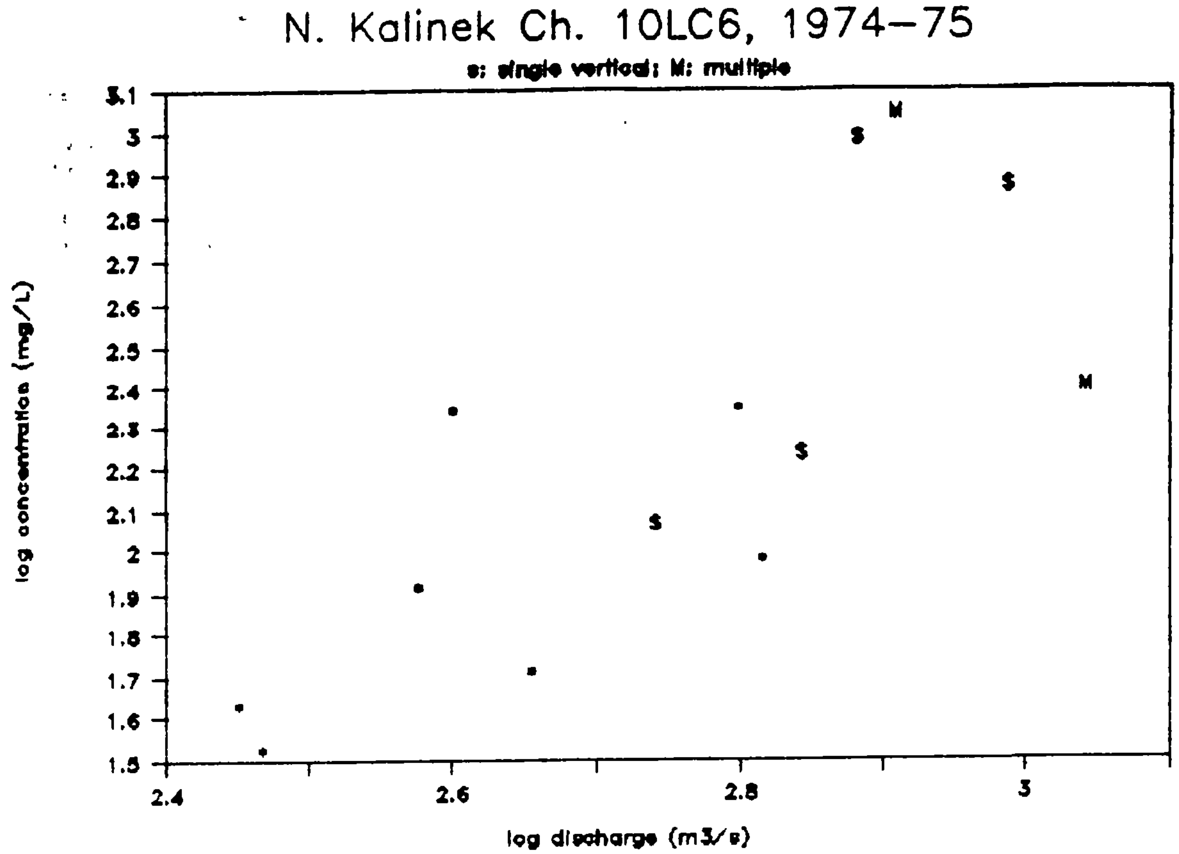
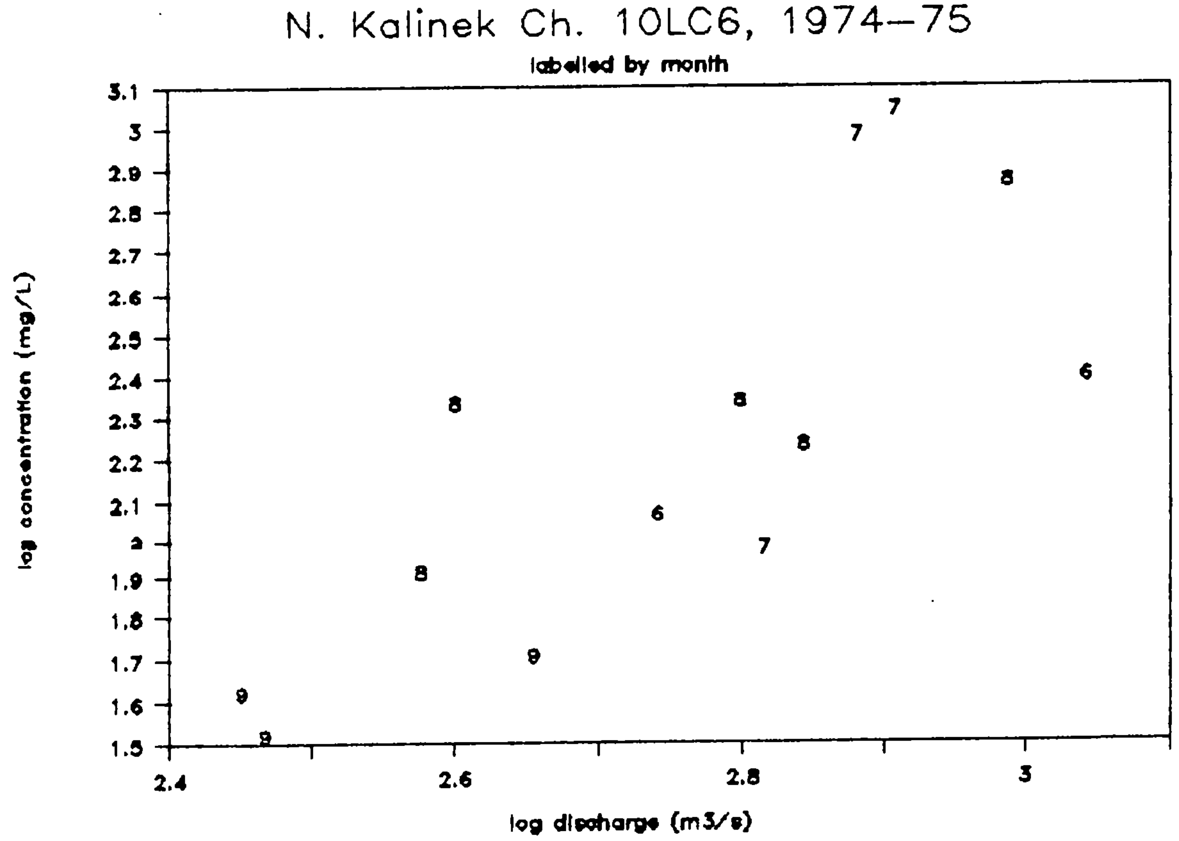

N. Kalinek Ch. 10LC6, 1974–75
s: single vertical; M: multiple
log concentration (mg/L)
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
2.4
2.6
2.8
3
log discharge (m3/s)
M
S
S
M
S
S

FIGURE 2.14


N. Kalinek Ch. 10LC6, 1974–75
labelled by month
log concentration (mg/L)
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
2.4
2.6
2.8
3
log discharge (m3/s)
7
7
8
6
8
8
8
6
7
8
9
9
9

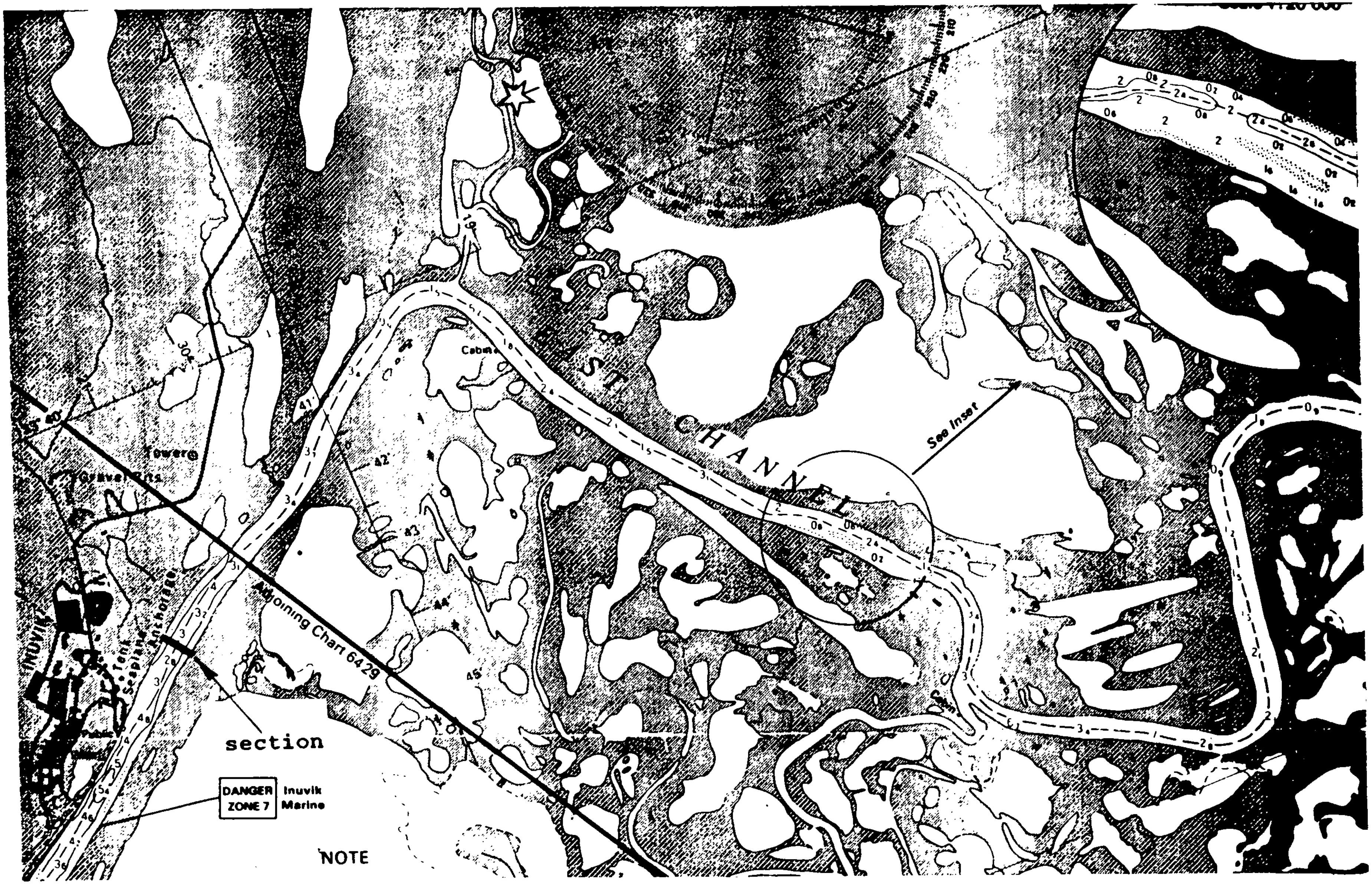
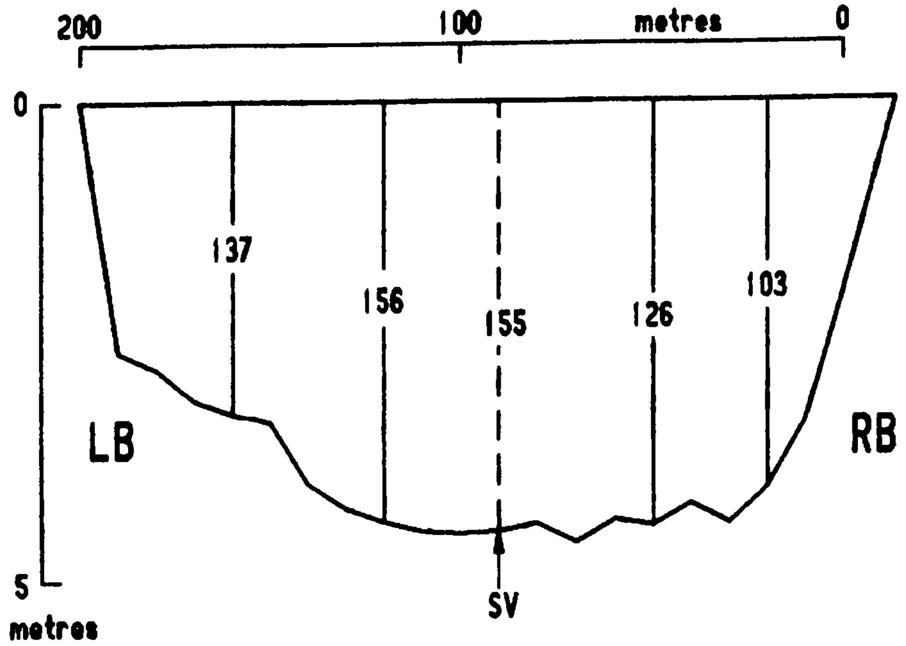


FIGURE 2.15

EAST CHANNEL AT INUVIK

(from CHS chart 6432)

Flow is to left



concentrations in mg/L

FIGURE 2.16

EAST CHANNEL NEAR INUVIK:
1991 JUNE 6 MV SAMPLING

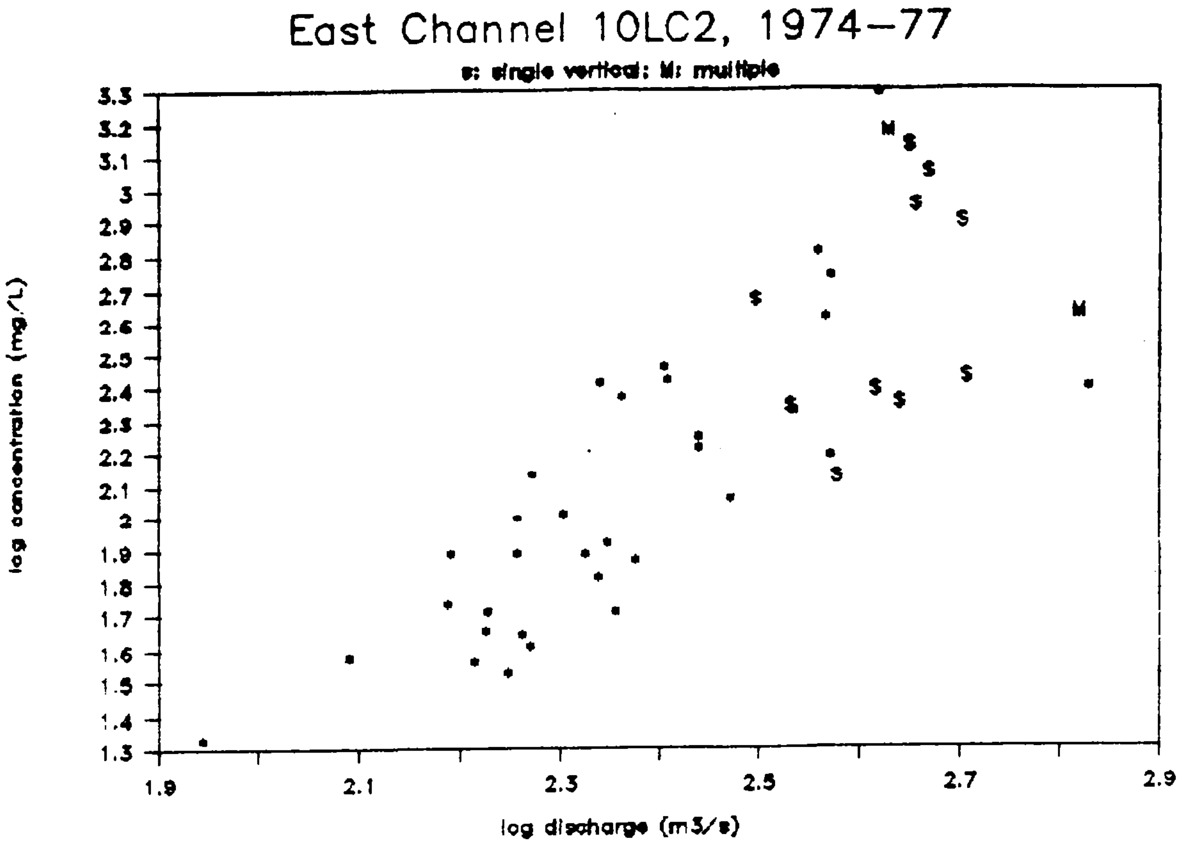
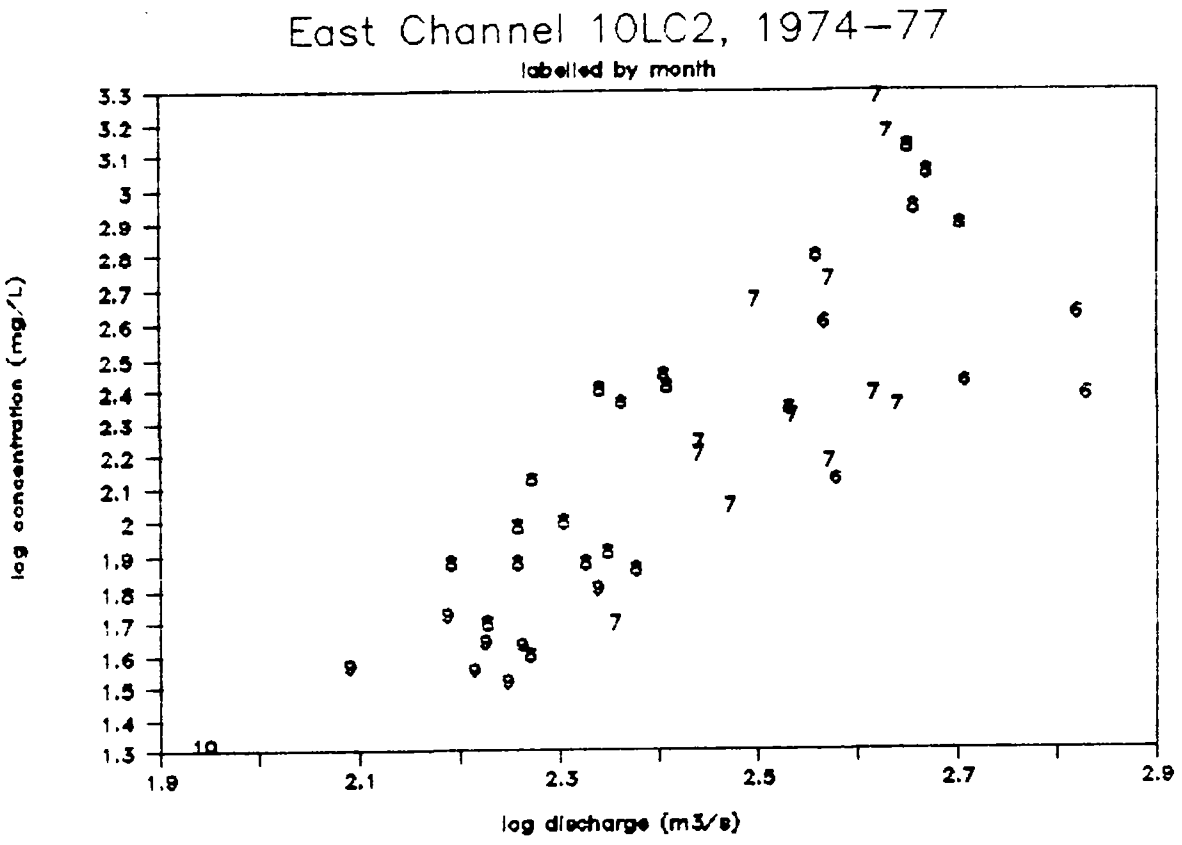

East Channel 10LC2, 1974–77
s: single vertical; M: multiple
log concentration (mg/L)
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.9
2.1
2.3
2.5
2.7
2.9
log discharge (m3/s)
M
S

FIGURE 2.17


East Channel 10LC2, 1974–77
labelled by month
log concentration (mg/L)
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.9
2.1
2.3
2.5
2.7
2.9
log discharge (m3/s)
6
7
8
9
10

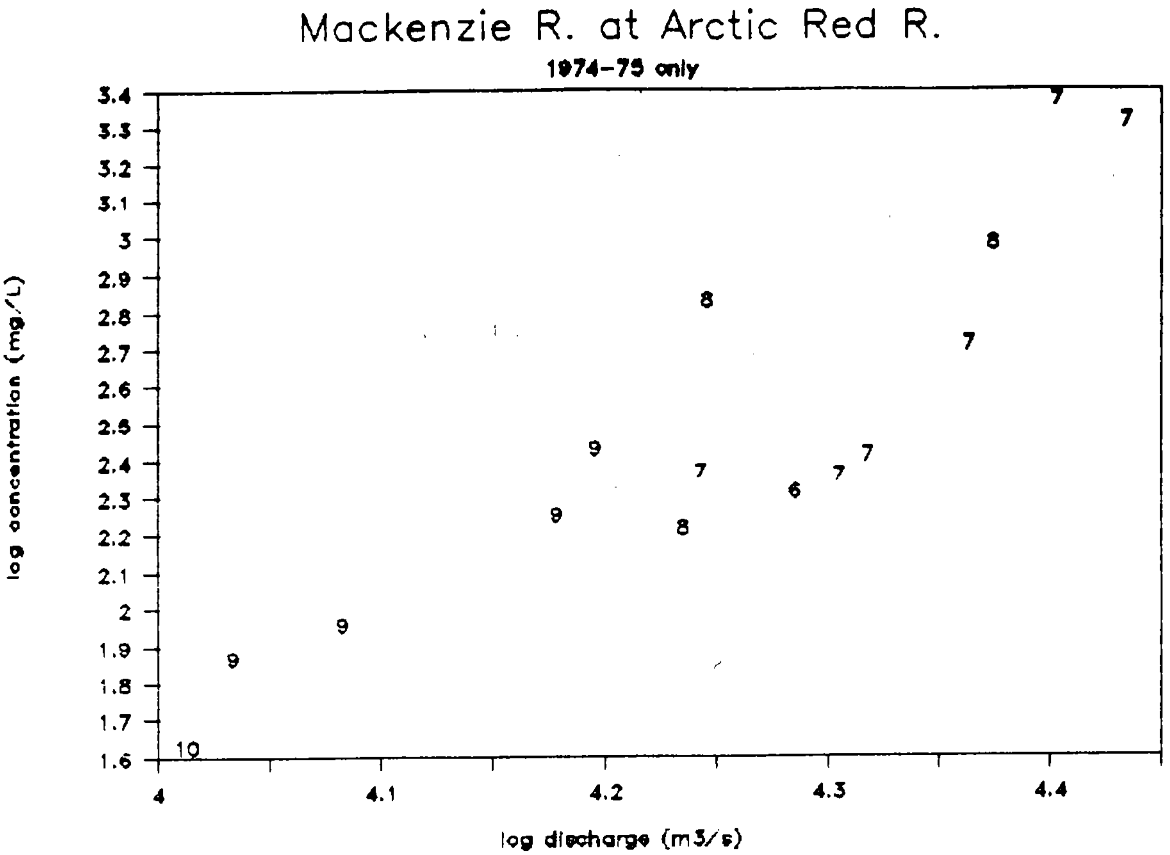
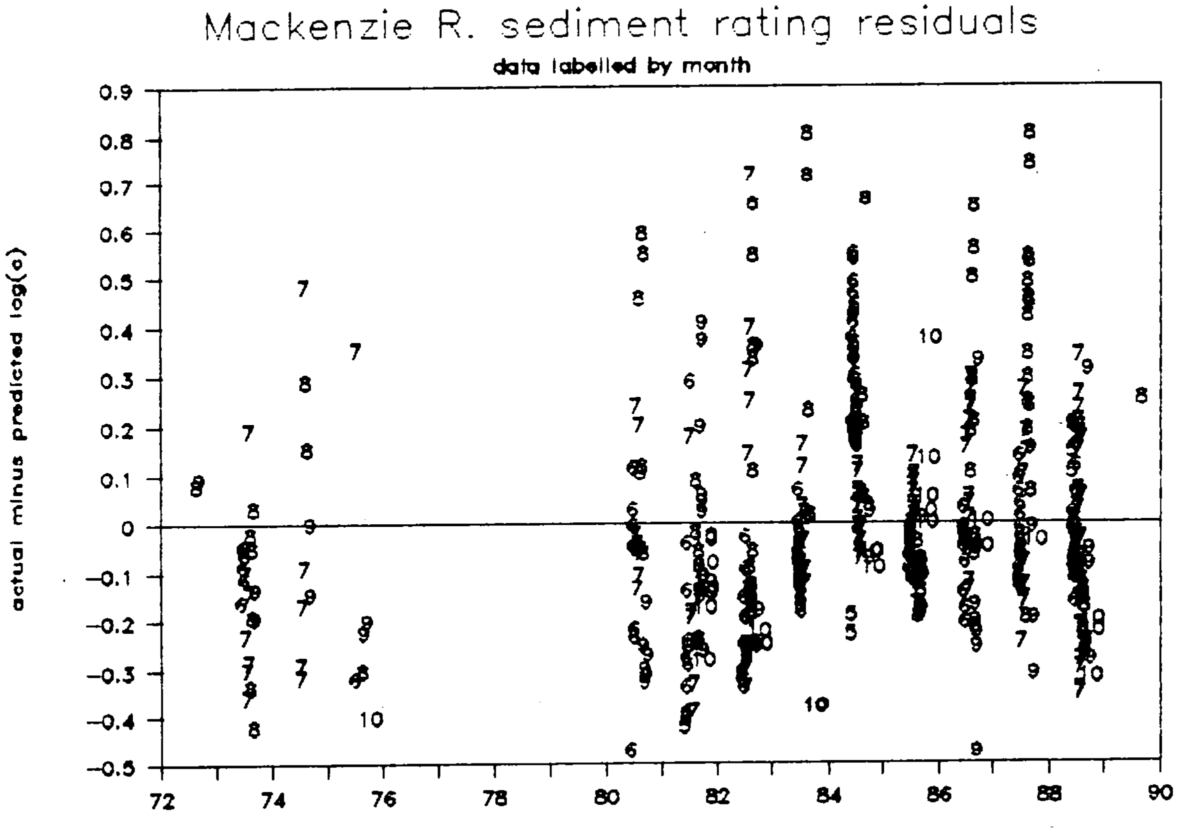

Mackenzie R. at Arctic Red R.
1974-75 only
log concentration (mg/L)
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
4
4.1
4.2
4.3
4.4
log discharge (m3/s)

FIGURE 2.18


Mackenzie R. sediment rating residuals
data labelled by month
actual minus predicted log(c)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
72
74
76
78
80
82
84
86
88
90

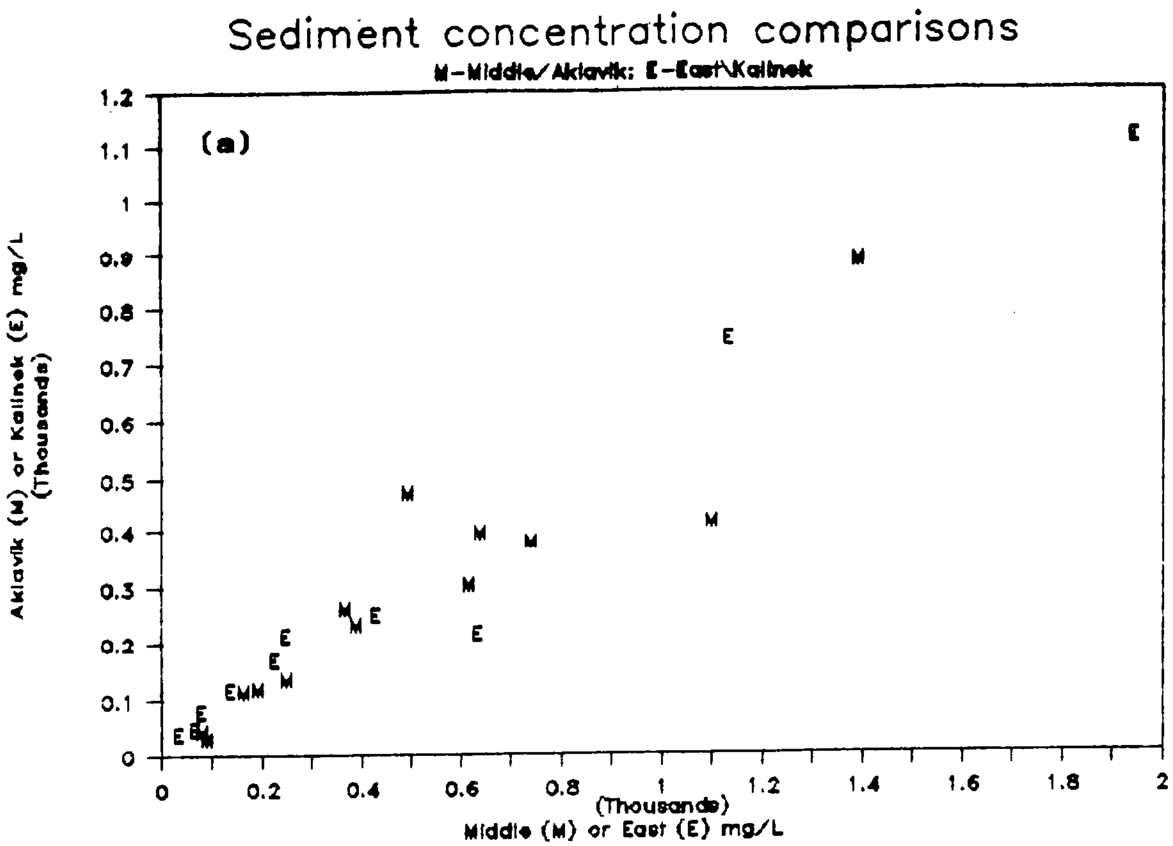
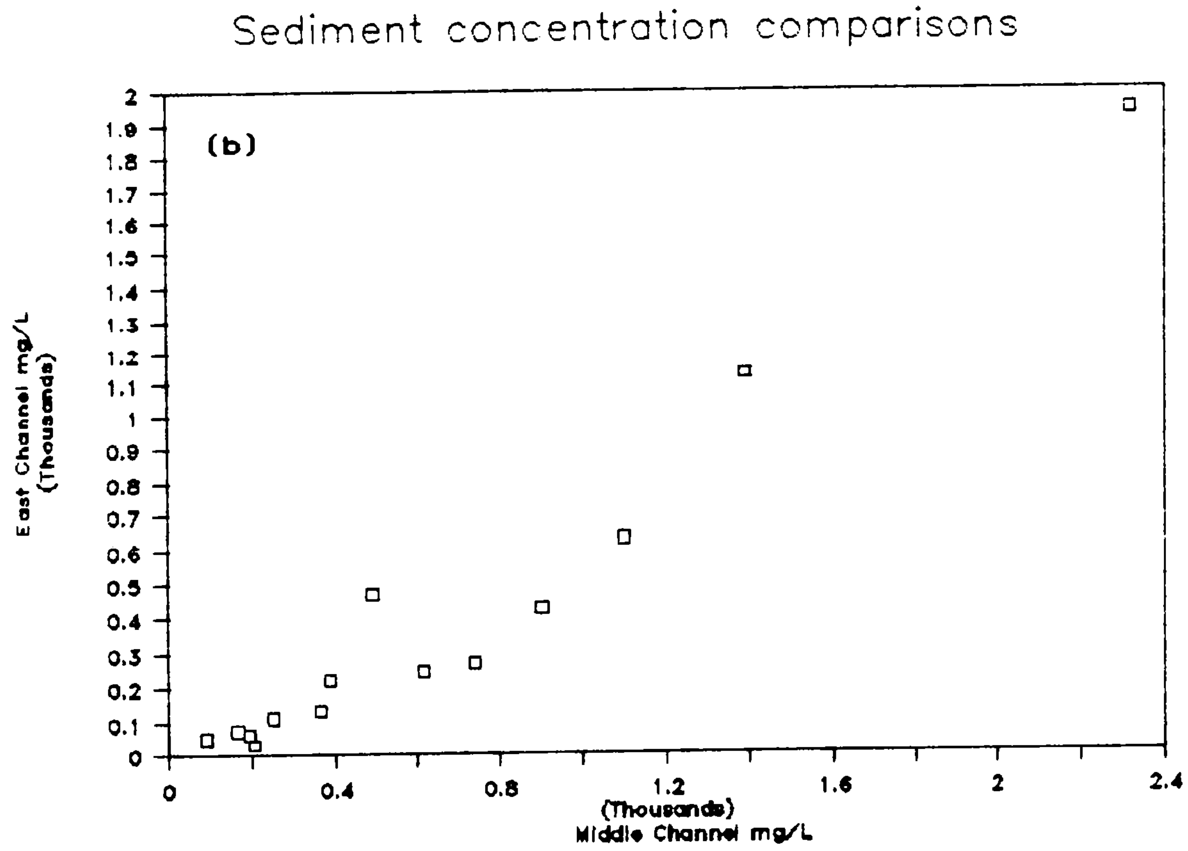

Sediment concentration comparisons
M-Middle/Aklavik; E-East\Kalinek
(a)
Aklavik (M) or Kalinek (E) mg/L
(Thousands)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
(Thousands)
Middle (M) or East (E) mg/L

FIGURE 2.19


Sediment concentration comparisons
(b)
East Channel mg/L
(Thousands)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
0
0.4
0.8
1.2
1.6
2
2.4
(Thousands)
Middle Channel mg/L

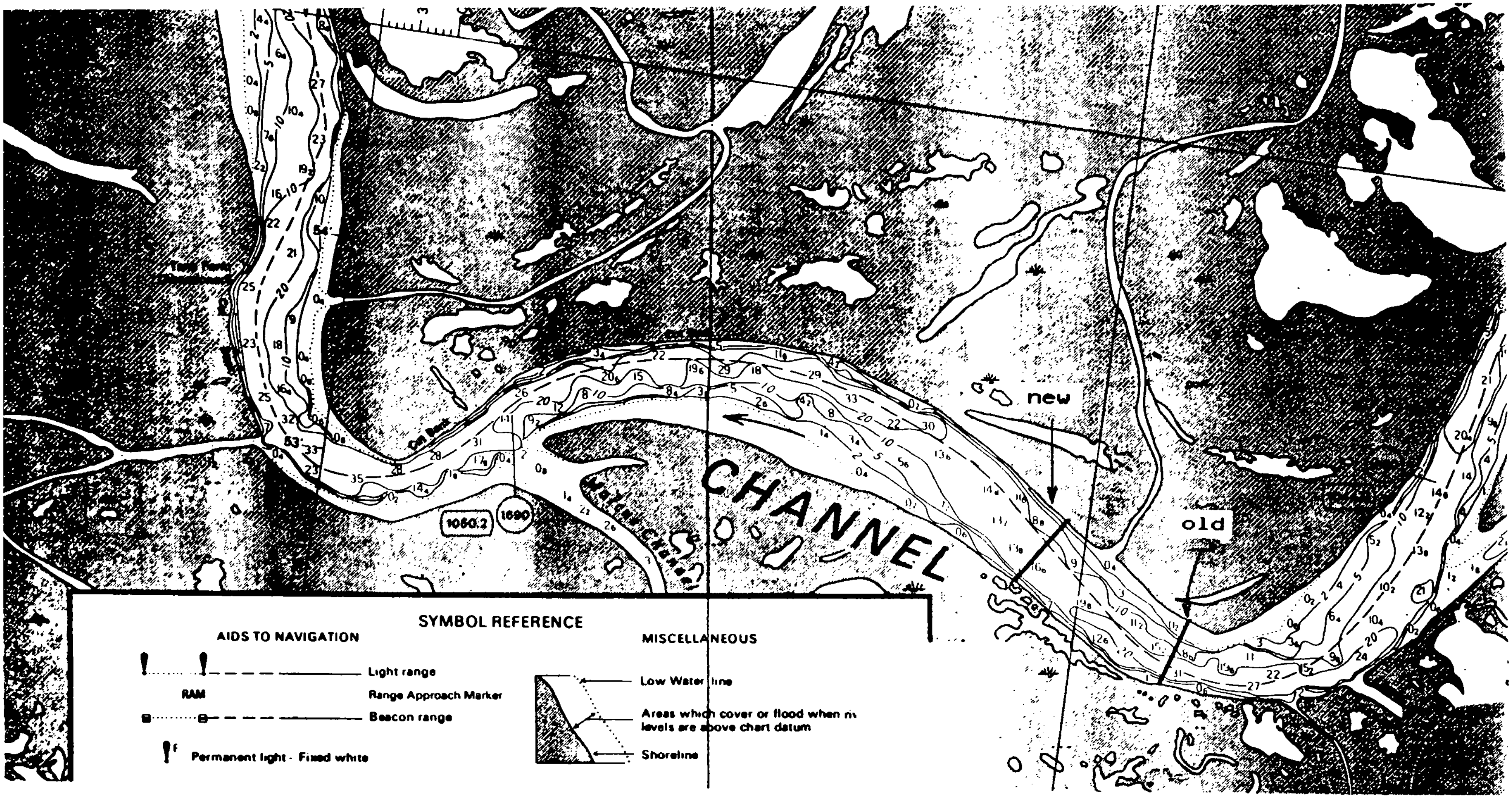
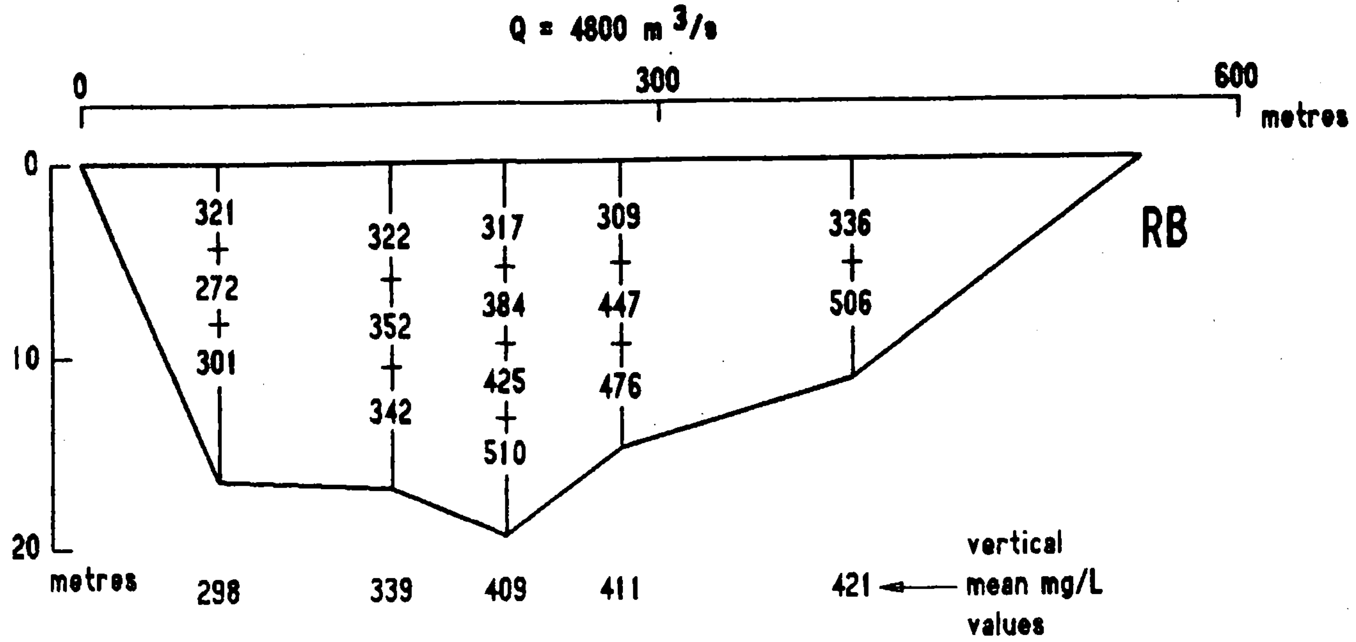


FIGURE 3.1

REINDEER CHANNEL BELOW LEWIS CHANNEL

(from CHS chart 6434)

Flow is to left



1987 AUGUST 25 MV SAMPLING
unweighted cross-section mean 378 mg/L

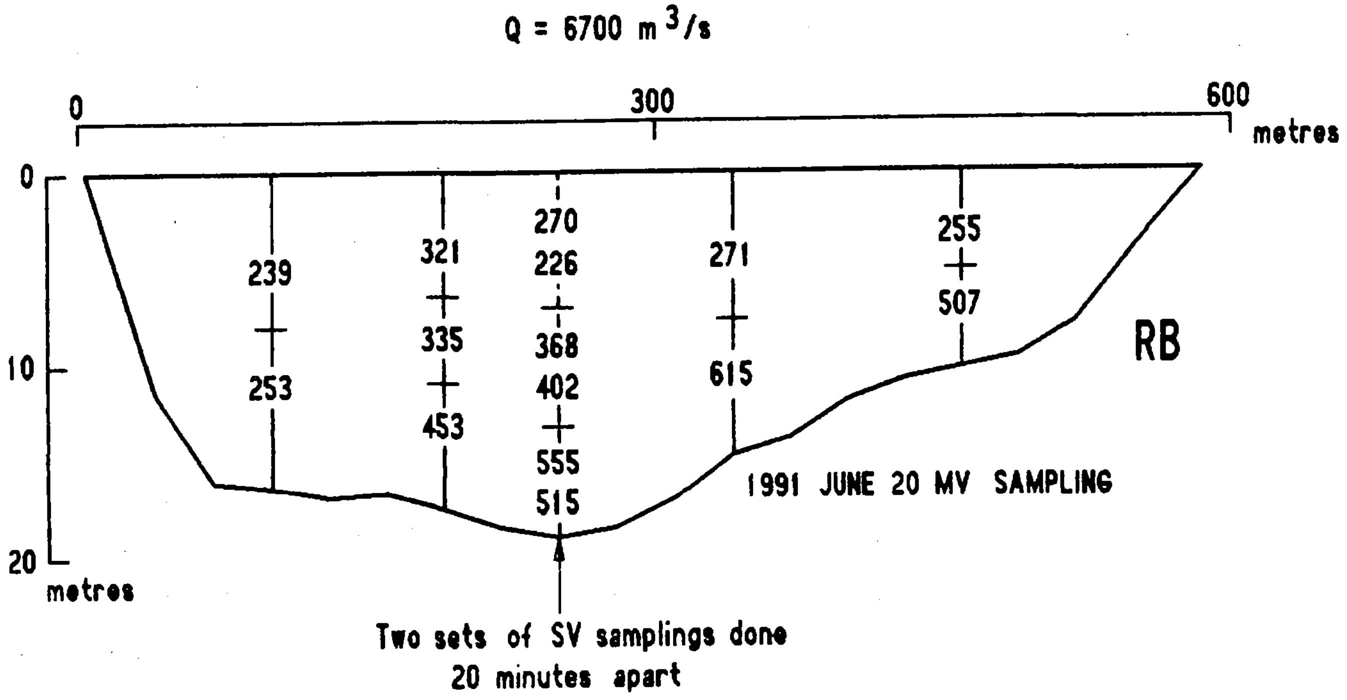


FIGURE 3.2

REINDEER CHANNEL BELOW LEWIS CHANNEL:
SUSPENDED SEDIMENT mg/L DISTRIBUTION

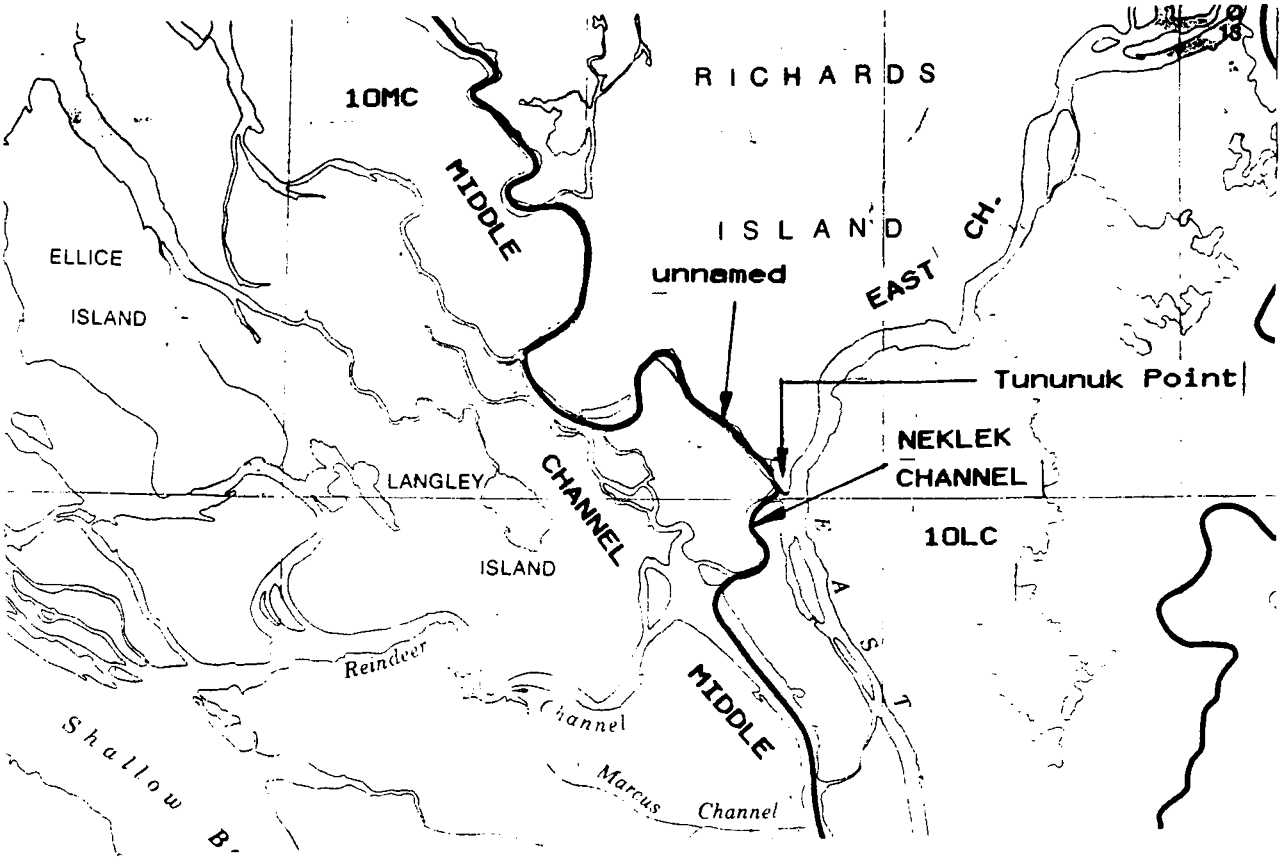
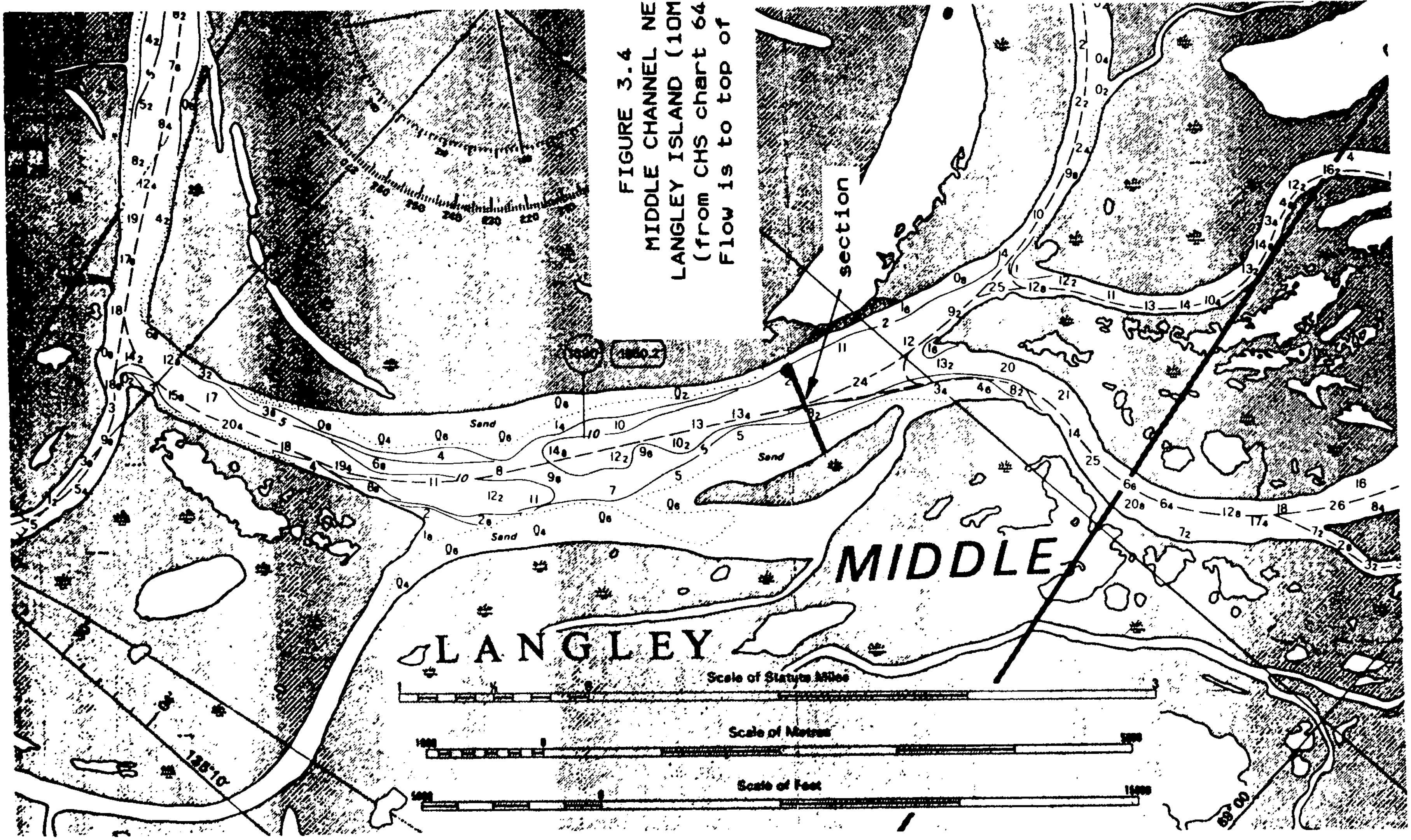
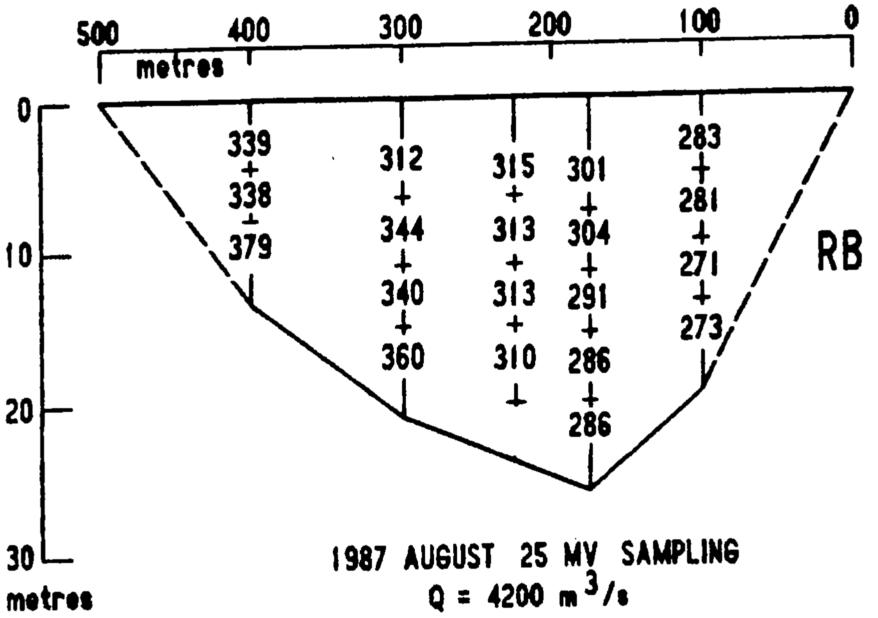


FIGURE 3.3

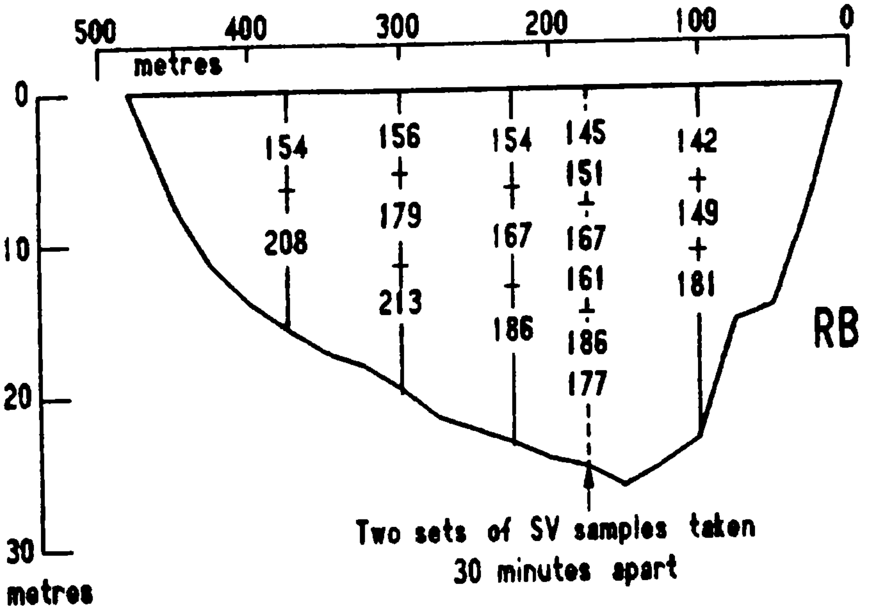
TRIPLE SPLIT OF MIDDLE CHANNEL AT LANGLEY ISLAND

FIGURE 3.4
MIDDLE CHANNEL NEAR
LANGLEY ISLAND (10MC901)
(from CHS chart 6435)
Flow is to top of page





1987 AUGUST 25 MV SAMPLING
Q = 4200 m^3/s



1991 JUNE 13 MV SAMPLING
Q = 5350 m^3/s

FIGURE 3.5

MIDDLE CHANNEL NEAR LANGLEY ISLAND

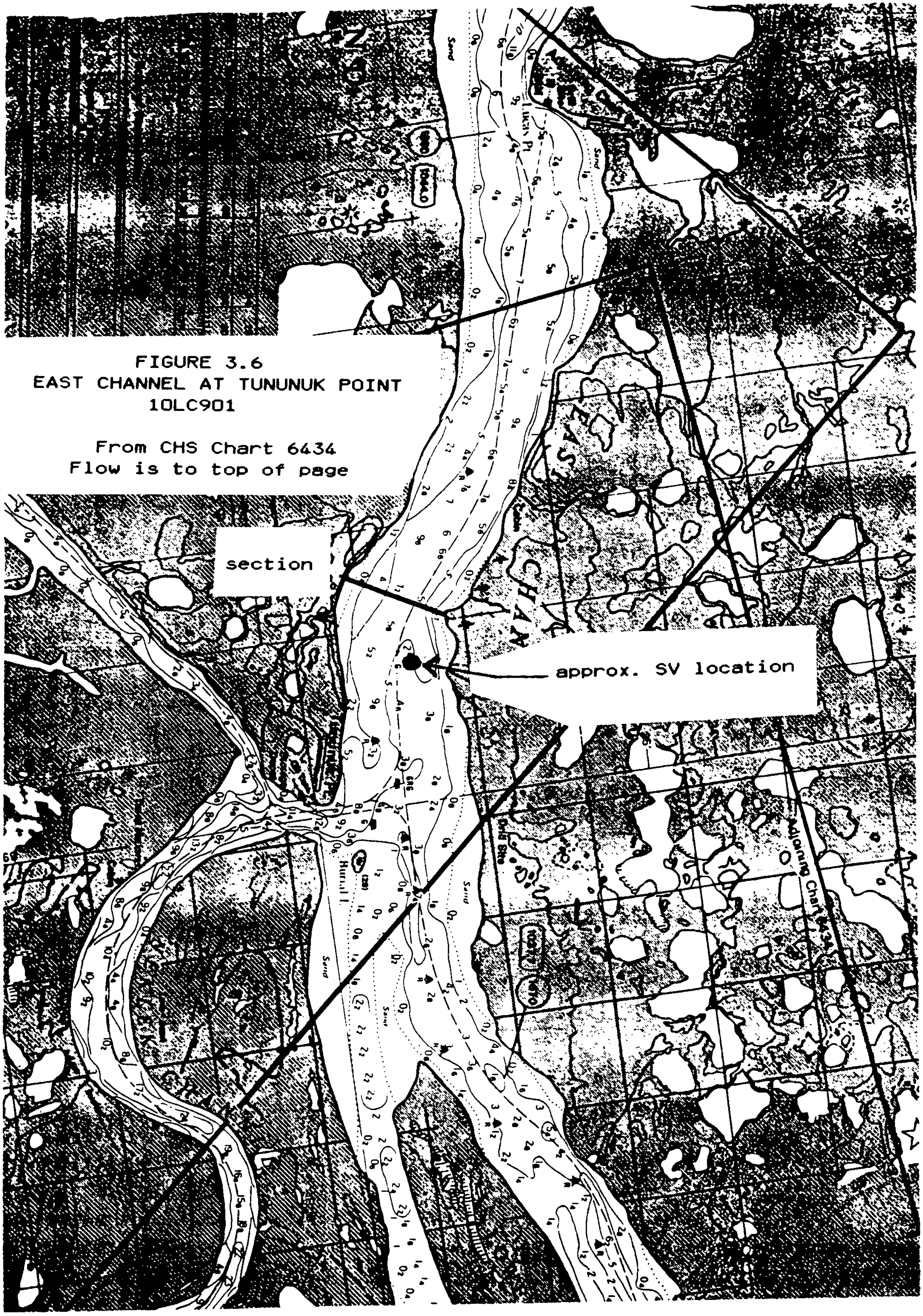
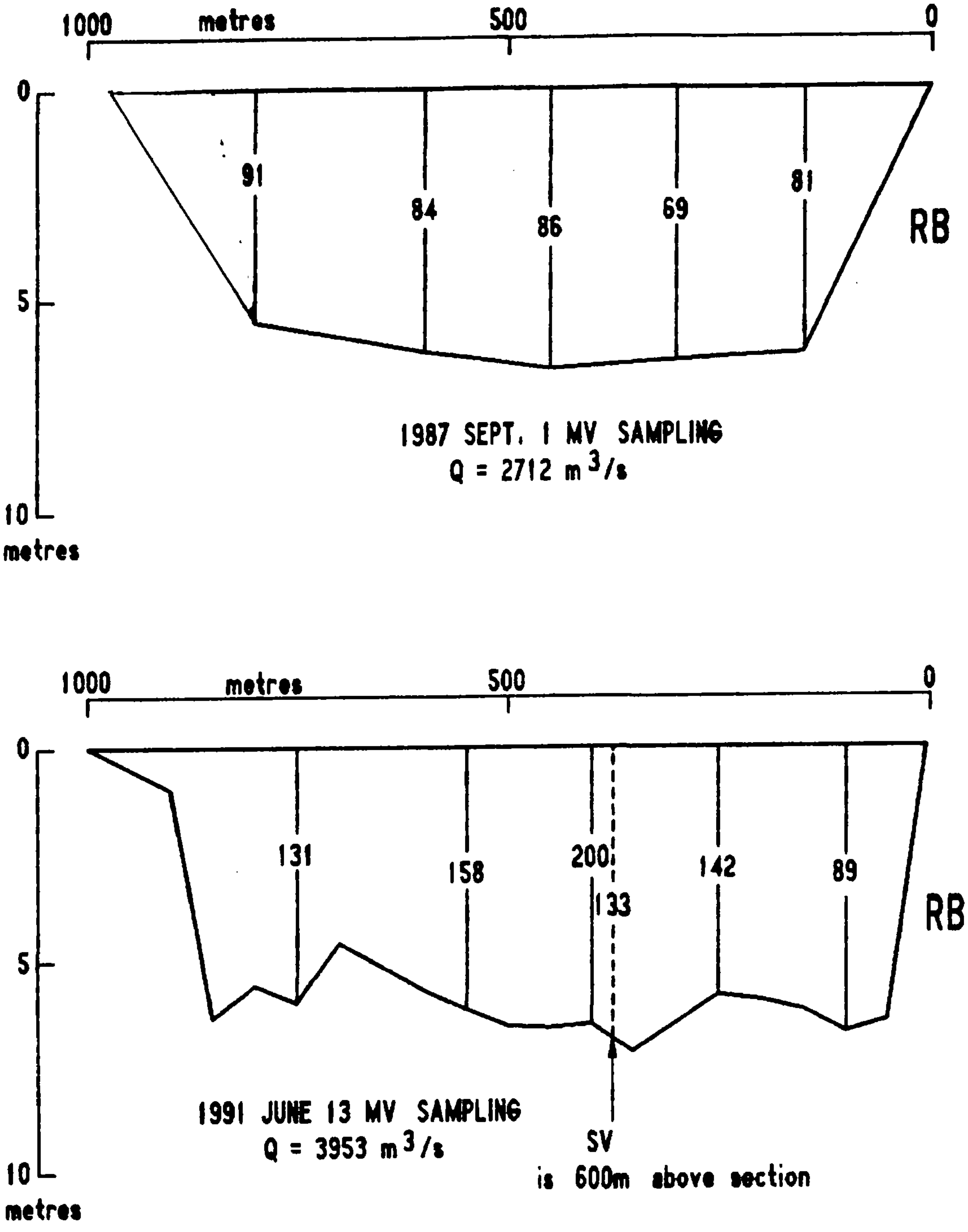


FIGURE 3.6
EAST CHANNEL AT TUNUNUK POINT
10LC901

From CHS Chart 6434
Flow is to top of page



all concentrations in mg/L

FIGURE 3.7

EAST CHANNEL BELOW TUNUNUK POINT

APPENDIX A

1974 MID-DELTA SEDIMENT LOADS

(from Davies, 1975)

CAMPBELL CREEK NEAR INUVIK - STATION NO. 10LC004

SUSPENDED SEDIMENT FOR 1974

	JUL				AUG				SEP				
DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	DAY
1		38.1	7	0.72	15.6	95.8 E	11 S	2.8		23.8	11	0.71	1
2		36.9	7	0.70		91.4 E	10	2.5		22.4	11	0.67	2
3		35.8	7	0.68		87.7 E	9	2.1		21.3	12	0.69	3
4		34.6	6	0.56		84.1 E	7	1.6	10.0	20.2	12 S	0.65	4
5	6.7	33.4	6 S	0.54		80.4 E	5	1.1		19.1	11	0.57	5
6		32.7	5	0.43	13.9	76.8 E	4 S	0.83	6.1	18.0	10 S	0.49	6
7		31.0	4	0.33		73.1 E	5	0.99		17.2	7	0.33	7
8	11.1	29.8	4 S	0.32		69.5 E	7	1.3		16.4	6	0.27	8
9		48.0	7	0.91	16.1	65.8 A	8 S	1.4		15.5	6	0.25	9
10	12.2	66.1	16 S	2.9		62.2	9	1.5		14.2	6	0.23	10
11		84.3	16	3.6		58.5	9	1.4	8.9	13.0	6 S	0.21	11
12		102	14	3.9		54.9	9	1.3		12.3	7	0.23	12
13		121	13	4.2		51.2	9	1.2		11.7	7	0.22	13
14		139	12	4.5		47.6	9	1.2		11.1	8	0.24	14
15	15.0	157	11 S	4.7		43.9	9	1.1		10.6	9	0.26	15
16		153	13	5.4	16.7	40.3	9 S	0.98	15.6	10.0	10 S	0.27	16
17		150	23	9.3		39.3	9	0.95		10.2	10	0.28	17
18	15.6	146	35 S	13.8		38.3	9	0.93		10.4	10	0.28	18
19		142	31	11.9		37.2	9	0.90		10.6	10	0.29	19
20		139	24	9.0		36.2	10	0.98		10.8	10	0.29	20
21		135	19	6.9	9.4	35.1	10 S	0.95		11.0	10	0.30	21
22		131	15	5.3		34.3	9	0.83		11.2	10	0.30	22
23		128	12	4.1	9.4	33.2	7 S	0.63		11.4	11	0.34	23
24	14.4	124	10 S	3.3		32.4	7	0.61		11.6	11	0.34	24
25		121	10	3.3		31.6	7	0.60		11.8	11	0.35	25
26		117	10	3.2		30.5	7	0.58		12.0	11	0.36	26
27		113	10	3.1		29.4	8	0.64		12.2	11	0.36	27
28		110	11	3.3		28.3	8	0.61		12.4 B	12	0.40	28
29		108	11	3.1		27.1	9	0.66		12.7 B	12	0.41	29
30		102	11	3.0		26.0	10	0.70	0.6	13.1 B	12 S	0.42	30
31		95.7	11	2.9		24.9	11	0.74					31
TOTAL		3004.9		115.89		1566.2		34.61		418.2		11.01	TOTAL
MEAN		96.9		3.9		50.5		1.1		13.9		0.37	MEAN

MACKENZIE RIVER (PEEL CHANNEL) ABOVE AKLAVIK - STATION NO. 10MC003

SUSPENDED SEDIMENT FOR 1974

	APR				MAY				JUN				
DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	DAY
1										83600	329	74300	1
2										87200	402	94600	2
3										91600	488	121000	3
4										96900	575	151000	4
5										104000	665	187000	5
6										104000	677	190000	6
7										98300	574	152000	7
8										91100	479	118000	8
9										85500	395	91200	9
10										78000	326	68700	10
11										71900	269	52200	11
12									6.1	66500	222 S	39900	12
13										61500	188	31200	13
14										57200	177	27300	14
15										53400	184	26500	15
16										50600	205	28000	16
17										47900	245	31700	17
18										45600	300	36900	18
19										43400	350	41000	19
20										41700	405	45600	20
21										40600	457	50100	21
22										39600	504	53900	22
23										38900	547	57500	23
24										38300	578	59800	24
25										37900	603	61700	25
26										37400	611	61700	26
27										37000	607	60600	27
28										37100	601	60200	28
29										36600	594	58700	29
30										36500	589	58000	30
31													31
TOTAL										1838700		2189100	TOTAL
MEAN										61300		73000	MEAN

MACKENZIE RIVER (PEEL CHANNEL) ABOVE AKLAVIK - STATION NO. 10MC003

SUSPENDED SEDIMENT FOR 1974

	JUL				AUG				SEP				
DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	DAY
1		37300	589	59300	15.6	39400 A	349 S	37100		33600	161	14600	1
2		36900	584	58200		38000 E	246	25200		33000	164	14600	2
3		36900	579	57700		36500 E	180	17700		33900	185	16900	3
4		36800	575	57100		35500 E	132	12700		33600	166	15100	4
5		36100	570	55600		34300 E	104	9630		32300	137	11900	5
6		35400	565	54000		34000 E	85	7800		30800	119	9900	6
7		35000	559	52800		34800 E	82	7700		29400	112	8890	7
8		34600	554	51800	16.1	35300 A	107 S	10200		28000	106	8010	8
9		34700	549	51400		37800	179	18100	7.2	27000	99 S	7220	9
10		34400	545	50600		40000	281	30300		25900	91	6360	10
11		34000	540	49600		41200	394	43800		24700	83	5540	11
12	13.3	33600	536 S	48600		42300 A	510	58200		23800	75	4820	12
13		33400	521	47000		43500 E	624	73300		23700	67	4200	13
14		33500	477	43100		44500 E	719	86400		22400	60	3630	14
15		32700	368	32500	13.3	45500 E	749 S	92000		21600	52	3030	15
16		31500	214	18200		46000 E	693	86100		20900	44	2480	16
17		30400	110	9030		47000 E	681	86400		20000	37	2000	17
18	16.9	29400	71 S	5640		50000 E	759	102000	6.1	19500 B	33 S	1740	18
19		29200	65	5120		52000 E	866	122000		19400 B	33	1730	19
20		29700	63	5050		54000 E	904	132000		19100 B	34	1750	20
21		29700	62	4970		54000 E	815	119000		18900 B	37	1890	21
22		29300	61	4830		52000 E	707	99300		19900 B	53	2850	22
23		29300	60	4750		50000 E	599	80900		19900 B	44	2360	23
24		29900	64	5170		48500 E	500	65500		19400 B	41	2150	24
25		31000	110	9210		47000 E	413	52400		18700 B	39	1970	25
26		32700	205	18100		45000 E	332	40300		18100 B	37	1810	26
27		34900	316	29800		42500 E	270	31000		17500 B	34	1610	27
28		37100	425	42600		40000 E	232	25100		17000 B	32	1470	28
29		38500	531	55200	10.9	37600 A	193 S	19600		16800 B	30	1360	29
30		39400	584	62100		36400	173	17000		17800 B	38	1830	30
31		39600	487	52100		34800	169	15900					31
TOTAL		1047000		1101270		1319400		1624830		706100		163700	TOTAL
MEAN		33800		35500		42600		52400		23500		5460	MEAN

MACKENZIE RIVER (AKLAVIK CHANNEL) ABOVE SCHOONER CHANNEL - STATION NO. 10MC005

SUSPENDED SEDIMENT FOR 1974

	APR				MAY				JUN				
DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	DAY
1										32000 E	250	21600	1
2										34000 E	300	27500	2
3										37500 E	350	35400	3
4										40000 E	390	42100	4
5										44000 E	484	57500	5
6										46000 E	608	75500	6
7										47000 E	700	88800	7
8										44200	584	69700	8
9										40600	443	48600	9
10										36900	293	29200	10
11										34300	195	18100	11
12									4.4	30900	182 S	15200	12
13										30800	166	13800	13
14										30700	173	14300	14
15										30600	197	16300	15
16										30500	255	21000	16
17										30400	304	25000	17
18										30300	344	28100	18
19										30200	388	31600	19
20										30000	435	35200	20
21										29200	476	37500	21
22										28400	514	39400	22
23										28100	569	43200	23
24										28000	593	44800	24
25										28000	595	45000	25
26										27800	584	43800	26
27										27000	572	41700	27
28										26800	564	40800	28
29										26900	555	40300	29
30										26900	541	39300	30
31													31
TOTAL										988000		1130300	TOTAL
MEAN										32900		37700	MEAN

MACKENZIE RIVER (AKLAVIK CHANNEL) ABOVE SCHOONER CHANNEL - STATION NO. 10MC005

SUSPENDED SEDIMENT FOR 1974

	JUL				AUG				SEP				
DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	DAY
1		27000	533	38900		26300	1450	103000		22700	205	12600	1
2		27000	524	38200	15.6	25600	1310 S	90500		22400	201	12200	2
3		27100	506	37000		24500	1120	74100		22900	227	14000	3
4		27100	494	36100		23300	896	56400		23200	242	15200	4
5		26900	482	35000		22200	642	38500		22200	192	11500	5
6		26400	470	33500		21700	403	23600		21100	159	9060	6
7		26200	458	32400		21900	292	17300		19900	143	7680	7
8		25900	445	31100	16.1	22600 A	416 S	25400		19000	131	6720	8
9		25800	433	30200		23500 E	517	32800	7.2	18100	120 S	5860	9
10		25700	421	29200		24200 E	585	38200		17300	113	5280	10
11		25400	409	28000		25100 E	652	44200		16700	105	4730	11
12	13.9	25100	395 S	26800		26100 E	715	50400		16300	96	4220	12
13		24900	384	25800		27500 E	793	58900		15700	88	3730	13
14		24900	365	24400		29000 E	893	69900		15200	79	3240	14
15		24200	297	19400	14.4	30600 A	887 S	73300		14700	71	2820	15
16		23400	209	13200		30300	748	61200		14200	62	2380	16
17		22400	156	9430		30200	681	55500		13600	54	1980	17
18	17.8	21600	136 S	7930		31600	832	71000	6.1	13100	46 S	1630	18
19		21100	128	7290		33800	1130	103000		12900	43	1500	19
20		21300	126	7250		36600	1350	133000		12600	42	1430	20
21		21100	120	6840		37100	1200	120000		12400	40	1340	21
22		20700	114	6370		35900	1050	102000		13100	71	2510	22
23		20500	117	6480		34600	909	84900		13300	76	2730	23
24		21000	215	12200		33300	738	66400		12900	70	2440	24
25		22100	428	25500		31600	590	50300		12400	64	2140	25
26		23500	712	45200		30200	485	39500		11900	59	1890	26
27		25300	1080	73800		28500	392	30200		11400	53	1630	27
28		26500	1420	102000		27200	295	21700		11000	47	1400	28
29		27200	1680	123000	10.6	26000	234 S	16400		10700	41	1180	29
30		27400	1690	125000		24800	220	14700		10800 E	55	1600	30
31		27000	1580	115000		23500	213	13500					31
TOTAL		761600		1152490		869300		1779800		473600		146610	TOTAL
MEAN		24600		37200		28000		57400		15800		4890	MEAN

MACKENZIE RIVER (WEST CHANNEL) BELOW AKLAVIK CHANNEL - STATION NO. 10MC004

SUSPENDED SEDIMENT FOR 1974

	JUL				AUG				SEP				
DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	DAY
1		71000	292	56000	15.6	65000	691 S	121000		58400	198	31200	1
2		69400	288	54000		63600	603	104000		57600	187	29100	2
3		69100	291	54300		61000	533	87800		60600	232	38000	3
4		68900	290	53900		58300	443	69700		59800	216	34900	4
5		67200	278	50400		55500	347	52000		57100	176	27100	5
6		65700	265	47000		53800	268	38900		54000	141	20600	6
7		65100	257	45200		53500	207	29900		50800	103	14100	7
8		64200	249	43200	16.1	56200	238 S	36100		48100	88	11400	8
9		64300	230	39900		63500	356	61000	7.2	46000	81 S	10100	9
10		63700	218	37500		67300	428	77800		44000	78	9270	10
11		62700	209	35400		69800	443	83500		42400	72	8240	11
12	14.4	61900	209 S	34900		72200	518	101000		41500	63	7060	12
13		61900	208	34700		75400	614	125000		41200 A	56	6230	13
14		62000	202	33800		76700	720	149000		39000 E	53	5580	14
15		60500	197	32200	13.3	77100	831 S	173000		37000 E	52	5190	15
16		58400	188	29600		76500	831	172000		36000 E	47	4570	16
17		55900	184	27800		76900	789	164000		35000 E	40	3780	17
18		53600	179	25900		81300	825	181000	6.1	33100 A	34 S	3040	18
19		52600	162	23000		89000	940	226000		33000	25	2230	19
20		53400	154	22200		99000	974	260000		32300	22	1920	20
21		52700	132	18800		99400	871	234000		31900	25	2150	21
22		51200	123	17000		95900	758	196000		34200	30	2770	22
23		50400	133	18100		92400	661	165000		34400	28	2600	23
24		50900	188	25800		88300	577	138000		33300	26	2340	24
25		52600	268	38100		83800	490 S	111000		31900	26	2240	25
26		55500	367	55000		79100	413	88200		30800	25	2080	26
27		59300	461	73800		74500	353	71000		29900	24	1940	27
28		62900	555	94100		70900	302	57800		29000	20	1570	28
29		65300	640	113000	10.0	67000	250	45200		28500	16	1230	29
30		65900	713	127000		63500	215	36900		28400 E	18	1380	30
31		65600	752	133000		60400	205	33400					31
TOTAL		1883500		1494400		2265400		3485200		1219200		293910	TOTAL
MEAN		60800		48200		73100		112000		40600		9800	MEAN

MACKENZIE RIVER (MIDDLE CHANNEL) ABOVE NAPOIAK CHANNEL - STATION NO. 10MC006

SUSPENDED SEDIMENT FOR 1974

	JUL				AUG				SEP				
DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	DAY
1		677000	793	1450000		605000 E	1910	3120000		590000 E	357	569000	1
2		665000	778	1400000		570000 E	1560	2400000		590000 E	357	569000	2
3		666000	764	1370000		533000 E	1240	1780000		600000 E	400	648000	3
4		666000	750	1350000		536000 E	996	1440000		606000 E	338	553000	4
5		654000	736	1300000		495000 E	887	1190000		606000 A	280	458000	5
6		646000	722	1260000		511000 E	838	1160000		590000 E	250	398000	6
7		646000	708	1230000		543000 E	908	1330000		580000 E	230	360000	7
8		633000	692	1180000	16.1	594000 A	1100 S	1760000		570000 E	211	325000	8
9		642000	673	1170000		720000 E	1520	2950000	7.2	555000 A	192 S	288000	9
10		639000	655	1130000		810000 E	2110	4610000		540000 E	178	260000	10
11	14.4	634000	639 S	1090000		850000 E	2600	5970000		530000 E	177	253000	11
12		626000	647	1090000		850000 E	2260	5190000		520000 E	164	230000	12
13		620000	642	1070000		820000 E	1760	3900000		510000 E	149	205000	13
14		618000	575	959000	13.9	765000 A	1390 S	2870000		500000 E	135	182000	14
15		602000	532	865000		735000 E	1170	2320000		490000 E	121	160000	15
16		583000	383	603000		705000 E	1040	1980000		480000 E	108	140000	16
17		569000	312	479000		700000 E	1040	1970000		470000 E	95	121000	17
18		557000	265	399000		710000 E	1240	2380000		460000 E	84	104000	18
19		558000	249 S	375000		720000 E	1510	2940000	7.8	446000 A	81 S	97500	19
20		567000	220	337000		725000 E	1840	3600000		440000 A	79	93900	20
21		557000	190	286000		720000 E	1800	3500000		430000 E	77	89400	21
22		548000	222	328000		700000 E	1500	2840000		425000 E	76	87200	22
23		552000	290	432000		680000 E	1180	2170000		420000 E	74	83900	23
24		573000	595	920000		650000 E	909	1600000		415000 E	72	80700	24
25		594000	911	1460000		630000 E	725	1230000		415000 E	70	78400	25
26		632000	1360	2320000		615000 E	597	991000		410000 E	68	75300	26
27		663000	1850	3310000		600000 E	515	834000		410000 E	67	74200	27
28		685000	2350	4350000		590000 E	441	703000		405000 E	65	71100	28
29		708000	2780	5310000	11.7	588000 A	387 S	614000		405000 E	63	68900	29
30		689000	2730	5080000		585000 E	376	594000		400000 E	61	65900	30
31	15.6	670000 A	2320 S	4200000		585000 E	367	580000					31
TOTAL		19338000		48103000		20440000		70516000		14808000		6789400	TOTAL
MEAN		624000		1550000		659000		2270000		494000		226000	MEAN

MACKENZIE RIVER (KALINEK CHANNEL) ABOVE ONIAK CHANNEL - STATION NO. 10LC006

SUSPENDED SEDIMENT FOR 1974

	JUL				AUG				SEP				
DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	TEMP. (C)	DAILY DISCHARGE (CFS)	MEAN CON-CENTRATION (MG/L)	TONS PER DAY	DAY
1		27500 E	1050	78000		27400	905	67000		21100	105	5980	1
2		27800 E	1040	78100		26400	733	52200		21300	117	6730	2
3		27400 E	1030	76200		24400	580	38200		22900	165	10200	3
4		27000 E	1030	75100		22700	409	25100		22900	168	10400	4
5		26700 E	1020	73500		21100	278	15800		21000	111	6290	5
6		26200 E	1010	71400		20400	190	10500		19200	75	3890	6
7		26200 E	1000	70700		20900	171	9650		17700	60	2870	7
8		26100 E	995	70100	16.1	22200	219 S	13100		16800	54	2450	8
9		26100 E	985	69400		25700	305	21200	7.2	16000	51 S	2200	9
10		26300 E	975	69200		28700	404	31300		15200	49	2010	10
11	14.4	26900 A	965 S	70100		30800	507	42200		14700	47	1870	11
12		26800	920	66600		32500	608	53400		14400	44	1710	12
13		26500	777	55600		33700	707	64300		13700	44	1630	13
14		26500	570	40800	13.9	34300	741 S	68600		13100	42	1490	14
15		25500	370	25500		33700	611	55600		12600	41	1390	15
16		24300	209	13700		32900	481	42700		11900	39	1250	16
17	15.0	23100	95 S	5930		32300	489	42600		11300	38	1160	17
18		22100	72	4300		33900	712	65200		10900	36	1060	18
19		21600	71	4140		36900	1120	112000		10600	35	1000	19
20		22200	69	4140		40600	1550	170000	8.3	10400	33 S	927	20
21		21600	68	3970		40500	1530	167000		10300	31	862	21
22		20800	72	4040		38200	1100	113000		11100	34	1020	22
23		20400	152	8370		35900	784	76000		11400	29	893	23
24		21300	308	17700		33500	566	51200		10800	24	700	24
25		22600	503	30700		31300	407	34400		9920	21	562	25
26		24600	673	44700		29200	304	24000		9450	21	536	26
27		27000	872	63600		27100	231	16900		9150	20	494	27
28		28700	1110	86000		25700	191	13300		8910	18	433	28
29		30200	1310	107000	12.8	24600	171 S	11400		8790	16	380	29
30		29700	1290	103000		22800	155	9540		10100	18	491	30
31		28600	1110 S	85700		21800	129	7590					31
TOTAL		788400		1577250		912100		1524980		417620		72878	TOTAL
MEAN		25400		50900		29400		49200		13900		2430	MEAN

MACKENZIE RIVER (EAST CHANNEL) AT INUVIK - STATION NO. 10LC002

SUSPENDED SEDIMENT FOR 1974

DAY	APR TEMP. (C)	APR DAILY DISCHARGE (CFS)	APR MEAN CON-CENTRATION (MG/L)	APR TONS PER DAY	MAY TEMP. (C)	MAY DAILY DISCHARGE (CFS)	MAY MEAN CON-CENTRATION (MG/L)	MAY TONS PER DAY	JUN TEMP. (C)	JUN DAILY DISCHARGE (CFS)	JUN MEAN CON-CENTRATION (MG/L)	JUN TONS PER DAY	DAY
1		280 B				340 B				25700	273	18900	1
2		282 B				342 B				25800	242	16900	2
3		284 B				344 B				26400	264	18800	3
4		286 B				468 B				27400	336	24900	4
5		288 B				593 B				29200	457	36000	5
6		290 B				717 B				31400	619	52500	6
7		292 B				841 B				30800	610	50700	7
8		294 B				966 B				28100	449	34100	8
9		296 B				1090 B				25500	329	22700	9
10		298 B				1210 B			3.9	23800	244 S	15700	10
11		300 B				1340 B				22200	212	12700	11
12		302 B				1460 B				20600	201	11200	12
13		304 B				1590 B				19000	200	10300	13
14		306 B				1710 B				17500	201	9500	14
15		308 B				1840 B				16300	201	8850	15
16		310 B				1950 B				15300	208	8590	16
17		312 B				2830 B				14500	218	8530	17
18		314 B				3180 B				13900	226	8480	18
19		316 B				3620 B				13300	243	8730	19
20		318 B				4370 B				12900	267	9300	20
21		320 B				5770 B				12700 A	291	9980	21
22		322 B				8110 B				12800 E	308	10600	22
23		324 B				10700 B				12800 E	336	11600	23
24		326 B				12900 B				12900 E	375	13100	24
25		328 B				15000 B			7.8	12900 E	404 S	14100	25
26		330 B				16500 B				13000 E	395	13900	26
27		332 B				19100 B				12900 E	382	13300	27
28		334 B				21900 B				12900 A	375	13100	28
29		336 B				24400 B				12800	371	12800	29
30		338 B				25200 B				12800	363	12500	30
31						25500 B							31
TOTAL		9270				215881				568100		512360	TOTAL
MEAN		309				6960				18900		17100	MEAN

[illegible]

MACKENZIE RIVER (EAST CHANNEL) AT INUVIK - STATION NO. 10LC002

SUSPENDED SEDIMENT FOR 1974

DAY	JUL TEMP. (C)	JUL DAILY DISCHARGE (CFS)	JUL MEAN CON-CENTRATION (MG/L)	JUL TONS PER DAY	AUG TEMP. (C)	AUG DAILY DISCHARGE (CFS)	AUG MEAN CON-CENTRATION (MG/L)	AUG TONS PER DAY	SEP TEMP. (C)	SEP DAILY DISCHARGE (CFS)	SEP MEAN CON-CENTRATION (MG/L)	SEP TONS PER DAY	DAY
1		13100	351	12400		14100	1540	58600		10500	130	3690	1
2		12900	332	11600		13700	1170	43300		10400	112	3140	2
3		12900	317	11000		13000	899	31600		10800	134	3910	3
4		12800	307	10600		12300	715	23700		10800	144	4200	4
5		12600	293	9970		11600	563	17600		10200	121	3330	5
6		12300	277	9200		11300	450	13700		9540	112	2880	6
7		12300	262	8700		11200	415	12500		8940	102	2460	7
8		12100	255	8330		11600	473	14800		8440	88	2010	8
9		12300	245	8140	15.0	12800	633 S	21900		8040	85	1850	9
10		12300	238	7900		13900	845	31700	6.7	7690	64 S	1330	10
11		12100	228	7450		14800	1060	42400		7380	56	1120	11
12		12000	214	6930	13.9	15800	1350 S	57600		7160	54	1040	12
13		12000	204	6610		16300	1410	62100		6890	50	930	13
14		12100	191	6240	13.9	16500	1130 S	50300		6560	48	850	14
15		11800	173	5510		16300	956	42100		6260	47	794	15
16		11200	159	4810		16000	892 S	38500	5.6	5950	44 S	707	16
17		11000	142	4220		15700	795	33700		5670	39	597	17
18		10600	123	3520		15900	723	31000		5390	38	553	18
19		10500	112 S	3180		17100	852	39300		5210	37	520	19
20		10700	108	3120		18400	1120	55600		4990	36	485	20
21		10600	104	2980		18500	1050	52400		4870	38	500	21
22		10400	107	3000	10.0	17800	791 S	38000		5090	40	550	22
23		10400	85	2390		17000	646	29700		5120	38	525	23
24		10700	85	2460		16000	537	23200		4890	26	343	24
25		11300	122	3720		15100	467	19000		4570	34	420	25
26	16.1	12100	209 S	6830		14200	410	15700		4380	36	426	26
27	16.1	13200	540 S	19200		13300	337	12100		4200	35	397	27
28	15.6	14000	871	32900		12600	267	9080		4090	33	364	28
29	16.7	14800	1110	44400	11.1	12000	222 S	7190		3980	29	312	29
30	16.7	15000	1500 S	60800		11300	178	5430		4340	24	281	30
31	15.6	14700	1960 S	77800		10800	151	4400					31
TOTAL		376800		405110		446900		938200		202340		40514	TOTAL
MEAN		12200		13100		14400		30300		6740		1350	MEAN

CHANNEL STABILITY IN THE MACKENZIE DELTA, NORTHWEST TERRITORIES: A REVIEW

by

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under contract
KE521-1-0085/01-XSG
Supply & Services Canada, Edmonton

November, 1991

Acknowledgments

This report was prepared as one part of Contract KE521-1-0085/01-XSG, administered by Supply and Services Canada with F. M. Conly of Inland Waters Directorate, Yellowknife, NWT as Scientific Authority. The assistance provided by Malcolm Conly and Jesse Jasper in the administration of this contract is duly acknowledged. John Kerr, IWD Yellowknife, also provided comments on the report, and Moe Hansen, WRB Inuvik, supplied supplementary information.

Cal Sikstrom, Evan Birchard and Mike Deyell of Esso Resources Canada, Calgary were extremely helpful in providing information in regard to likely pipeline crossings in the outer delta. Ross Goodwin is also thanked for provision of the catalogue of Canadian Arctic Gas Study Limited publications held by the Arctic Institute at the University of Calgary.

Scott Dallimore, Terrain Sciences Division, Geological Survey of Canada, provided valuable information regarding the work of TSD on channel stability and alluvial sediments in the outer delta, though much of this information is still preliminary.

Dan Dobson of the Canadian Hydrographic Service in Sidney, B.C., provided information on the dates of bathymetric surveys in the delta. Mr A.R. Mortimer of CHS, Sidney, was consulted regarding future bathymetric surveys in the area.

C.R. Neill of Northwest Hydraulics Consultants Limited (Edmonton) is thanked for provision of information on the Swimming Point area of East Channel.

Peter Lewis, Mike Miles and Ted Yuzyk are thanked for the loan of various reports dealing with the delta.

Executive Summary

1. The report provides a review of literature dealing with channel stability in the Mackenzie Delta, Northwest Territories, to assist Inland Waters Directorate, Yellowknife in designing monitoring programs in the context of hydrocarbon development and transport in the outer delta.

2. Chapter 2 provides a summary of this literature in chronological order beginning with Mackay's (1963) overview of the delta and ending with the long report on deltaic sedimentation by Lewis (1988). Most of these reports deal with the entire delta and provide only limited information in the context of the outer delta. References are made to many proprietary reports describing specific sites in the outer delta as part of work done for oil, gas and pipeline companies in the 1970s. Most of these reports have not been examined, but abstracts of many of them are provided in Appendix I.

3. Chapter 3 deals specifically with the outer delta region with emphasis on areas of potential pipeline crossings. The chapter begins with a summary of the most current scenario of hydrocarbon development. This is followed by observations on channel stability in the region derived from other reports and from inspection of bathymetric charts and aerial photographs. The chapter provides a general discussion of the morphology of the main outer delta channels, followed by specific observations in areas of potential pipeline crossings, viz. Niglintgak Island, the Taglu area and East Channel.

4. Chapter 4 provides a summary of channel stability issues, with special reference to the outer delta, dealing in turn with the following topics: stability of the channel bed; stability of channel banks; stability of the permafrost table; and stability of the drainage network.

1. CHANNEL STABILITY IN THE MACKENZIE DELTA: INTRODUCTION

1.1 Terms of reference

This report was commissioned as part of the NOGAP-funded program of Inland Waters Directorate, Yellowknife, NWT under the project heading C.11 Sediment-related aspects of northern hydrocarbon development. The report is part of subproject C11-6 entitled Mackenzie Delta channel stability.

The description of that program reads:

> "A sequential descriptive and predictive approach will be used to investigate delta channel stability. Existing delta bathymetric and bank erosion data and studies will be examined in 1991/92 to assess historical channel stability near likely pipeline channel crossings. Intensive hydraulic and morphologic characterizations will be carried out in 1992/93 and 1993/94 at highest priority sites."

Recommendations regarding appropriate sites for these hydraulic and morphologic studies are not made here, but are deferred to a separate report (Carson, 1991). The present report deals simply with the examination of channel stability data, as a background to the hydraulic and morphologic fieldwork.

The contract terms of reference require the contractor to:

- review existing bathymetric and bank erosion data and studies;
- identify and analyze the current stability of the major channels of the Mackenzie Delta with linkages to past studies;
- assess channel stability near likely pipeline crossings

The first two of these requirements is undertaken in Chapter 2 which provides an overall assessment of channel stability in the Mackenzie Delta. The third requirement is undertaken in Chapter 3.

1.2 Channel stability issues in the Delta

There are three main channel stability issues in the context of pipeline crossings of river channels in the Mackenzie Delta:

- the possibility that scour of the channel bed may undermine pipelines if they are not buried deeply enough;

- the possibility that erosion of the channel bank may expose and undermine pipelines where they come ashore;

- the possibility that frost heave or thaw settlement may occur beneath the pipeline.

The last of these is likely to be a problem throughout the Delta, but it is a particular concern in the vicinity of channel crossings where permafrost is discontinuous and where the regime is generally unstable. In some places permafrost is building up (aggrading) leading to heave, while in other areas it is decaying (degrading) leading to settlement. This problem is, in addition, related to other aspects of channel of stability: buildup of channel sediment, for example, may induce permafrost aggradation through thinning (and disappearance) of the non-frozen winter cover of flowing water.

The second of these issues - bank erosion - is not peculiar to northern channels, but does involve certain distinctive features associated with thaw of ice-rich permafrost sediments. In addition, the floodplain sediments of the delta appear, in some places, to be susceptible to massive instability in a short period, e.g. Wedel (1990, p. 13) reports "rapid erosion of approximately 80 m of river bank (and about 40 m into the bank: Hansen, 1992, pers. comm.) on the western border of Langley Island in the space of three weeks in August 1986 at the site of one of WSC's lower boundary water level stations (10MC010). The triggering process is not understood. The site had been stable for many years prior to the event."

The first topic - channel bed scour - is also not restricted to northern channels, but, again, takes on a different perspective in these regions. Little is known about channel bed scour during rising flows under ice-covered conditions. High channel velocities have been reported in association with ice jam releases on the Mackenzie River just upstream of the delta (Petryk, 1985) and may be capable of local scour in excess of that expected under normal open water conditions. Observations of unusual "scour holes" in the channels of the Mackenzie Delta (Lapointe, 1984, 1985) also raise the question as to whether engineering procedures of estimating bed scour in mid-latitude regions are sufficient in northern areas.

These, therefore, are some of the concerns with regard to channel stability in the Mackenzie Delta, and provide the context for the review and analysis in the next chapters.

1.3 Summary of available information

- **Reports**

Henoch (1961) provided information on channel bank undercutting in the upper part of the delta (Peel Channel). The earliest comprehensive description and interpretation of the Mackenzie Delta channel system as a whole appears to be that by Mackay (1963). Subsequently, interest in channel behaviour in the delta was spurred by the need to locate safe channel crossings for potential pipelines: this led to several reports by consulting firms working for oil and gas development companies (Blench and Associates, 1975; Cooper and Hollingshead, 1973; NESCL, 1976; Hollingshead and Rundquist, 1977). Church (1971, 1977, 1981) has also provided commentary on the geomorphology of northern channels, including some reference to the Mackenzie Delta. The likelihood of oil and gas development in the delta also led to investigations by Environment Canada personnel, initially in the 1970s (Outhet, 1974), and more extensively in the 1980s with the work of Lapointe (1984, 1985, 1986a,b) at the National Hydrology Research Institute. The most recent and most comprehensive review of sedimentation and channel processes in the Mackenzie Delta is provided in the long report by Lewis (1988): this includes sedimentation at the delta front (Chapter 4) and the behaviour of delta channels (Chapter 5). The major findings of these various reports are presented in the next chapter.

Investigations into delta sediments and erosional processes in the delta, funded through NOGAP, have also been undertaken recently by the Geological Survey of Canada. Forbes (1991) has summarized the work of the Atlantic Geoscience Centre as follows:

> "The GSC NOGAP program was initiated in 1984 and has included extensive work on coastal erosion rates and processes, nearshore wave climate, littoral and shoreface sediment transport processes, shallow stratigraphy, geotechnical and geothermal conditions, and a study of sedimentation processes at the Mackenzie Delta front in the Olivier Islands area.
>
> The focus of activity since reactivation of NOGAP funding in 1990 has been on coastal dynamics and geotechnical conditions in the northeast Richards Island area. Some work has also been carried out in the outer Mackenzie Delta and in the Tuktoyaktuk area."

Additional NOGAP-funded work by GSC, undertaken by the Terrain Sciences Division, is perhaps more directly relevant to IWD's channel stability program. This work involves survey of geology and ground ice conditions of river channels in the vicinity of proposed pipeline routes in the outer delta (Dallimore, 1991, pers. comm.) and is reviewed in Chapter 3.

Bathymetric surveys

Bathymetric surveys of the major channels of the delta, at 1:50,000, have been undertaken by the Canadian Hydrographic Service at different times during the 1960s and 1970s. Ideally, in areas where repeat surveys have been undertaken, it should be possible to use the information to document changes in bed elevations and bank positions in that time period. This method has been used on the Mackenzie River mainstem, upstream of Arctic Red River, for example, to assess volumetric rates of bed material transport (Church et al., 1986; Carson, 1988). In the case of the delta, however, few of the chart areas have been surveyed more than once. The location of delta bathymetric chart areas is shown in Fig. 1.1. The dates for each survey are given below:

Chart	6441	1977/78
	6437	
	6436	1972/77
	6435	1972/73
	6434	1977
	6433	1974/77/78
	6432	
	6431	1976
	6430	1975
	6429	1975
	6428	1974/79
	6427	1974/78/79

No survey dates have been found for charts 6432 and 6437. Dobson (1991, pers. comm.) believes that these charts are based on 1960s surveys, with spot soundings only, rather than proper bathymetric profiles. Those charts with multiple surveys indicated do not usually represent repeat surveys of the same areas: in the case of 6433, for example, the 1978 survey refers to the main West Channel, while the 1974 survey refers to other distributary channels, with no overlap on the 1978 survey.

The only chart with repeat survey of a large area appears to be 6427, with both the 1974 and 1979 surveys being quite comprehensive. Unfortunately, Chart 6427 is not especially relevant from the perspective of the present report, because it refers to the stretch of Middle Channel directly downstream of Point Separation. Discussions with Canadian Hydrographic Service (Mortimer, 1991, pers. comm.) indicate that there are no plans for resurvey of any of these charts in the next year or two, a reflection of the high cost and limited funding, rather than the need to undertake such resurveys. According to Mortimer, the only resurveys taking place at the present time are those by Department of Public Works in Edmonton in relation to dredging programs.

- **Dredging data**

The usefulness of morphologic and sediment transport data for the delta to the Canadian Hydrographic Service and Canadian Coast Guard was noted by Wedel (1990, p. 9). In turn, dredging data (and information from resurveying of dredged areas) might be useful in assessing bed material transport rates in the main delta channels. Public Works Canada has been contacted in this regard, but to date no response has been received.

2. SUMMARY OF PREVIOUS WORK

The present chapter provides a summary of earlier reports, in chronologic order, dealing with channel stability in the Mackenzie Delta.

Mackay (1963)

Only part of Mackay's report (p.100-130) deals with the Mackenzie Delta channel system, and though much of it is quantitative, the discussion does not deal with channel processes in a detail physical manner. There are, nonetheless, several interesting points that are highlighted.

- Most channels in the delta were noted as not meandering back and forth, but wandering (p. 127). "The migrating cut-and-fill river meanders with oxbow lakes and narrow necks are not typical of the delta channels." The upper part of Aklavik Channel and the central part of Middle Channel were seen as exceptions.

Though Mackay provided no mechanistic interpretation of this observation, it is possible that the absence of cutoffs throughout the delta may be related to changing flow dynamics. In many anastomosing channel networks like the delta, it is typical for most flow to be concentrated in one channel, with occasional avulsions diverting the flow to a new channel, leaving the former channel as a misfit (Smith et al., 1989). These misfits can usually be recognized by large meander wavelengths relative to channel width. In normal meandering channels, this ratio is of the order of 7 to 11 (Leopold et al., 1964, p. 297); in the Mackenzie Delta it is generally greater than 11 (Mackay, 1963, p. 109); on East Channel near Inuvik, it is about 17 based on Chart 6432. Other explanations for the non-meandering "twisting" style of the distributaries nearer to the delta front are discussed by Lewis (1988).

- There has been no extensive channel shifting during the past several hundred years. This comment is made for the delta as a whole and is based on aerial photograph analysis and the distribution of spruce trees. Fig. 2.1 is a map of principal channel shifts. It is significant that the outer delta is marked as an area of "much channel shifting" - in contrast to the middle and upper delta where the channels are more deeply incised in the delta plain. It is not clear whether Mackay uses the term channel shifting to denote switching of flow from one channel to another (avulsion) or simply lateral migration of a channel, or both.

Cooper and Hollingshead (1973)

This article examines (albeit briefly) channel stability at four specific sites in the permafrost area of northwest Canada: the Liard River near Watson Lake; Eagle River at Eagle Crossing; Porcupine River at Old Crow; and East Channel near Swimming Point. The authors concluded that:

- bank erosion appears to be dependent on the thermal regime within the river banks;
- the presence of permafrost at shallow depths within a bank tends to stabilize material that in an unfrozen condition would be inherently unstable;
- the thawed active layer is easily erodible (and often unstable geotechnically): "this results in a rate of annual erosion that is relatively constant from year to year";
- the thickness of the active layer (and hence rate of bank erosion) is strongly influenced by the vegetation cover on the bank and on the adjacent floodplain.

The comments on East Channel at Swimming Point are particularly relevant here. They note (Fig. 2.2) that there is a deep sub-channel (the banks of which are fine sand and silt) meandering within the main river channel, separated from the main river bank by a platform no deeper than 5 metres. They comment:

> "Because of the erodibility of the bank material in the sub-channel, and because of the configuration of this channel, it is difficult to understand why the channel has not migrated laterally to a point where erosion would be arrested because of the high main channel bank. One possible explanation is that the sub-channel has shallow permafrost which significantly increases its resistance to erosion." However, the surveyed cross-section in Fig. 2.2 shows the submerged boundary material to be unfrozen, though the degree of detail in the surveying of the permafrost table is not known.

NESCL, 1976

This report provides cross-sections (and one summer high flow discharge measurement) at three sites along the former "Cross-Delta" CAGSL (Canadian Arctic Gas Study Limited) pipeline route (Fig. 2.3): in North Reindeer Channel downstream of the western arm into Shallow Bay; in Middle Channel in the Langley Island reach that contains the present WSC sediment measurement section 10MC901; and in East Channel downstream of Tununuk Point, again in the reach used by WSC.

The last two sets of cross-sections and bathymetric maps would be useful to Inland Waters Directorate in connection with hydraulic and morphologic changes in the reaches containing the hydrometric sections. They are less relevant in the context of potential pipeline crossings, however, given the abandonment of the old Cross-Delta route as a probable transmission line.

Hollingshead and Rundquist 1977

This article reports the results of several years of fieldwork in the outer Mackenzie Delta (Fig. 2.3) sponsored by Canadian Arctic Gas Study Limited. The authors note the following points:

- boreholes in Shallow Bay and nearby channels along the proposed CASGL pipeline route (Fig. 2.4) show the sediments to be predominantly silt, have comparatively high dry densities in the range 1.44-1.59 gm/cm3, and that the strata near bed level are highly overconsolidated: "These results indicate that, unlike other major deltas, Shallow Bay sediments form an overconsolidated crust which extends for a significant depth." This overconsolidation was attributed to one or more previous cycles of freezing: "Upon freezing, the pore water may be redistributed locally resulting in ice lens growth at some points and consolidation of the soil strata elsewhere. If some of this pore water is lost upon thawing, the net result will be an overconsolidated deposit."

- the morphology of channels in the outer delta departs from normal fluvial character in:

  (1) the large depth of some of the smaller channels (e.g. Fig. 2.5 in the vicinity of the WSC sediment station 10MC901; no explanation was offered;

  (2) the existence of unusually steep side slopes (Fig. 2.6); this steepness was attributed to the overconsolidated character of the sediment;

  (3) the occurrence of submerged benches at some cross-sections (Fig. 2.7); the location of such benches away from zones of obvious fluvial erosion (e.g. on the inner bend at Swimming Point) led the authors to attribute them to wave erosion;

  (4) the presence of deep holes in the channel bed at sites where (unlike bend and confluence locations) their existence would not be expected; no general mechanism was put forward for these scour holes;

- outer delta channels shift, meander, create cutoffs, and abandon distributaries as do channels in many deltas, with shifting at rapid rates in some locations; most of this bank erosion does not occur during spring flood and ice breakup, but during summer, when water levels are lower; this was attributed to the fact that banks are still frozen during breakup;

- erosional processes in delta channels were listed as :

  ice erosion, viewed as insignificant because of the protection afforded against ice scour by both near-bank shore ice and ice pans, and by the frozen bank sediment, as well as the tendency of river ice to breakup by candling;

  thermal erosion, thought to be a contributing factor in the outer delta, though no deep thermal niches had been noted in the field;

  wave erosion, especially in Shallow Bay, but "several of the major channels in the outer delta are either wide enough or oriented so that wave action is a significant factor in the erosion of their banks";

  fluvial erosion, viewed as supplementary to thermal and wave erosion, but not very effective on its own, because the currents in the outer delta are generally not sufficient to scour the banks, although capable of transporting bank material which has been previously loosened by thermal or wave action; it was noted that the mean channel gradient through the delta is only 2.5 x 10-5.

Some indication of the relatively low mean velocities in these outer delta channels is provided by the hydrometric surveys of NESCL (1976):

North Reindeer Ch.	1975.08.05	3370 m3/s	V = 52 cm/s
Langley Island Ch.	1975.08.13	4450 m3/s	V = 59 cm/s
East Channel	1975.08.10	3030 m3/s	V = 53 cm/s

compared to Middle Channel:
upstream of Neklek 1975.08.14 14780 m3/s V = 81 cm/s.

Though this comparison may have been affected by storm surge development, the data are consistent with those collected this summer by Water Survey of Canada:

Reindeer Ch.	1991.06.20	6700 m3/s	V = 88 cm/s
Langley Island Ch	1991.06.13	5350 m3/s	V = 65 cm/s
East Channel	1991.06.13	3950 m3/s	V = 79 cm/s

compared to Mackenzie River
at Arctic Red River 1991.06.04 17600 m3/s V = 156 cm/s.

- ice thickness in delta channels averages 1.5 to 1.8 metres: thus many of the smaller distributaries freeze to the bed each year.

Church (1971, 1977, 1981)

These three reports by Church do not deal directly with Mackenzie Delta channels, but do provide useful commentary on channel behaviour generally in northern areas. The first is an unpublished report dealing with the rivers in northern Alaska and Yukon prepared for Mackenzie Valley Pipeline Research Ltd. in connection with the proposed Prudhoe Bay - Edmonton pipeline. The second is a short review paper on northern rivers for Geoscience Canada dealing with the use of channel morphology in northern rivers as a guide to channel behaviour. The third deals with possible impacts of damming of the Liard for hydro-electricity generation on the sedimentation of the Mackenzie River. Among the points noted by Church which are relevant here are the following:

- Major erosional activity along the main channels in Mackenzie Delta is associated with the breakup flood. Cut banks which are under attack continue to be eroded through the summer, a major erosional mechanism being thermoerosional niche development followed by block slumping. The emphasis placed on breakup contradicts the opinions of Hollingshead and Rundquist noted earlier.

- The near-surface stratigraphy of the delta floodplain, into which the channels are cut, includes frequent peat beds. These are extremely tough and resistant to water erosion: they will promote stability wherever they outcrop in a channel.

Lapointe (1984, 1985, 1986a)

The work by Lapointe at NHRI in the mid-1980s provides the first comprehensive physical examination of channel behaviour in the Mackenzie Delta. It is reviewed here in some detail.

The 1984 report provides an overview of the fluvial geomorphology of the delta, based primarily on field observations (and detailed bathymetric surveys) in 1983 in the eastern middle Delta, along East Channel between Point Separation and Inuvik, and along Napoiak Channel to Shallow Bay. Subsequent reports provided more detailed investigations into two of the issues identified: a synoptic map of channel migration rates in the delta; and the origin of deep "scour holes". The main conclusions reached in these studies were as follows.

- **Bed material contrasts between Middle Channel and its distributaries.**

Exploratory bed material sampling indicated medium to coarse sands (and even gravel) just downstream of Point Separation, with medium and fine sands along most of Middle Channel as far as Oniak Channel. In contrast, mid-summer sampling along most smaller delta channels indicated a predominance of silt-slurry bed material, with variable (but usually minor) admixtures of fine sand. Larger accumulations of sand were found in the upstream part of East Channel, and near the entrance to Napoiak Channel. The limited extent of sand in the distributaries off Middle Channel (and its restriction to the upper reach of the channel) appears to result from the fact that entrances to these distributaries are perched high above the thalweg of Middle Channel, separated from it by an abrupt wall.

Lapointe believed that this channel-entrance sand (which spills over these thresholds in the high flows of spring) is eventually swept down the distributaries during the summer. He noted, in support of this view, that sand appears to occur in slower parts of the bed of Napoiak Channel further downstream from the channel entrance, and begins to dominate the full channel bed as it approaches Shallow Bay.

■ Channel bathymetry: inner channels and side platforms

Inspection of existing bathymetric maps, together with new surveys, indicated the widespread existence of "inner channels" that are separated from the true channel banks by submerged platforms. This observation is consistent with the unusually high channel width, at bankfull stage, compared to mean channel depth. Width-depth ratios generally range between 10 and 90, which are appreciably higher than those normally found in cohesive alluvium (Lapointe, 1984).

■ Channel bathymetry: deep "scour holes"

Reconnaissance bathymetric surveys of sandy mud-bedded distributary channels in 1983 also indicated chaotic "hole and mound" zones, especially but not exclusively, in channel bend areas. The existence of these deep "scour holes" is potentially very significant in the context of pipeline crossings to the extent that they may indicate unusual, present-day, bed scour processes that could undermine pipelines once installed.

Detailed bathymetric surveys were undertaken in the following years (Lapointe, 1985, 1986a) in reaches of Kalinek Channel, East Channel near Inuvik (and some small distributaries), and Napoiak Channel. Lapointe defines these scour holes as "localized areas where a channel's depth is significantly greater than the average for the thalweg". Depths can be appreciable: on a small (90 m wide) distributary of East Channel, a depth of 16 m occurs in a hole near a bend apex; a similar depth occurs in a hole in the wider Napoiak Channel (Fig. 2.8) but in a straight channel reach rather than at a bend location (Lapointe, 1985).

Though insufficient bathymetric data currently exist (especially for smaller distributaries) to map the distribution of these channel bed scour holes through the whole delta, some inference can be drawn from channel morphology as indicated by aerial photographs. Lapointe (1986a, p. 6) notes that most deep scour holes impinge on one (or both) channel banks to produce an embayment (scour bay) in the bank. The distribution of these scour bays (as indicated by 1:20,000 to 1:50,000 air photography) is given in Fig. 2.9.

At the synoptic scale, scour bays are particularly uncommon in the Outer Delta (north of the south end of Shallow Bay as far as latitude 69°N, the limit of the study), and are most abundant south of the Aklavik-Inuvik line. No hypothesis was advanced for this distribution, and the question of whether the rarity of scour bays applies to the unmapped part of the Outer Delta (where oil and gas development is proposed) was not addressed.

No mechanism for these holes was established. It seems probable that the holes are some form of thermokarst that has not infilled with bed sediment, but Lapointe (1986a, p. 16) expresses reservations about this view. Many of the holes occur in tight bends, but there are many tight bends which lack them, and such holes are also found in straight reaches. Nonetheless, Lapointe (1986a, p. 17-28) emphasizes the preferential location of such holes in bend locations, and directed much effort to examining the relationship between bathymetry, sediment texture and flow in such bends on small distributaries. The main conclusion appears to be that bed load movement down these side channels is extremely limited; thus the thalweg is swept clear of mobile bed sands (which are found primarily in lateral shoals downstream of bends) and is underlain by clayey (20-30%) silt, probably older delta plain deposits rather than current alluvium.

The limited movement of bed load along these side channels might thus account for the failure of scour holes to infill, though it does not explain the origin of the holes. The observation is nonetheless consistent with the apparent absence of deep scour holes along the larger channels of the delta, where bed load movement is much greater.

Apart from scour hole genesis, a key question in the context of pipeline crossings (assuming that scour holes are found in the Outer Delta) is their stability: Are the holes capable of moving within, or as part of, the channel pattern? In an attempt to answer this question, Lapointe (1986a, p. 29) established a series of transects across a deep hole in East Channel (15 km upstream of Inuvik), with bench marks for later surveying. The bathymetry of the channel is given in Lapointe's (1986) Fig. 2, and the sections in his Fig. 18. It would be instructive to resurvey these sections, especially in view of the large sediment flows that occurred in 1988.

The peculiar geometry of the holes (and ridge-mounds: Fig. 2.8) suggest that inhomogeneity in bed materials plays an important role. Lapointe (1985, p.7) notes one streamlined hole in which a 7 m high side slope exists with a 50° dip, suggestive of material with much greater strength than that of the loose mud commonly sampled on distributary beds. The delta is likely to contain appreciable spatial variability in sediment texture, degree of consolidation and ice-contents, all of which might affect scour hole genesis. Acquisition of such data (down to depths of 20 m or more below the delta plain) was beyond the resources of Lapointe's investigation, and little information exists from other studies, except from current work by the Geological Survey of Canada in the Outer Delta (Chapter 3).

- **Channel planform style**

The channels of the delta have quite contrasting planform styles: while much of Middle Channel and parts of Peel and Aklavik channels show typical meandering traces, most smaller channels are quite irregular in their twisting patterns (Fig. 2.10), as noted by Mackay (1963). Lapointe (1984, p.44) suggests that, in some cases, these small irregular channels may reflect the processes involved in their formation (as prograding reverse delta channels into floodplain lakes) with little subsequent modification. (Lewis (1988) makes the same point.) The persistence of the irregular channel trace, long after the disappearance of the lake into which the channel extended, would imply that bank erosion produces little shifting, once the channel has been created. The last conclusion appears to be supported by Lapointe's study of migration rates in the delta, discussed next.

- **Channel shifting rates**

Extensive 30-year air photo comparisons (1950-1981) of the upper and middle delta indicate rapid shifting along Middle Channel, but relatively subdued bank scour along most other delta channels. This suggests that flow intensity, rather than hydrothermal erosion and ice-run erosion, is the main control on bank erosion rates. Estimates of bed shear stresses (based on velocity profiles) in the two-week period following breakup in 1983 were typically about 10 Pa in Middle Channel, approximately an order of magnitude greater than bed stresses in the deeper parts of smaller channels; these tend to confirm the importance of fluvial erosion in Middle Channel. Little is known about the critical stresses needed to erode channel banks in the Mackenzie Delta, but based on grain size (Grissinger et al., 1981), once thawed, they may well be less than 1 Pa.

Maximum migration rates on tight channel bends in the southern delta tend to increase with channel width, averaging about 1.3% of channel width per year. Lapointe noted that there appears to be a regional pattern to these rates: small channels (< 400 m width) shift at about 1.3% per year in the southern delta, decreasing to 0.5% in the middle delta; larger channels average 1.3% in the middle delta, about 0.5% on Reindeer Channel and about 0.1% on the lower reaches of West Channel. There appears to be a trend to lower shifting rates moving down-delta, which would agree with the assumed decrease in channel gradient.

Lapointe noted that deep thermoniching was common in rapidly eroding banks along the upper part of Middle Channel, but very rare on smaller channels in the eastern part of the delta. Though this might be taken to support the view that the existence of massive ice and thermoniching leads to higher rates of bank retreat, Lapointe favoured the reverse argument: that segregated ice exists in the banks of smaller streams also, but is simply not exposed because normal bank scour on these channels is insufficient to remove the active layer covering (about a metre) on the bank.

It is acknowledged that thermoniching in ice-rich sediments is likely to produce more rapid bank retreat rates (for a given current strength) than in ice-poor sediments, but Lapointe pointed out that this is likely to be restricted only to the niche level (and above). The main, permanently submerged, part of channel banks is likely to be much less susceptible to hydrothermal erosion because of the rapid decrease in segregated ice contents that is assumed to occur in the first ten metres below the delta plain surface. In this case, hydrothermal erosion would be likely to produce rapid banktop retreat creating a submerged platform between an inner channel and the main bank, as indeed is commonly found in the delta. No profiles of ice contents in the vicinity of channel banks were provided in an attempt to assess the hypothesis.

- **Channel abandonment**

Sediment accumulation at distributary entrances seems to provide a mechanism leading to the eventual abandonment of side channels. Lapointe (1984, p. 47) noted this, not so much in terms of settling of sand from suspension on top of the threshold (as described in the previous point), but in terms of building up of shoals adjacent to the threshold. He notes this in the case of both East Channel and at Raymond Channel. The point here is that, while channel diversions tend to occur at the outer bank of bends (these sites being swept clean of bed material by the deflection of near-bed currents, and sediment, to the inner shore), downstream migration of the meander pattern can shift a point bar accumulation towards the diversion entrance some years later. This is certainly happening at the mouth of Raymond Channel.

Lapointe (1986b)

This brief report by Lapointe (1986b) provides miscellaneous data on Mackenzie Delta channels collected during 1984-86. It comprises:

- an updated map of channel shifting rates in that part of the delta between Point Separation and Reindeer Channel, one that is more complete than the previous version in the 1984 report;

- a similar, but new, map of channel shifting for the Outer Delta north of 69° N, one that should be much more useful in the context of hydrocarbon extraction and transport; the map is discussed in Chapter 3;

- additional data (August 1984) on bed material texture along a 130 km reach of East Channel, from the branching of Kalinek Channel to slightly downstream of Reindeer Depot; the data are given individually for three (usually) samples across the channel at each site; they confirm the general trend to decreased sand percentages downstream;

- four floodplain surveys in the upper and middle delta done to contrast floodplain levels on opposite sides of a meander bend, in an attempt to gain information on whether aggradation or degradation appeared to be occurring.

Lewis (1988)

Several chapters in this report are directly relevant in the present context. Stability of present delta channels is discussed in Chapter 5. Present day sedimentation processes at the delta front are discussed in Chapter 4. The latter are relevant, not only in understanding present-day delta front morphology (islands and estuaries), but also in the interpretation of the delta plain landward of the delta front. This is because, at some time in the recent past, the outer delta plain was also "delta front" and was thus being formed by processes similar to those taking place at the delta front at the present. The main observations put forward by Lewis in these chapters were:

- The Mackenzie Delta conforms in many respects to the classic anastomosing alluvial plain, in which low energy gradients, together with fine-textured, erosion-resistant banks result in low rates of lateral migration. Sedimentation tends to be dominated by vertical accumulation rather than lateral accretion.

- The degree of lateral stability of the delta channels is somewhat unusual, and cannot be attributed simply to the low stream energy and cohesive banks. Frozen ground conditions are regarded as important in this context: at precisely that time when erosive forces are greatest in channels (during May and June), active layer thawing of cut-banks has only just begun, and relatively little material is available for easy removal.

- The channel network of the delta is also stable with little switching of flows from one channel to another. This is attributed to the meagre bed load moved down the side channels (which in other situations would lead to a channel perched above the plain) and to the resistance of the channel levees to breakthrough (crevassing) arising from the cohesive makeup and frozen condition at the time of high spring flows.

- The pronounced lateral stability of the channels (except Middle Channel) means that, in many cases, there has been relatively little modification of channel morphology from the initial planform geometry developed at the time the channels were created by extension seawards at the delta front. It is for this reason that many of the channels (especially away from the older, upper delta) have an irregularly sinuous or twisting pattern rather than a true meandering pattern.

- The front of the Mackenzie Delta lacks the "bird's foot" plan and the rapid progradation of other river-dominated deltas such as that of the Mississippi River. This is partly because of the lack of density stratification in the estuarine channels, arising from the absence of salt-wedge penetration. In non-stratified channels, outflow deceleration tends to involve much more lateral expansion, producing funnel-shaped mouths, shallow depths and accumulation of sediment in front of mouths as "middle ground bars" (Fig. 2.11). These bars lead to bifurcation of the extending channels, though in many cases one of the arms will silt up, leading to an irregularly twisting single channel.

- Though the plan geometry of the Mackenzie Delta front does show some resemblance to Fig. 2.11, its features are usually much less well-defined, and the shoreline is more comparable with the sketch in Fig. 2.12: levees are only weakly developed, if at all, and tend to be replaced by side island-bars, usually occurring in groups. These differences are attributed to: (a) the limited supply of sand available to settle out in levees - the dominantly silt load diffusing over a broader area to form low mounds; (b) the presence of bottomfast ice on the 0-to-2 m offshore platform during spring breakup which acts to encourage by-passing of the delta front by sand during the one period of time in which it might be supplied by the high flows; (c) the accentuation of this pattern of broad islands with the more rapid aggradation of permafrost in subaerial tracts of sediment.

- The same factors which contribute to the morphology of the delta front also act to retard progradation of the front: (a) the dominantly silt load is able to disperse far from the front; (b) sediment by-passing of the ice-bound frontal zone occurs during spring; and (c) storm surges in late summer and autumn act to remove sediment from the delta front zone. Numerical modelling indicates that these surge effects would be greatest in Shallow Bay and at the mouth of East Channel, areas which (because of their enclosed setting) might otherwise be expected to show the most rapid rates of progradation.

Endnote

Some of these observations are likely to be repeated in the discussion, in the next chapter, of specific areas of the delta earmarked for hydrocarbon development. An attempt will be made to synthesize the various points in the final chapter.

3. CHANNEL STABILITY IN AREAS OF POTENTIAL PIPELINE CROSSINGS

This chapter begins with a brief review of probable hydrocarbon development in the outer delta in the next two decades and the likely routes of transmission of petroleum products across the delta. The two subsequent sections then provide an overview of channel shifting and river morphology in the outer delta. The last three sections provide specific information on channel stability in the three main areas of likely pipeline crossings: Kumak Channel (Niglintgak Island); Kuluarpak and Harry Channels (Taglu) and East Channel.

3.1 Hydrocarbon development in the Outer Delta

The most recent statement regarding possible hydrocarbon development in the Mackenzie Delta appears to be Chapter 2 of the 1990-1991 Final Report of the Beaufort Region Environmental Assessment and Monitoring Project (BREAM). This report notes the following points:

- Immediate development of both natural gas and oil is seen as unfeasible because of low prices in the case of both gas and oil, and insufficiency of known reserves in the case of oil; both demand and prices for gas are likely to increase in the late 1990s.

- The three principal delta gas reserve owners - Shell (Niglintgak), Esso (Taglu) and Gulf (Parsons Lake) - received conditional approval from the National Energy Board in 1989 for the right to export natural gas from the delta.

- The likely scenario for the first phase of gas development would be the construction of a gas processing plant at Taglu and at Parsons Lake (Fig. 3.1). This map shows a gas plant at Niglintgak, but it now seems more likely that raw gas would be piped from that site to the plant at Taglu. An alternative scenario involves a single gas plant at Swimming Point, but this would not substantially change the geography of the pipeline network.

- Development of oil reserves is likely to involve initial production from the major oil discovery at Amauligak (Fig. 3.2), with a pipeline coming ashore at North Point and crossing East Channel at Swimming Point. (However, such development requires additional large proven oil reserves before production is regarded as economically feasible; such discoveries, if they are made, may require reconsideration of the processing network.)

In the light of these observations, it would seem appropriate to direct most attention in terms of channel stability to three geographic areas: around Niglintgak Island, around Taglu, and on East Channel. Deyell (1991, pers. comm.) has provided maps of possible pipeline routes and channel crossings for these three areas, and they are examined later in the separate discussions of the three areas.

3.2 Channel shifting rates in the Outer Delta: overview

The map of channel shifting rates (1950-81) in the outer delta, produced by Lapointe (1986b), is given as Fig. 3.3 for the area west of Tununuk Point Enlargements are provided for Ellice and Langley Islands (Fig. 3.4), for the hydrocarbon development area between Middle Channel and Richards Island (Fig. 3.5) and for East Channel (Fig. 3.6). The accuracy of these rates is given as 0.2 m/yr.

Lapointe (1986b) provides only limited comment on the map. He merely notes the following points.

- Away from the delta front, peak bend shifting rates average about 0.5% of channel width, on an annual basis; these rates are comparable with those previously documented for Reindeer Channel.
- Near to the delta front (where channels become wider and less sinuous than upstream), channels commonly undergo simultaneous erosion of both banks, presumably due mostly to wave and storm surge attack. There is, in fact, a systematic increase in bank scour rates downstream in the estuarine parts of these channels attaining a peak at the delta front, approaching 10 m (or more) on Mackenzie Bay.
- Along East Channel, which is incised into older Pleistocene delta deposits, many reaches exhibit bank retreat on both sides of the channel, with rates in the range 0.5 m/yr to 2.5 m/yr.

3.3 Morphology of the main Outer Delta channels

There are marked contrasts in the morphology of the main channels in the Outer Delta. These contrasts may seem somewhat incidental to engineering issues of channel stability, but they should at least be documented: channel morphology is usually a clue to formative processes.

3.3.1 East Channel and Middle Channel

The difference in morphology - particularly channel width - between Middle Channel (between Langley Island and Mackenzie Bay) and East Channel is pronounced. CHS Chart 6435 indicates the following contrasts:

- the width of Middle Channel is generally much less (typically 350 m where it parallels Yaya River) compared to more than 1000 metres over most of East Channel;

- there is also generally little evidence of an inner channel flanked by a near-bank platform on Middle Channel: this contrasts with East Channel;

- the thalweg is much deeper in Middle Channel (usually 15-20 m below low water datum upstream of Harry Channel and 10-15 m between Harry and Kumak channels), whereas in East Channel it is generally only 8-10 m below low water datum except near constrictions such as Lucas Pt, Swimming Pt and Lousy Pt.

The exception to the comments above is just downstream of the IWD sediment sampling station 10MC901 (Fig. 2.5) where Middle Channel broadens out appreciably, but the network of channels in this area suggests that two or more channels may have fused into one in this reach because of channel shifting. It is also not clear whether the side shallows in this reach are depositional (bars) or erosional (platforms). Lapointe's data indicate bank erosion on both sides to be about 0.5 m/yr.

The shrinkage in width of lower Middle Channel (downstream of its trifurcation point where Reindeer and Neklek channels branch off) compared to further upstream is, of course, to be expected, but the extent of shrinkage is surprising. Upstream of the triple split point, Middle Channel is 1500 m to 2000 m wide, though much of this is submerged platform on both sides of an inner channel. Lapointe's map of the mid- and upper-delta indicates channel bank retreat of 2 m/yr to 3 m/yr in this straight reach just upstream of the trifurcation. It is possible that the contrast between the lower Middle Channel and the mid-delta Middle Channel is the result of age: the outer channel may simply be much younger and not have had time to develop lateral platforms and hence a wide channel.

3.3.2 Reindeer Channel

Reindeer Channel, while not as wide as East Ch, is still 500 m - 1000 m wide in the vicinity of the IWD sediment sampling station, and wider than Middle Channel. Upstream of its estuarine area, it, like Middle Channel in the Langley Island reach, also appears to lack near-bank platforms; this may indicate an ability for deep-seated bank scour on outer banks to keep pace with surface erosion through hydrothermal and wave erosion.

3.3.3 The Middle Channel triple split

The split of Middle Channel at the southeast end of Langley Island is one of the most puzzling morphological components of the Mackenzie Delta drainage network.

It is surprising that it has apparently not attracted previous discussion, though, in the absence of much data, most interpretative commentary will inevitably be speculative.

The limited hydrologic data so far available suggest that, of the three branches downstream of the split, it is Reindeer Channel that carries most of the flow. The main river thus turns more than 90° to the southwest at this point. The Langley Island extension of Middle Channel is second, and Neklek Channel is the smallest of the three. There appear to be insufficient data to quantify this partition.

The abrupt turns of both Reindeer and Neklek channels where they turn off Middle Channel suggest that this juncture is far from stable in the long term, and that the proportion of flow along each route may well have changed during historical time, and may continue to do so in the future. This is true of other points of channel splitting in the outer delta (discussed next), but is especially important here, because the partitioning of flow at this one point controls the entire hydrologic pattern of the outer delta.

The main map of channel bank scour rates by Lapointe (1986b) includes data for the area (Fig. 3.7). There is minimal bank retreat in the bend of the north entrance to Reindeer Channel, implying that the major flow enters Reindeer Channel through the south arm. Both sides of this arm are experiencing bank scour at the rate of 3 to 4 metres per year. Yet there is no clearly- defined trench in Middle Channel which leads into this south arm. The twisting of Middle Channel back into the south entrance to Reindeer Channel would seem to be increasingly difficult as more and more sediment accumulates on (and progrades from) the "mud" bar documented on the left side of Middle Channel (Fig. 3.8 near km 1670). (How much of this bar is depositional and how much is an eroded platform is unknown, though Lapointe's (1986b) data do indicate bank migration here).

Notwithstanding the severe deflection in flow required at this point, the Reindeer outlet would seem to be favoured, compared to Middle Channel, by the general pattern of the delta network. The distance from the triple point to the Shallow Bay outlet of Reindeer Channel is only 40 km. The distance to the South Niglintgak outlet of Middle Channel is 60 km, and much of the flow must continue further than that along the east side of Niglintgak Island as Kumak Channel. The more infilled the south Niglintgak arm becomes, the greater will be the flow deflection along Kumak Channel, and thus the longer will be the overall route for Middle Channel flow.

The second outlet, the entrance to the Langley Island extension of Middle Channel, shoals initially (the thalweg rising from about 15 m to 10 m above LWD) before the channel narrows and deepens. Lapointe's (1986b) data indicate very rapid bank scour rates here in the range 6-15 m annually. High rates are not restricted to "outer" banks of bends. Whether this is indicative of channel enlargement (and a greater proportion of the flow from Middle Channel along this route) is unclear. The key data needed here are bathymetric sections, and nothing is apparently available other than that indicated in the CHS chart.

The branching of Middle Channel into Neklek Channel, the third outlet, resembles, in many ways, that of Reindeer on the opposite side. Lapointe (1986b) provides much less data on bank retreat here, however, with only two sites (on the outer banks of the two bends) averaging 0.5-1.5 m per year. These are much less than in the other two channels, indicative of the smaller flow along Neklek Channel. The thalweg is as deep as the other two channels, but the channel width is less.

3.3.4 Channel splitting

There are other differences between Middle and Reindeer channels, on the one hand, and East Channel, on the other, besides those noted in Section 3.3.1. East Channel (CHS Chart 6430), being essentially confined within the high-level Pleistocene Delta (see Section 3.6), shows only limited channel splitting, around islands, and none of the distributary branching that is typical of delta channels.

In the case of Reindeer Channel (CHS Chart 6434), there are several tiny branches downstream of Marcus Channel, but the major channel split occurs at km 1710, where a broad channel enters Shallow Bay to the west, while the main channel swings north to enter Mackenzie Bay (Fig. 3.9). The Shallow Bay arm is much shallower than the Mackenzie Bay arm, and appears to be a largely infilled channel distributary. (Neither arm appears to have been given names: the northern arm, which retains the fluvial morphology of the upstream reaches, should perhaps be continued as Reindeer Channel. Some maps mistakenly label this Mackenzie Bay arm of the river as Middle Channel.)

Middle Channel (CHS Chart 6435) involves more distributary branching than Reindeer Channel. In some cases, the bifurcations are simple in geometry (km 1691 downstream of the IWD sediment station 10MC 901); but in other cases, the bifurcations involve a twisting back of one channel so that water separates at more than 90° from the main flow, as previously noted in the trifurcation of Middle Channel into Neklek and Reindeer channels. One such large-angle bifurcation occurs at km 1693 with the branching off of Arvoknar Channel, but the most spectacular is at the Harry Channel branching (km 1708) (Fig. 3.10). It is difficult to accept that much bed material from Middle Channel enters Harry Channel at such an angle (and bearing in mind the threshold at the channel entrance).

The origin of these strange channel junctures is unclear; it is possible that they are related to storm surge flow upchannel from Mackenzie Bay. The stability of all channel junctures is clearly relevant in the present context, because the spatial allocation of water flow in the distributary network will change as some junctures close and others are enlarged.

The exit of Middle Channel into Mackenzie Bay is not unlike the mouth of Reindeer Channel in one respect. There is a pronounced bifurcation at the southeast end of Niglintgak Island (Fig. 3.11): the westerly arm (on the south side of the island) is broad and extremely shallow, but retains the name Middle Channel; the northerly arm (on the east side of the island) maintains the fluvial character of further upstream (though narrower and only about 5 m deep below LWD) but is now renamed Kumak Channel. The shallowness of the Middle Channel arm presumably reflects sediment-infilling of the old main channel. Again, it seems that longterm changes in the bathymetry of this juncture (as well as short term changes in surge levels at either end of Kumak Channel) could have appreciable effect on the allocation of flow around Niglintgak Island.

3.3.5 The estuarine inlets

The funnel-shaped mouths of the Mackenzie Delta distributaries have already been noted (Chapter 2). What is interesting is the marked discordance, in many cases, between mouth size and river size (Fig. 3.12). This observation may be important, because it may be indicative of instability in the flow partitioning among the different distributaries.

As an example, the inlet north of Ellice and Langley islands (which is comparable in size to the Middle Channel mouth, south of Niglintgak Island) extends upstream splitting into several small channels that originate either in Middle Channel (just upstream of Arvoknar Ch.) or just to south of Middle Channel in a lake complex. It is presumed that the old channels which were responsible for the inlet have gradually become abandoned because of sediment infilling.

Similarly, the inlet at the mouth of Arvoknar Channel (which is only slightly smaller than the mouth of Middle Channel) appears to receive only a small amount of flow, its water being derived from the branching off Middle Channel noted in the previous subsection. It seems likely, from the morphology of the branching, that flow volumes down Arvoknar Channel are much smaller than in the past. Sediment infilling would occur preferentially in the upstream part of the channel leaving the mouth still wide.

The northward-flowing Harry Channel splits into four, sometimes unnamed tributaries, before entering Mackenzie Bay. The most westerly of these has the largest inlet mouth, whereas Harry Channel itself (the most easterly of the four) is somewhat narrower. The relationship between inlet mouth and river discharge is difficult to assess given the scarcity of discharge data on the four branches.

In the areas near the delta front, the inherent instability of channel bifurcations appears to be affected by an additional set of processes. As noted in the previous subsection, it appears that the western arms of both Reindeer Channel and Middle

Channel mouths have become blocked with sediment (possibly due to up-estuary movement of sediment from the bays). In both cases, this has presumably deflected an increasing percentage of the river flow to the eastern arm (which in the case of Middle Channel is Kumak Channel).

The morphological evidence suggests, therefore, that where distributaries branch away from the main channel, the proportion of the flow directed along the distributary can change appreciably over the long term, often decreasing, and perhaps even resulting in complete channel abandonment. The corollary of this is that other channels will be forced to take up more of the flow, either enlarging themselves to do so, or spawning new side channels (through avulsion) to take the extra discharge. The distributary network is therefore highly unstable, and this needs to be borne in mind in any assessment of bed and bank stability in any given channel reach.

3.4 The Niglintgak Island area

The exact location of the likely crossing of Kumak Channel by the Niglintgak-Taglu pipeline (Fig. 3.13) has still not been established. Deyell (1991, pers. comm.) provided two maps of possible routes. One showed a crossing immediately opposite the "plant" site. The other showed a crossing further north, with the pipeline staying on the north side of Aklak Channel before crossing three more channels just west of the Taglu plant (Fig. 3.13).

Stability of channels in this area has been examined by the Geological Survey of Canada (Traynor and Dallimore, in prep.). This work includes comparison of aerial photographs (to determine lateral shifts in the channels) and resurvey of old cross-sections (undertaken in the mid 1970s) to assess the pattern of bed scour and infill. The pattern of bank shifting is shown in Fig. 3.14. The location of cross-sections is given in Fig. 3.15. An example of cross-sectional change is provided for Section 34 on Kumak Channel (Fig. 3.16). The general bathymetry of the Kumak branch-off from Middle Channel is indicated on CHS Chart 6435 shown in Fig. 3.11.

The 1970s surveys were undertaken by various consulting firms for the petroleum companies. The data are provided in several reports, including EBA (1974), Hardy and Associates (1977a,b,c; 19??), and Slaney, F.F. and Company (1974, 1976). None of these reports has been seen in the preparation of the present overview. No comment can be made regarding the accuracy of relocating the cross-sections, and no interpretation is offered regarding the significance of the fragmentary information from GSC that is available to date. It should be clear, however, that the stability of Kumak Channel must be affected to a large extent by the ability of Middle Channel flows to bypass on the south side of Niglintgak Island.

3.5 The Taglu area

The map provided by Deyell (1991, pers. comm.) for the Taglu area shows two possible routes from Niglintgak across channels to the west of the Taglu plant (Fig. 3.13), but no information pertaining to stability of these channels has been seen. The GSC report (Traynor and Dallimore, in prep.) does include reference to two sections on the channel immediately west of the Taglu plant (Kuluarpak Channel).

Two possible routes are shown east of the Taglu plant on the map provided by Deyell (Fig. 3.17) across the Harry Channel complex of streams. One of the outward routes is the proposed Polar Gas route with crossings of Seal Channel and Harry Channel. The alternate possible route is about one kilometre upstream, and involves three crossings: Back Channel, Harry Channel and an unnamed channel. The GSC report includes cross-section surveys in this area (Fig. 3.18).

Again, no analysis of the GSC report, nor of the 1970s field surveys done for the petroleum companies, is presented here. The GSC surveys do indicate, however, that Kuluarpak Channel (Fig. 3.19) is substantially deeper than the downstream continuation of Harry Channel (3.20): the naming of distributaries in this part of the delta should not, therefore, be taken as any indication of flow dominance.

It is not known how detailed an interpretation of these bathymetric data is provided by the GSC report. Again, however, it should be clear that the stability of the lower Harry Channel complex is strongly affected by the stability of the branch outflow junctures, as well as by the stability of Kuluarpak Channel. In turn, however, these channels are affected by the magnitude of flow down upper Harry Channel, and this is strongly influenced by the hydraulics and morphology of the branch-off of Harry Channel from Middle Channel (Fig. 3.10).

3.6 East Channel

The continuation of East Channel, downstream of Tununuk Point, presents a contrast to both Middle and Reindeer Channels, as previously noted. This is because East Channel is not part of the broad contemporary Mackenzie Delta, but is incised through a higher-level Pleistocene delta. Rampton (1988) has mapped the surficial deposits of the region (Fig. 3.21).

3.6.1 Surficial deposits

Much of this surficial deposit, in the area bounding East Channel, both upstream and downstream of Tununuk Point, is glaciofluvial sediment (G): this includes ice-contact deposits (indicated by the solid dark shading) as well as outwash plain sediment. The sediments are dominated by sand, with only minor amounts of pebbles and gravels. Moraine, which makes up much of the valley walls in the lower part of the East Channel (near Lousy Point and downstream) is described as being a stony, clayey diamicton with 30-50% clay, 25-45% silt, 10-30% sand and 3-25% gravel (>2 mm).

The surficial geology map does not necessarily adequately represent the full thickness of deposits into which East Channel has cut down. Fig. 3.22 is a cross-section through the coastlands: much of the west bank of Kugmallit Bay is sand, but the basal member is marine clay. Sections along the east bank of East Channel, just upstream of Tununuk Point, are indicated in Fig. 3.23. Rampton (1988) provides the following interpretation of the deposits of the East Channel area.

Much of the thickness of Quaternary sediment is pre-Wisconsin (especially in the Richards Island section of Fig. 3.22), including interglacial sediments laid down when relative sea-level was higher than today. Most surface glacial deposits in the area date from the Early Wisconsin (Toker Point stade) when a lobe of glacial ice extended well beyond Richards Island (Fig. 3.24). A significant phase ("Tuk" phase) of the deglaciation of Toker Point ice involved temporary halt of the ice front along the axis of the Tuktoyaktuk Peninsula (Fig. 3.25) leading to northward-draining meltwater channels and outwash valley trains in the present area. The surfaces of these deposits are now well above sea level (10-20 m). There was, presumably, incision of these deposits during some of the subsequent ice-free period.

The next (and last) ice advance (the Sitidgi stade of the late Wisconsin) is believed to have reached its maximum extent about 13,000 years ago. The ice front of the Mackenzie Delta lobe (Fig. 3.26) was then located at about the present position of Reindeer Channel. Rampton (1988, p. 71) suggests that many of the drowned valleys of the coast (and of east-bank tributaries to East Channel, such as Devil Creek near Tununuk) were probably excavated to their deep levels during this time. During the Holocene (last 10,000 years), accompanying the rise in sea level, aggradation occurred throughout the delta, infilling the mouths of these valleys (e.g. producing Devil Lake). Radiocarbon dating of wood at a depth of 38 metres is given at 6900 BP, indicative of the rapid sediment build-up in that time, averaging slightly more than 5 mm per year. This is roughly comparable with the rate of sea level rise in the same period, as inferred by Hill et al. (1985).

3.6.2 Channel morphology

This recent sediment buildup along East Channel is reflected in the morphology downstream of Tununuk Point. The alluvial floodplain that flanks the channel shows a highly sinuous pattern with marked embayments into the Pleistocene sediments (Fig. 3.27). The present East Channel is much less sinuous than its floodplain and appears to be much wider than the river that cut the low-level meander scars that now form its floodplain. The radius of curvature of these low-level scars seems small compared with the present width of the channel. It seems likely, therefore, that there has been a marked change in regime during the late Holocene, though it should be remembered that the inner channel of East Channel is substantially narrower than at the surface.

The present East Channel is wide and relatively straight, except where headlands of Pleistocene sediment impinge upon its margins (as at Lucas, Swimming and Lousy points). It is also relatively shallow, and its thalweg bed is "perched" at a higher elevation than that of Middle Channel. This is, of course, true along its full length, reflecting the much weaker flow in the East Channel. The important point here, however, is that the abrupt rise in the thalweg floor is not at the offshoot from Middle Channel i.e. at the entrance to Neklek Channel (which would be comparable with the "threshold" at the entrance to East Channel downstream from Point Separation), but occurs where Neklek Channel enters East Channel (Fig. 3.28).

The conditions at Tununuk Point are worth further comment: the thalweg of Neklek Channel (which splits into West Tununuk Channel and East Channel at the Point) rises abruptly from about 15 m below LWD to only 5 m in East Channel. The depth of the narrow continuation along West Tununuk Channel is comparable with that of the wider East Channel. Much of the flow in the lower East Channel seems to originate from Neklek Channel, judging by the contrast in cross-sectional area up- and downstream from Tununuk Point (Fig. 3.29). It is not known how much of the Neklek flow continues along West Tununuk Channel, but flood flows in East Channel downstream of Tununuk are presumably comparable with those in Neklek Channel. These observations then seem to imply that scour of bed material along East Channel is much more difficult than in the Neklek-Middle channel system.

The reasons for the shallower bed along East Channel are not clear. The increased channel width begins about 30 km upstream of Tunununk Point, at the downstream end of Williams Island (CHS Chart 6429) where it is joined by the Chicksi Channel offshoot from Middle Channel. Between here and Tununuk Point, East Channel has a <u>bankfull</u> width that is only slightly less than Middle Channel, though it carries appreciably less flow.

One possible explanation for the limited depth along East Channel would be lag deposits of coarser sands (and perhaps gravel) supplied to East Channel through erosion of the margins of the Caribou Hills and the Pleistocene sediments there and downstream of Tununuk Point. Bed material samples taken by WSC this year at the East Channel sediment station will be instructive in this respect, especially in comparison with those taken at the Reindeer and Middle Channel stations. (These samples have not yet been analyzed at the time of writing this report.)

It has been noted that areas in which the Pleistocene sediments abut East Channel tend to produce headlands (or "points") in the channel margin. The implication seems to be that these sediments are, in some way, more resistant to bank erosion than the floodplain alluvium. The hydraulic forces on Tununuk Point (shown by Rampton as ice contact fluvioglacial sediment), for example, must be severe, though no data on cliff retreat appear to be available. Such increased resistance, if valid, could be related to thinner active layers and/or more extensive permafrost in cliffs of the older Pleistocene sediments than at the floodplain margin. It is unclear, however, whether these older sediments are substantially more resistant to bank scour than floodplain alluvium along East Channel. In some respects, the "headland" projections of older sediment into the channel simply reflect the meandering outline of the old channel, now partially infilled with more recent alluvium.

3.6.3 Studies of channel stability

Some investigation of channel stability along East Channel has been undertaken as part of the former CAGSL studies (at sections J and K shown in Fig. 2.3).

As noted in Section 3.1, the Swimming Point site is still considered the most likely crossing on East Channel for both gas and oil pipelines. This is the crossing used for East Channel by Polar Gas in its 1984 application to NEB and INAC. The Polar Gas application includes a cross-section of the river crossing (immediately downstream of Swimming Point) prepared by Canuck Engineering Ltd. (The same section is shown in Fig. 2.2 previously.) The Polar Gas application notes: "There has been no significant change in bank locations for many years." The deposits at the undercut right bank on the section appear to be ice-contact glaciofluvial sediment based on Rampton's (1988) map. Lapointe (1986b) does not show bank erosion rates at the crossing site, but immediately upstream (opposite the point) they are given as 0.5 m/yr.

Neill (1988, pers. comm.) indicated that the Polar Gas application was based on earlier reports (mid-1970s) covering the region. These reports, which include one by Blench and Associates (1975), have not been seen. Neill quotes from that report as follows:

> "Because the crossing is located on a sharp bend in the channel, a moderately severe level of erosive attack can be expected on the right bank of the sub-channel at the crossing. However, the fact that this underwater bank has not migrated out to the high bank on the right side of the crossing (Fig. 2.2) suggests that it is relatively stable with regard to lateral erosion. Such stability could be due to the presence of permafrost near the edge of the bank during periods when erosive attack is severe."

No other information has been found regarding channel stability along East Channel downstream of Tununuk Point. Nonetheless, it is evident that considerable investigation of this reach was undertaken in connection with the CAGSL program of the 1970s. The Arctic Institute of North America (University of Calgary) has an extensive collection of CAGSL reports. The computer-based catalogue of CAGSL reports has been examined under five headings (Mackenzie Delta, River Crossings, River Ice Conditions, River Hydrology, and Permafrost): abstracts relevant to channel stability at pipeline crossing sites are provided in Appendix I.

The Terrain Sciences Division of GSC plans to undertake resurveys of old cross-sections on East Channel during the summer of 1992 (Dallimore, 1991, pers. comm.).

4. CHANNEL STABILITY ISSUES: SUMMARY

4.1 Preamble

This summary chapter provides a synthesis of points raised in the reviews of previous chapters, dealing, in turn, with different aspects of channel stability.

The emphasis in the section, however, is on conditions in the outer delta, given that this is the most likely area of oil and gas development, and therefore the area of most interest to Inland Waters Directorate in the context of its NOGAP program. This is an important point because most published literature dealing with channel stability in the Mackenzie Delta pertains to the middle and upper delta. Reports for the outer delta do exist, but tend to be "grey" literature, and usually proprietary to the oil and gas companies. Little of this literature has been seen to date. The few reports that have been examined tend to be data reports with little interpretative assessment. A list of reports done by, or for, CAGSL is provided in Appendix I, as noted previously.

The distinction between the outer delta and the middle and upper delta is significant. Though various authors refer to sandy bed load as being moved right through the delta to the Beaufort Sea, it is clear that there is a major reduction in channel slope and velocity at the head of the delta. This would be expected to produce extensive in-channel accumulation of bed sediment at this site. The marked contrast in morphology between the "braided" reach of Middle Channel downstream of Point Separation and the single-thread character of the same channel by the time it reaches Horseshoe Bend appears to be consistent with this view. It seems likely that both the amount and calibre of bed material moved in the outer delta are much smaller than in the middle and upper delta. Insufficient sediment data exist to verify this speculation. Information on water surface long profiles through the delta, tied to recently-acquired geodetic benchmark data (Kerr and Fassnacht, 1991), is likely to be useful in this context though.

The ongoing reduction in flow through channel splitting will also affect channel efficiency to move bed material, as well as decreasing erosive stresses on channel banks. The marked decrease in velocities between Arctic Red River settlement, Middle Channel at mid-delta, and the outer delta channels has been noted. The general impression conveyed for the outer delta is that bank instability is, overall, somewhat less pronounced than in the middle and upper delta.

These differences in channel flow strength are probably accompanied by differences in channel bed and bank materials between the outer delta and inland. The contrast within the outer delta between East Channel and the channels west of Tununuk Point has been noted. Again, however, the amount of data available regarding channel boundary sediment appears to be meagre.

The summary of channel stability in the outer Mackenzie Delta given below is broken down into four headings: bed stability; bank stability; stability of the permafrost table in the vicinity of channels; and network stability, that is changes within the channel network itself. The summary merely highlights points previously raised in earlier sections.

4.2 Stability of the channel bed

Information regarding stability of the channel bed is meagre. The cross-section surveys by GSC (Traynor and Dallimore, in prep.) for the Niglintgak and Taglu areas will be useful in this regard. Similar surveys by WSC at its measurement sections will add to knowledge regarding bed instability.

Such information is, however, fragmentary. What is needed is an overall understanding of bed morphology changes in the river system (whether bedforms are moving downstream, and if so, how quickly; how important upstream bed material inputs are compared to local inputs from bank erosion, etc.) in order to put these isolated observations into some perspective, and thus assist in proper interpretation.

As an example, the thalweg of Middle Channel (Chart 6435) shows appreciable fluctuation in level, with the deepest parts more than 25 m below low water data (LWD) and the shallowest parts less than 5 m below LWD. The channel "meanders" and therefore it might be expected to have such variation, with pools in meander bends, and with shallow zones in the inflection points. Yet this is not the pattern that actually exists. The first two bends downstream of Harry Channel are overwidened and the thalweg shoals to about 5 m below LWD at both sites. Overall there appears to be a general association between deep reaches and areas of channel constriction, and it is assumed that this reflects variations in channel bank (and bed) sediment along the course of Middle Channel.

The issue may take on a different perspective in the side channels; and it is these (except for East Channel which is in any case quite different from Middle Channel) that are more likely to undergo pipeline crossings. For various reasons outlined previously, it seems likely that these side-channels receive little bed material from Middle Channel. Thus, changes in bed morphology are probably due mostly to local sources of coarser sediment associated with bank scour, together with wash load from Middle Channel that now settles out along the courses of these weaker flows. Which of these two processes is more important is unclear. It does seem likely that bed sediment will be much finer in these side channels (deposited wash load from Middle Channel), but no data have been found on grain size, though such data may exist in reports to the petroleum companies.

Such deposition of washload from Middle Channel is important because, if valid, it would provide a contrast with mid-delta side channels where Lapointe (1984) concluded that input and movement of bed sediment are also relatively small: the influx of bed sediment from Middle Channel is limited by the tall walls (thresholds) at the entrance to the distributary channel, and flow velocities within side channels appear able to transport most of the wash load that enters from Middle Channel. Thus circumstances which would tend to maintain deep scour holes in the mid-delta side channels (limited bed sediment movement) might be absent in the outer-delta side channels.

Bed stability conditions are likely to be quite different in East Channel in view of the difference in size, cross-sectional shape, and (probably) bed sediment. The bathymetry depicted by CHS Chart 6430 seems relatively simple: there is an inner channel in which the thalweg depth below LWD is relatively constant at about 7 metres, except at channel constrictions such as bend sites (Lucas Point, Swimming Point, Lousy Point). The reason for the narrowing (and therefore deepening) immediately downstream of Holmes Creek is unclear. No data for channel bed change or bed sediment have been found for East Channel, though it is believed that such information exists from studies at river crossings considered by CAGSL (Appendix I). Terrain Sciences Division of the Geological Survey of Canada (Dallimore, 1991, pers. comm.) proposes to resurvey crossing sites in 1992, but the number of existing surveys is not known.

No information has been found dealing with scour holes associated with jamming during ice breakup or scour beneath hanging ice dams. The matter has been investigated by Blench and Associates (1974, 1975 a,b): abstracts are given in Appendix I.

4.3 Stability of channel banks

Abundant data on bank migration rates in the outer delta have been provided by Lapointe (1986b), but these all refer to exposed bank positions. The discussion in Chapter 2 indicates that in many channels in the delta, where flow strength is relatively weak, various processes act on thawed surface bank sediment to produce retreat that exceeds that of the subsurface channel bank. In this way, an inner channel, separated from the exposed bank by a nearshore platform, is created. Such platforms are apparently found even in smaller channels in the outer delta, e.g. Kumak channel (Fig. 3.16) and Harry Channel (Fig. 3.20: top). Thus a distinction is needed between surface and subsurface bank stability.

Most observations (including aerial photograph comparisons) have been done in connection with surface bank stability. Factors affecting the thermal regime of the active layer, and the ground ice content, have been shown to be important in controlling rates of surface bank scour (Cooper and Hollingshead, 1973). These are likely to vary appreciably between reaches.

Investigation of subsurface bank migration has been much more limited. The resurveyed cross-sections in the Niglintgak and Taglu areas by GSC (Traynor and Dallimore, in prep.) will provide useful information here. It is not known, however, whether the issue of subsurface bank stability at these sites has been tied in to observations on permafrost distribution and ground ice occurrence. Hardy and Associates (1976) prepared an information data bank on permafrost distribution at river crossings; this has not been seen, but an abstract is provided in Appendix I.

The role of permafrost in river scour of submerged banks is still somewhat unclear. Some reports emphasize the high erodibility of ice-rich sediment; others, in contrast, indicate that the frozen character of ice-poor sediment actually increases resistance to erosion. Walker and Arnborg (1963) and Walker (1983) documented bank erosion in the Colville Delta, Alaska: while they noted spectacular short term erosion rates where ice-wedges promoted block collapse, the long-term erosion rates at these sites were little different from sites without block collapse.

The most extensive work on hydrothermal erosion has probably been undertaken in the Soviet Union, but little reference to this literature has been found in reports dealing with the Mackenzie Delta, and none has been seen in preparation of the present report. In view of the interest in channel stability in the Delta, it would seem appropriate that a review of the translated Russian literature dealing with this topic be undertaken.

It is also clearly important to obtain much more detailed information on the temperature and sediment properties of submerged channel banks in the delta. This is no simple task but needs to be done in any assessment of channel stability. The inference that the Swimming Point (submerged) right bank is probably stable because of permafrost at depth needs verification, especially given that the published cross-section (Fig. 2.2) shows that part of the bank adjacent to the flow to be unfrozen. It is possible that detailed borehole data are available for all old potential crossing sites, but such data have not been seen as part of this review.

As noted in Chapter 2, various investigators have claimed that bank erosion is minimal during breakup because the banks are frozen at this time of year. Though this point may be valid for surface bank erosion, it may not be relevant in the context of subsurface bank scour if there is a talik zone at the side of (as well as beneath) the channel.

4.4 Stability of the permafrost table

One issue that does not appear to have been widely considered is the impact of channel sedimentation, or bed scour, on aggradation or degradation of permafrost. Smith and Hwang (1973) considered this in a general way in relation to a large laterally-shifting channel, but no reference to the impacts of sedimentation or bed scour in smaller channels such as distributaries of the outer Middle Channel have been seen.

Accumulation of sediments in shallower parts of the bed could lead to sufficient shallowing that ice might develop through the full water column in winter. This would lead to increased heat loss from that part of the bed and could produce extension of any permafrost in underlying sediment. In turn this could produce (through ice growth) heaving of sediments. Conversely, scour of shallow parts of the bed that are normally covered by frozen river in the winter, could lead to insulation by deeper ice-free water, reduction in the loss of heat in winter, and degradation of any permafrost. In turn this could produce thaw-consolidation and settlement of the bed sediments, depending upon the ice content. This may be of special significance if the deep "scour holes" are indeed thermokarst phenomena. Side platforms flanking inner channels would seem to be particularly marginal for permafrost and therefore susceptible to change.

It is assumed that the Terrain Science Division of GSC has been exploring this issue, but no information has been seen for the Niglintgak or Taglu areas that it has studied, nor for any other areas.

4.5 Network stability

The issue of channel network stability has attracted little attention. There is a general feeling that the channel network of the delta is relatively stable, the comment frequently being made that the main channels seem to be in the same positions as in the days of early exploration by Mackenzie and others. Mackay's (1963) map of channel shifting (Fig. 2.1) refers to "much channel shifting" in the outer delta, but it is unclear whether this means bank migration or actual switching of channels.

In any case, irrespective of the role of sudden channel switching (avulsion) in the outer delta, the major control on the stability of the channel network is probably the ongoing change in flow strength of different distributaries: some channels become blocked by sediment deposition, in turn forcing more water along other channel routes. What is particularly important here is the stability of the channel branch-off, i.e. whether, and how quickly, the branch-off is being blocked by sediment accumulation, and the response of the other channel to any increase in flow.

Little attention appears to have been paid to this point. Yet the ultimate control on the strength of channel flow down, for example, Harry Channel opposite Taglu, is how much of the discharge of Middle Channel continues past Tununuk Point (rather than being deflected into Reindeer and East Channels at the triple-split point), how much of the lower Middle Channel flow enters Harry Channel, and how much of the Harry Channel flow continues down Kuluarpak Channel.

Changes in overall channel stability in the outer delta will be determined by changes in flow strength and bank resistance, as might be affected by climatic change; but changes in channel stability in any individual channel reach will also be controlled, perhaps more strongly, by the changing allocation of flow discharges through the distributary network. These changes will affect all three aspects of channel stability previously discussed.

4.6 Endnote

There are more general issues of channel stability which relate to the overall stability of the outer delta itself. These include the possibility of submergence of low areas through sea-level rise (due to global warming), widespread delta subsidence arising from permafrost degradation (from global warming) and more local subsidence arising from the extraction of large quantities of buried gas. These issues have been raised before (INAC, 1988; Lewis, 1988) and are not pursued here.

The terms of reference, budgetary scope and time limitations of this review dictated that it take the form primarily of an overview of channel stability issues in the Mackenzie Delta. It is hoped, nonetheless, that the report provides a useful framework for guiding future work on channel stability in the delta. It does explicitly identify several issues which, while doubtless recognized by individuals working in the delta, have not apparently been emphasized before.

It is clear that additional information related to channel stability, not documented in this report, exists in various consulting reports done for the petroleum companies. Some, but probably not all, of these reports are included in the list of references and/or Appendix I. The ongoing work of Terrain Sciences, GSC, will also provide information in the next few years.

Any reach-specific studies of channel stability, e.g. hydraulic and morphologic surveys by Inland Waters Directorate, will clearly need to examine these unpublished data before implementation of the studies.

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LIST OF FIGURES

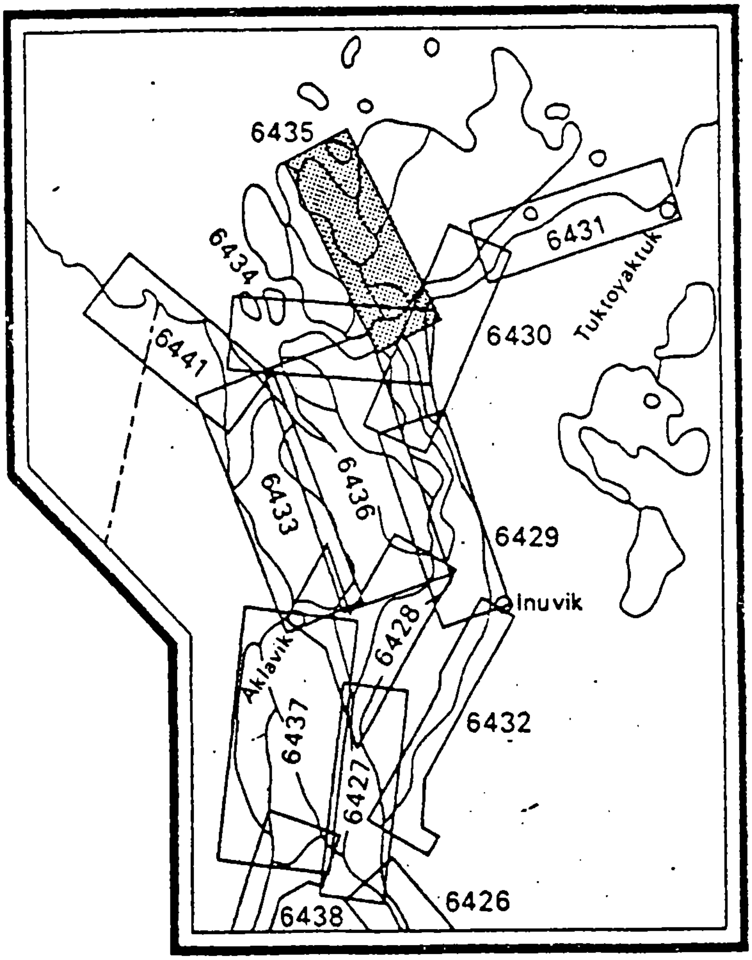


FIGURE 1.1

BATHYMETRIC CHARTS OF MACKENZIE
DELTA: CHS INDEX

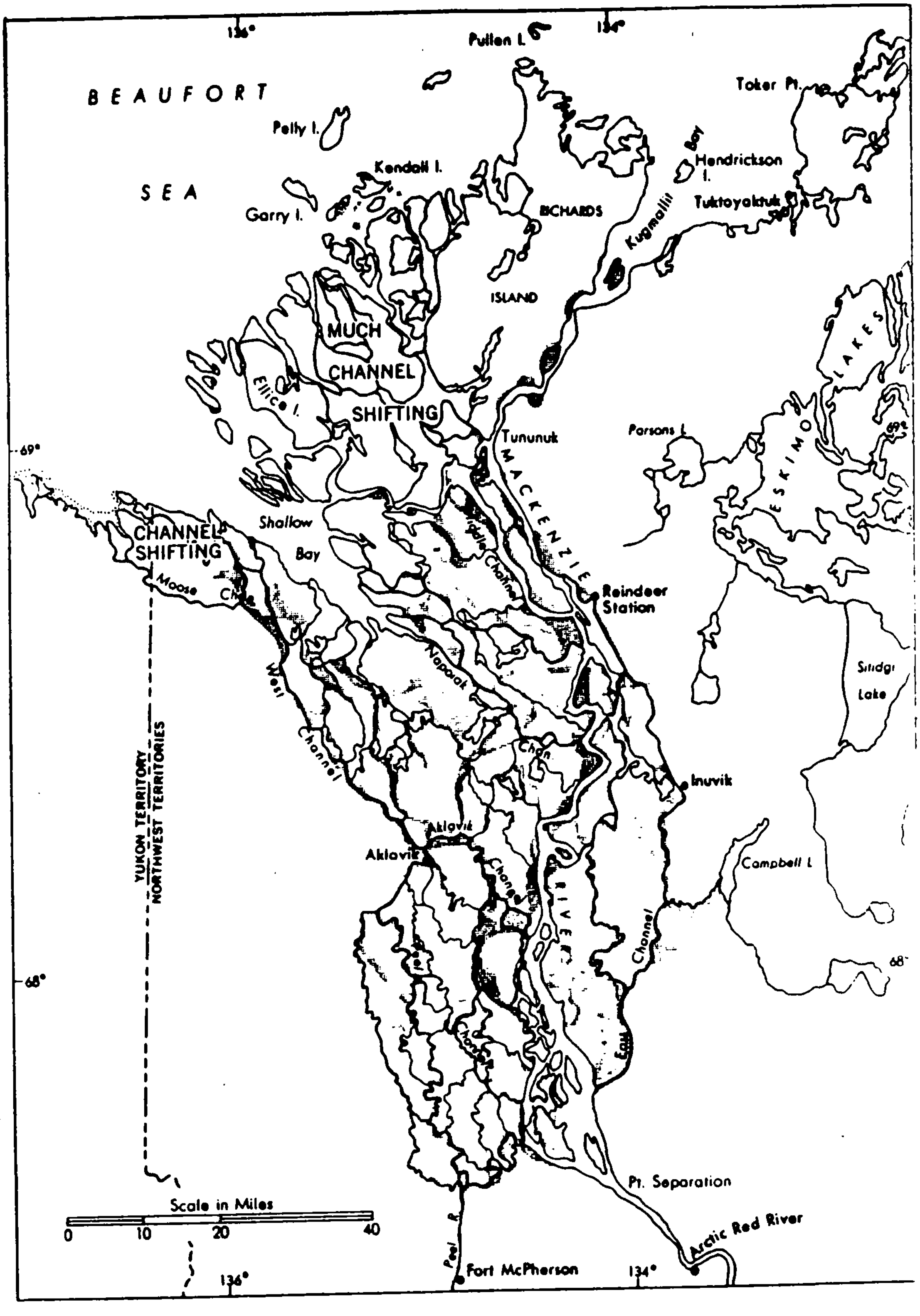
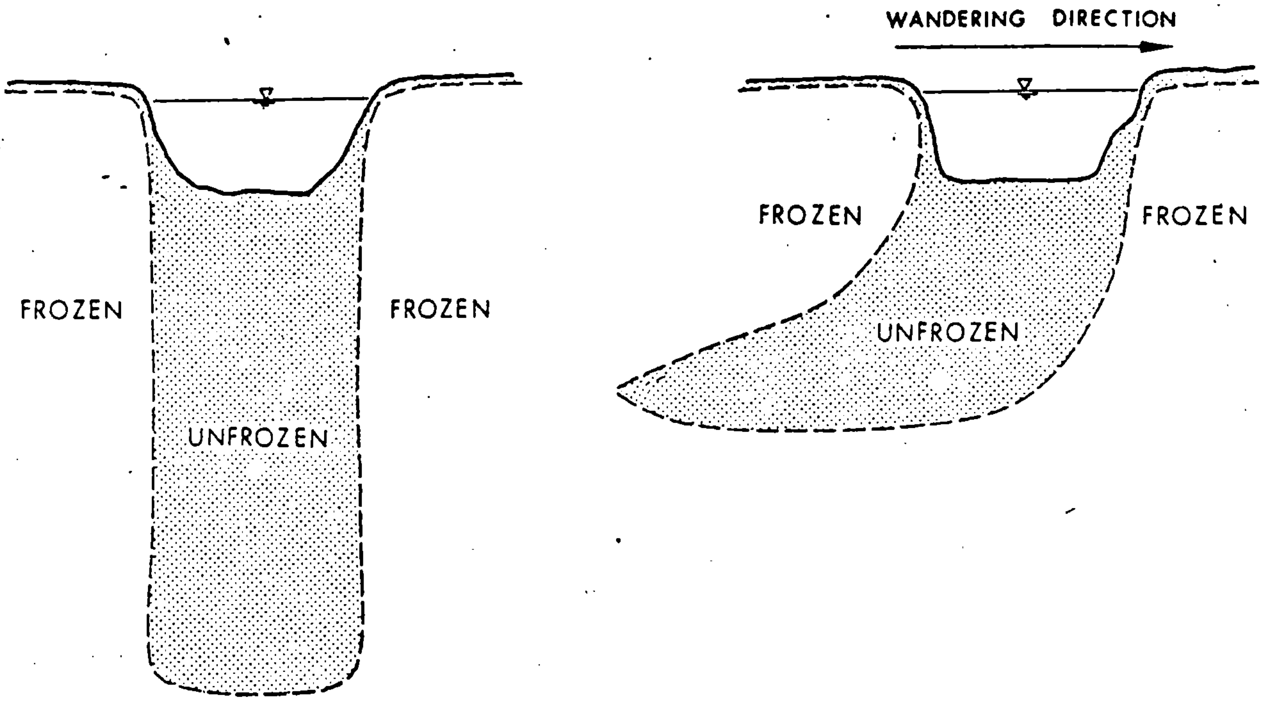


FIGURE 2.1

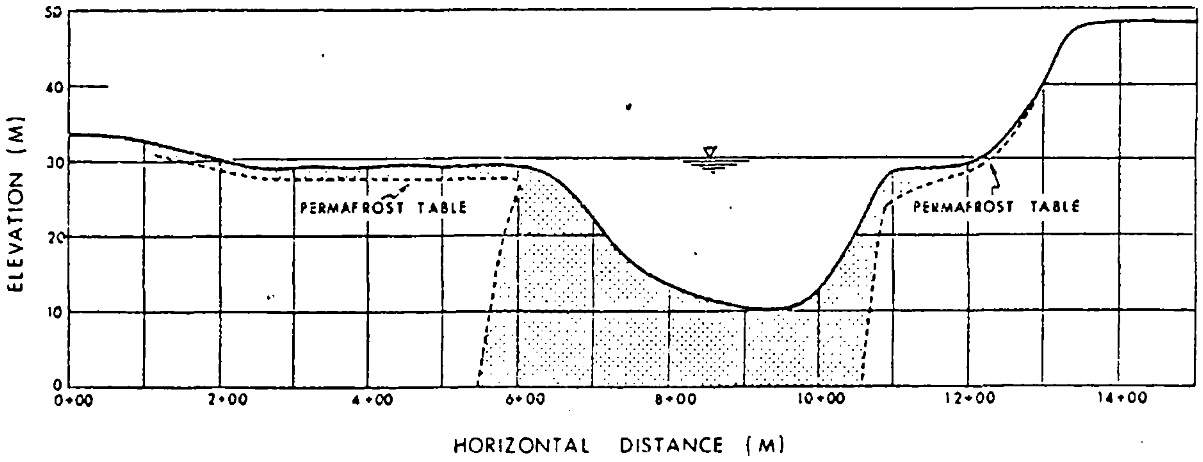
Principal channel shifts in the Mackenzie delta.

(from MacKay, 1963)



a. STABLE CHANNEL

b. WANDERING CHANNEL



c. CROSS SECTION AT SWIMMING POINT IN EAST CHANNEL (SECTION K)

FIGURE 2.2 - EFFECT OF WANDERING CHANNEL ON TALIK SHAPE

(from Cooper and Hollingshead, 1973)

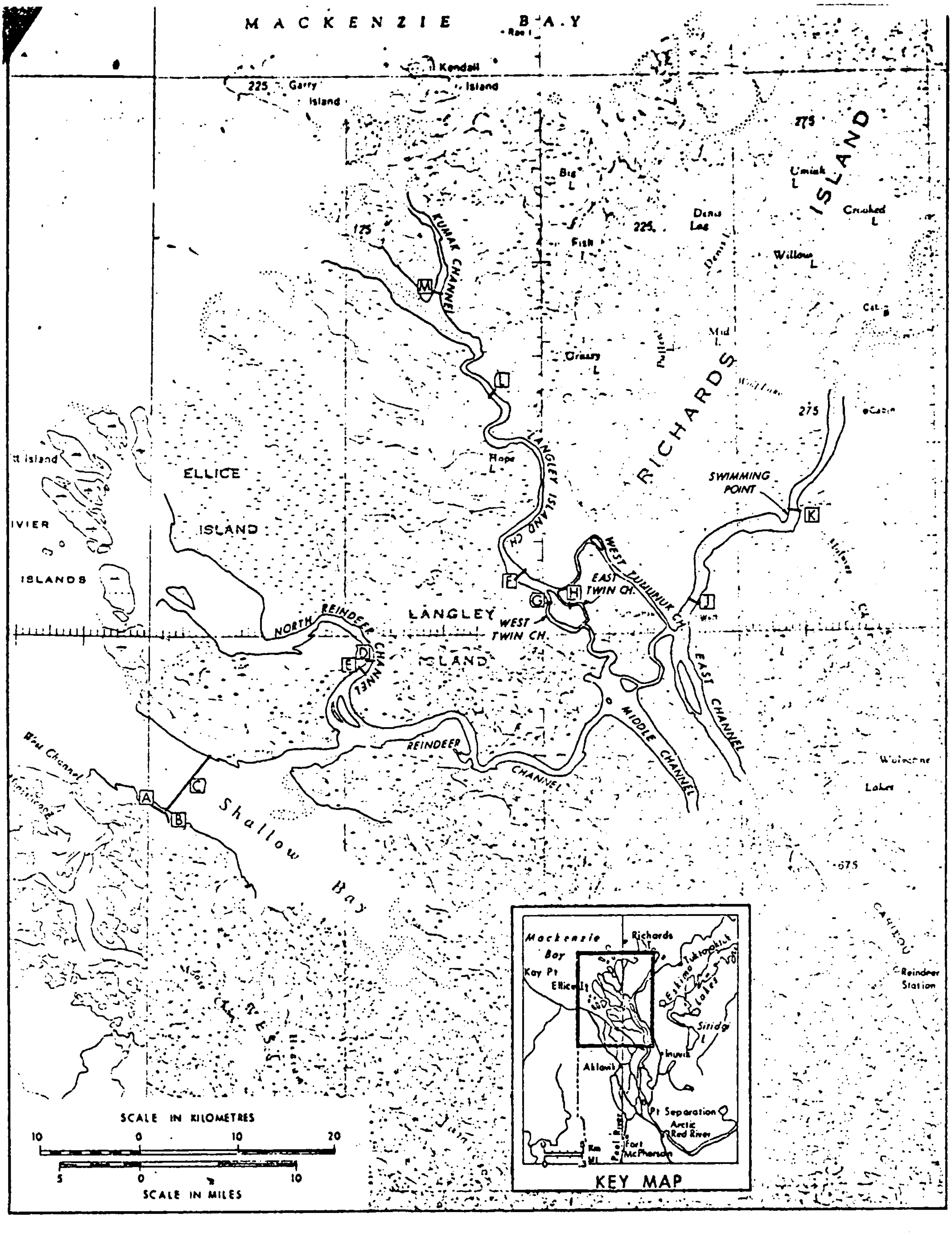
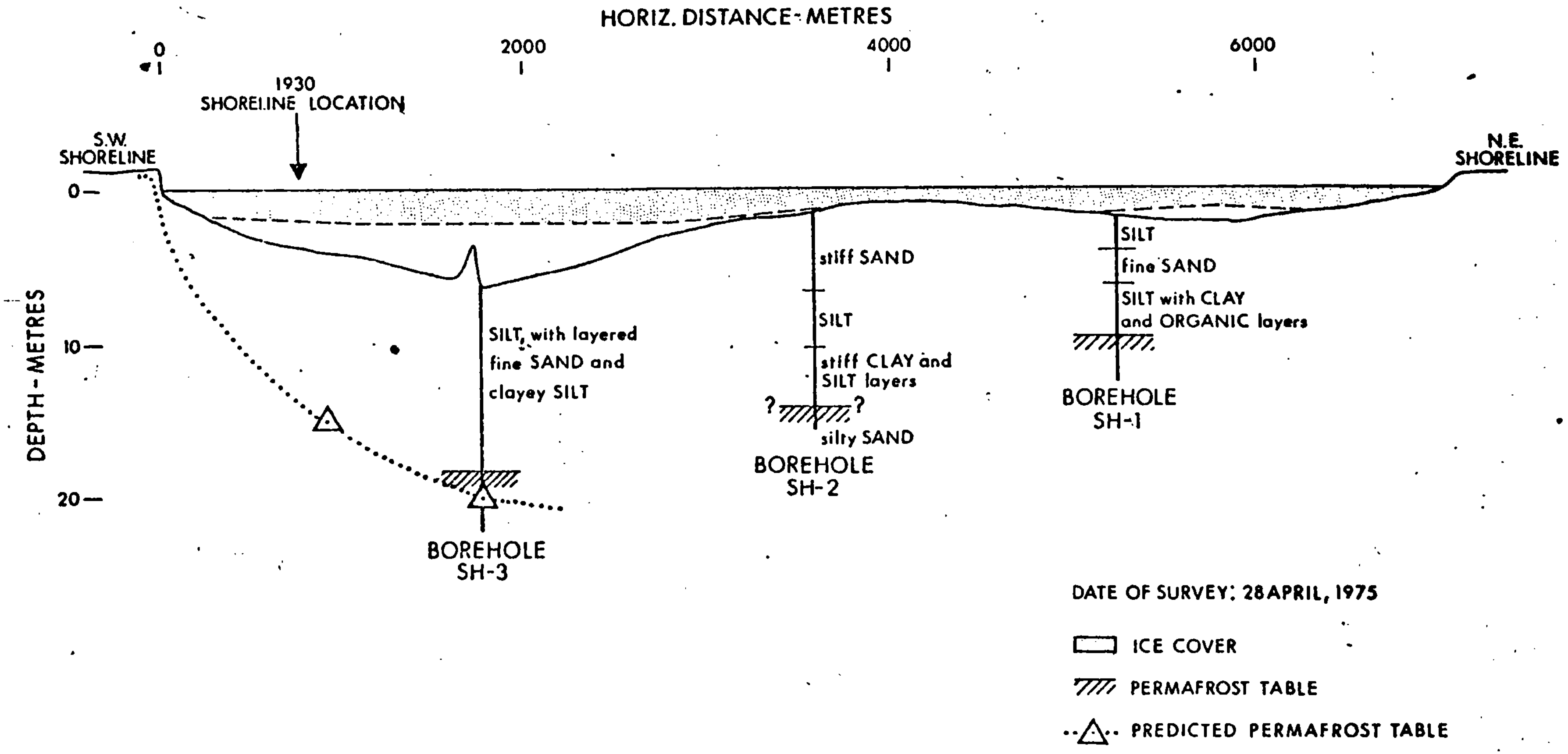


FIGURE 2.3 LOCATION MAP OF MACKENZIE RIVER - OUTER DELTA

(from Hollingshead and Rundquist, 1977)

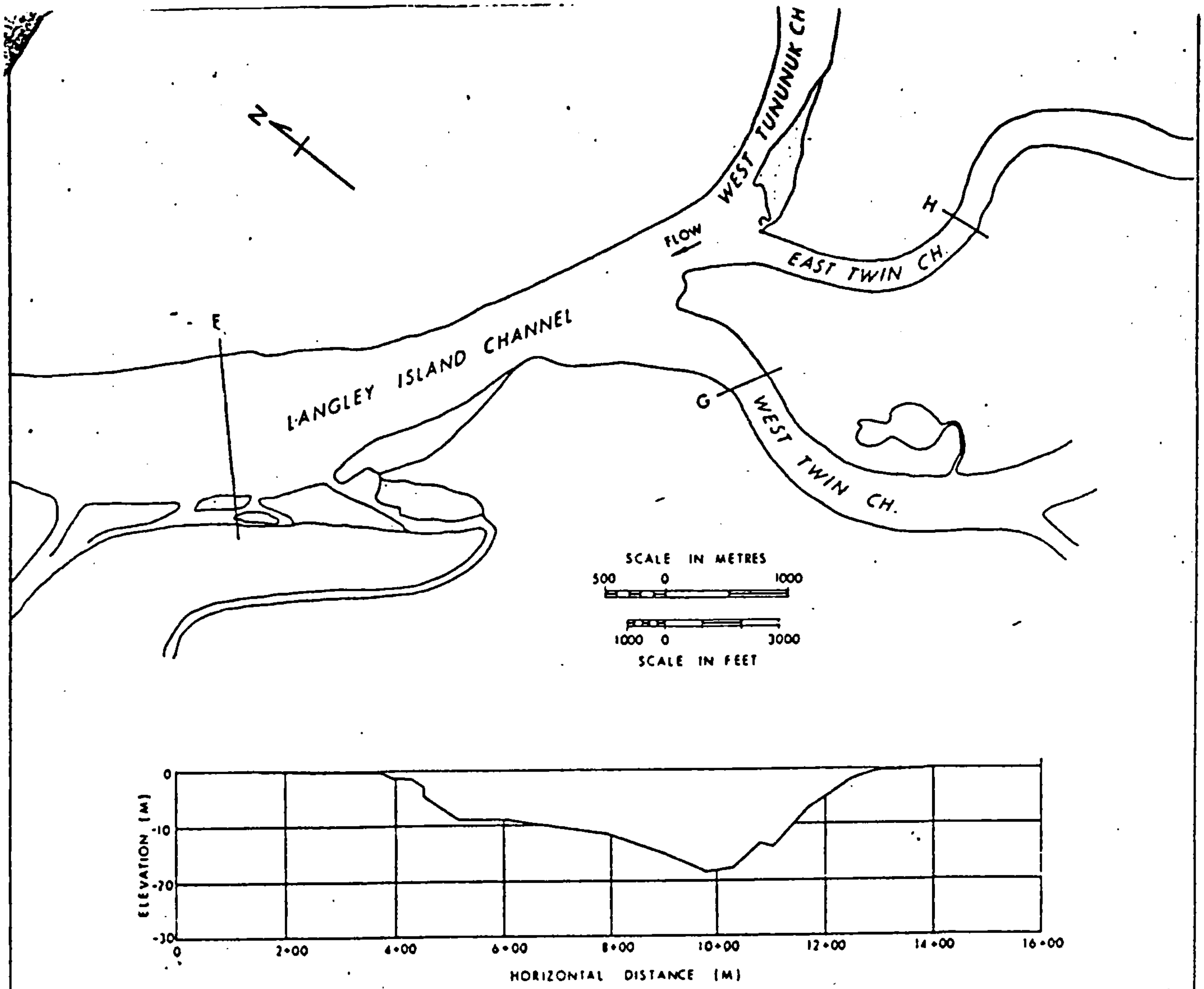


DATE OF SURVEY: 28 APRIL, 1975

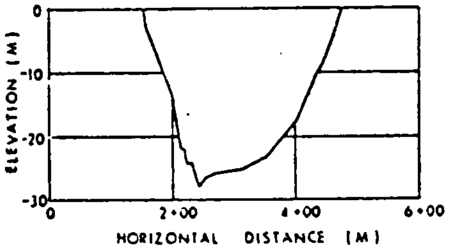
FIGURE 2.4

SHALLOW BAY CROSS SECTION (C)

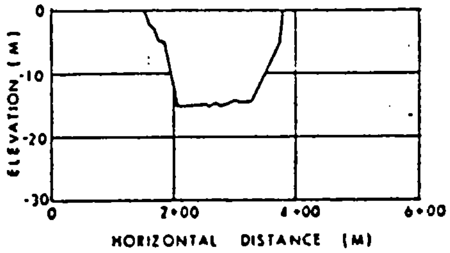
(from Hollingshead and Rundquist, 1977)



SECTION F LANGLEY ISLAND CHANNEL



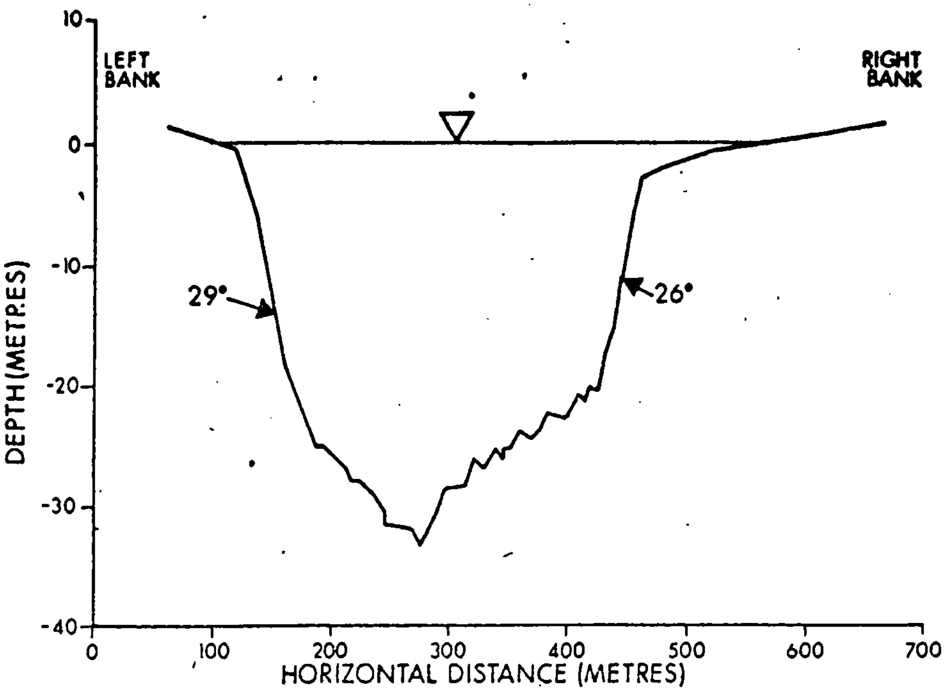
SECTION G WEST TWIN CHANNEL



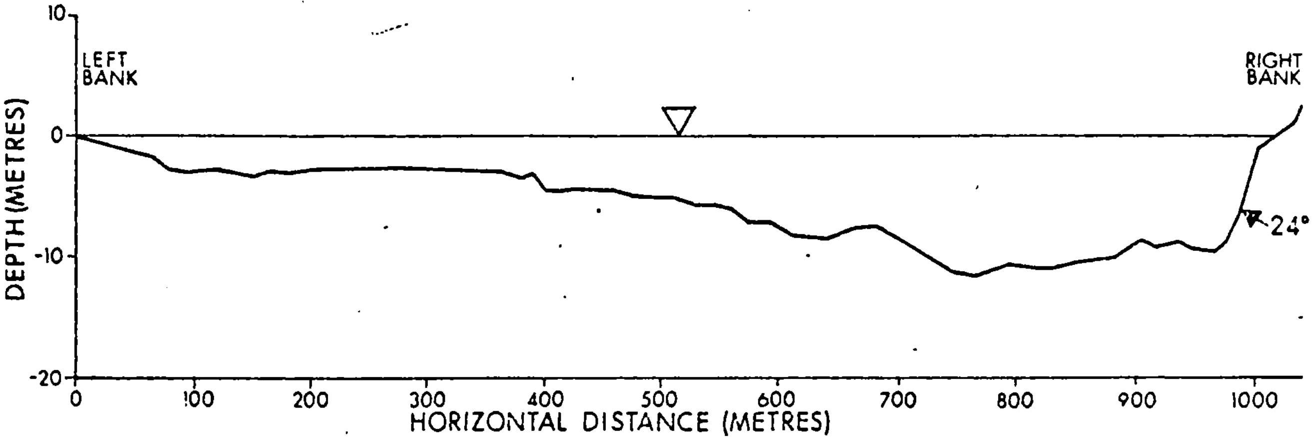
SECTION H EAST TWIN CHANNEL

FIGURE 2.5 COMPARISON OF DEPTHS IN SMALL AND LARGE CHANNELS

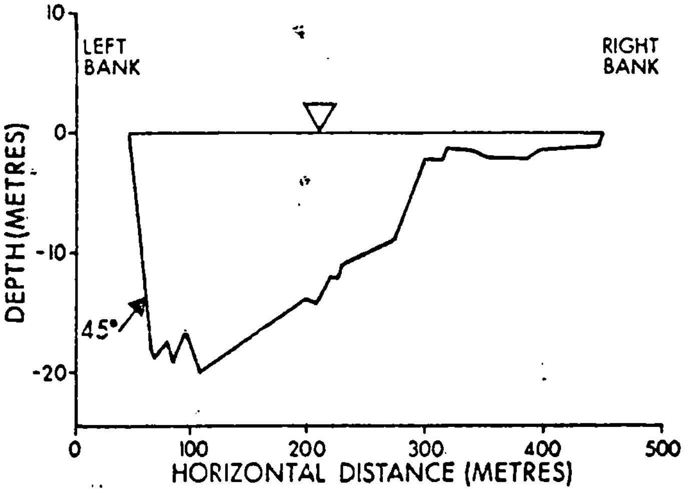
(from Hollingshead and Rundquist, 1977)



a. NORTH REINDEER CHANNEL (SECTION D)



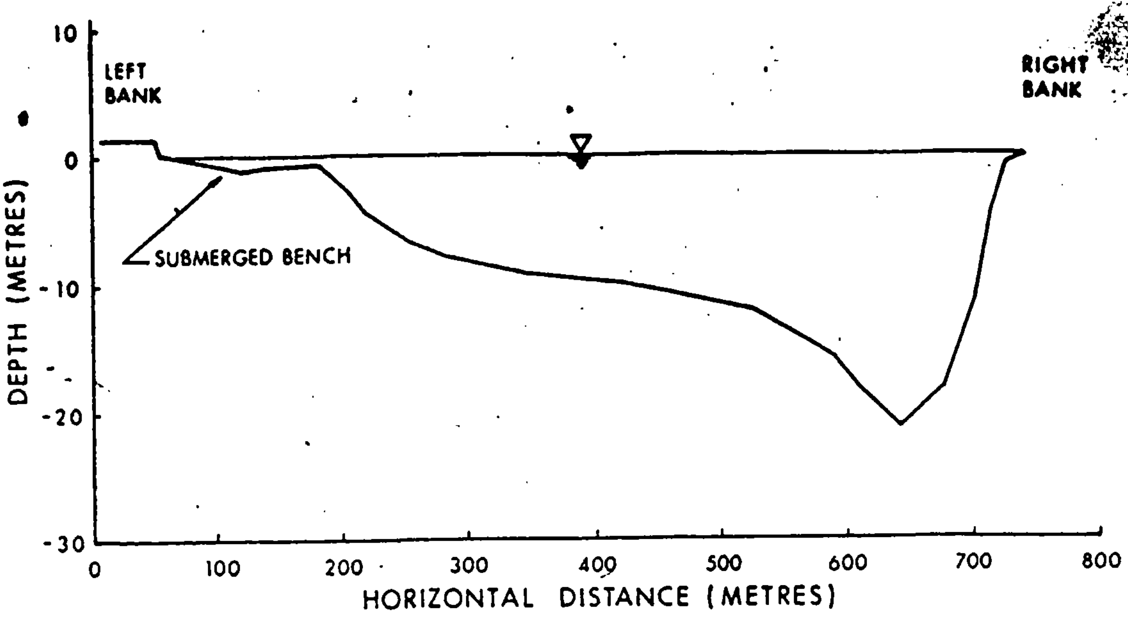
b. EAST CHANNEL (SECTION J)



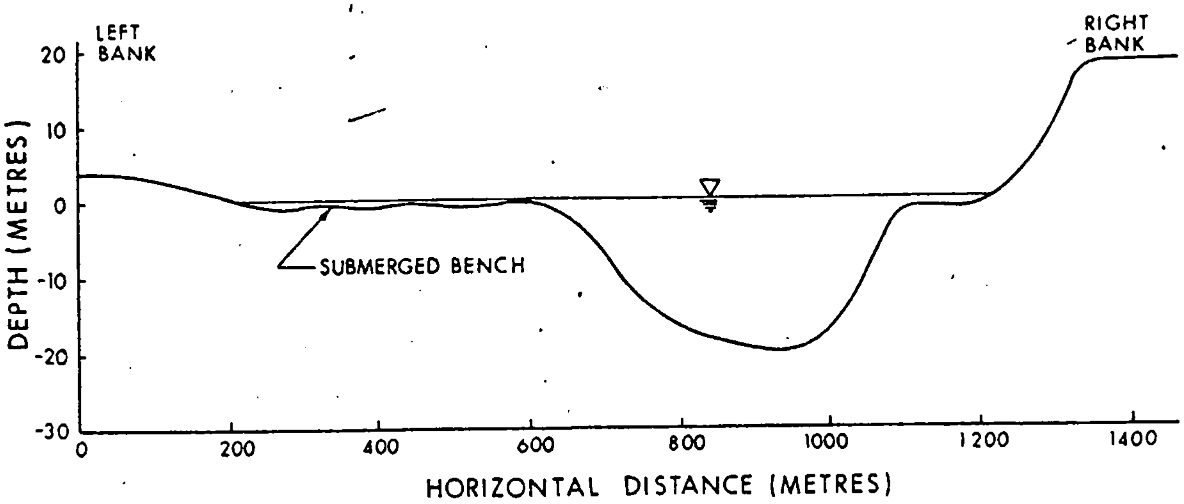
c. KUMAK CHANNEL (SECTION M)

FIGURE 2.6 CHANNEL CROSS SECTIONS WITH STEEP SIDE SLOPES

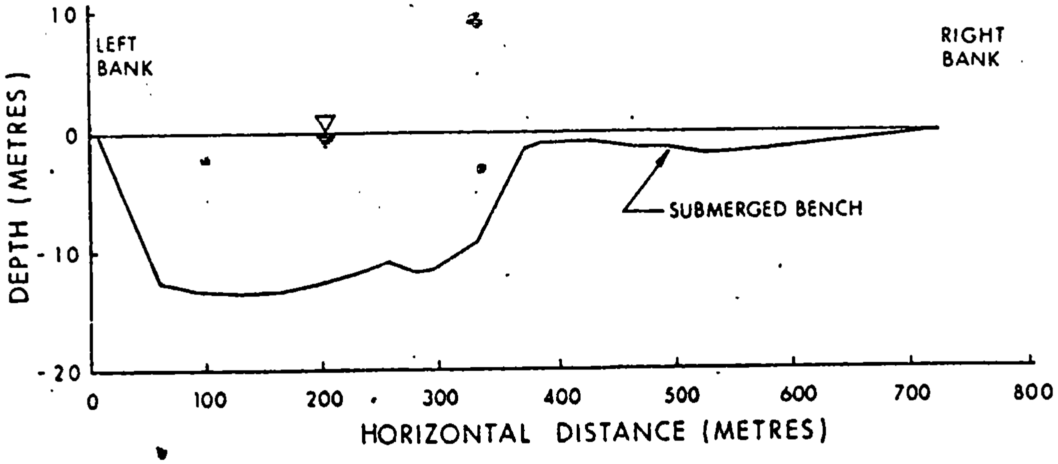
(from Hollingshead and Rundquist, 1977)



a. NORTH REINDEER CHANNEL (SECTION E)



b. EAST CHANNEL - SWIMMING POINT (SECTION K)



c. LANGLEY ISLAND CHANNEL (SECTION L)

FIGURE 2.7 CHANNEL CROSS SECTIONS WITH SUBMERGED BENCHES

(from Hollingshead and Rundquist, 1977)

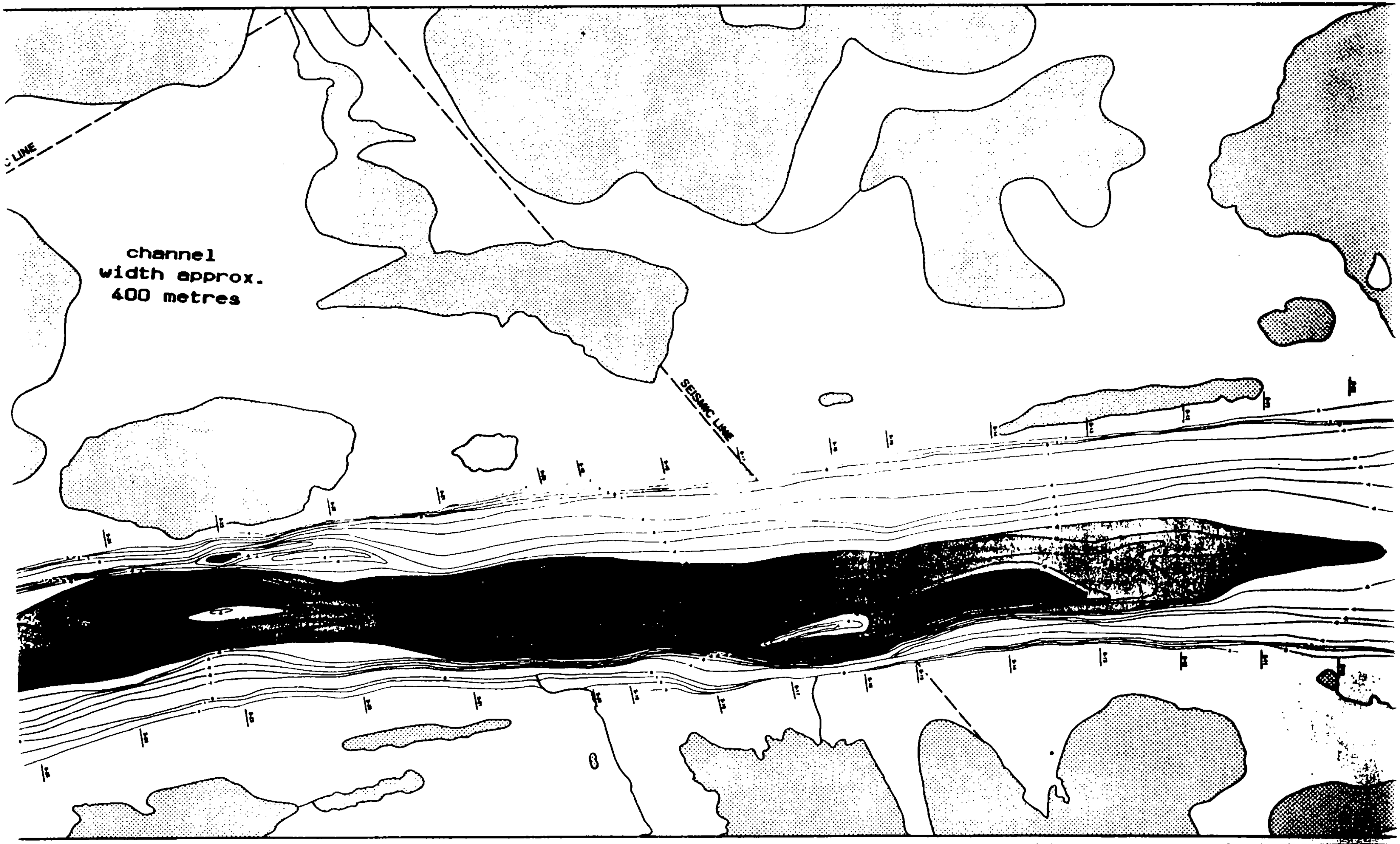


FIGURE 2.8

MOUND-HOLE BATHYMETRY OF NAPOIAK CHANNEL BETWEEN SCHOONER AND TAYLOR CHANNELS

(from Lapointe, 1985)

unshaded = less than 6m deep   dark shading = more than 10m deep   flow is to right

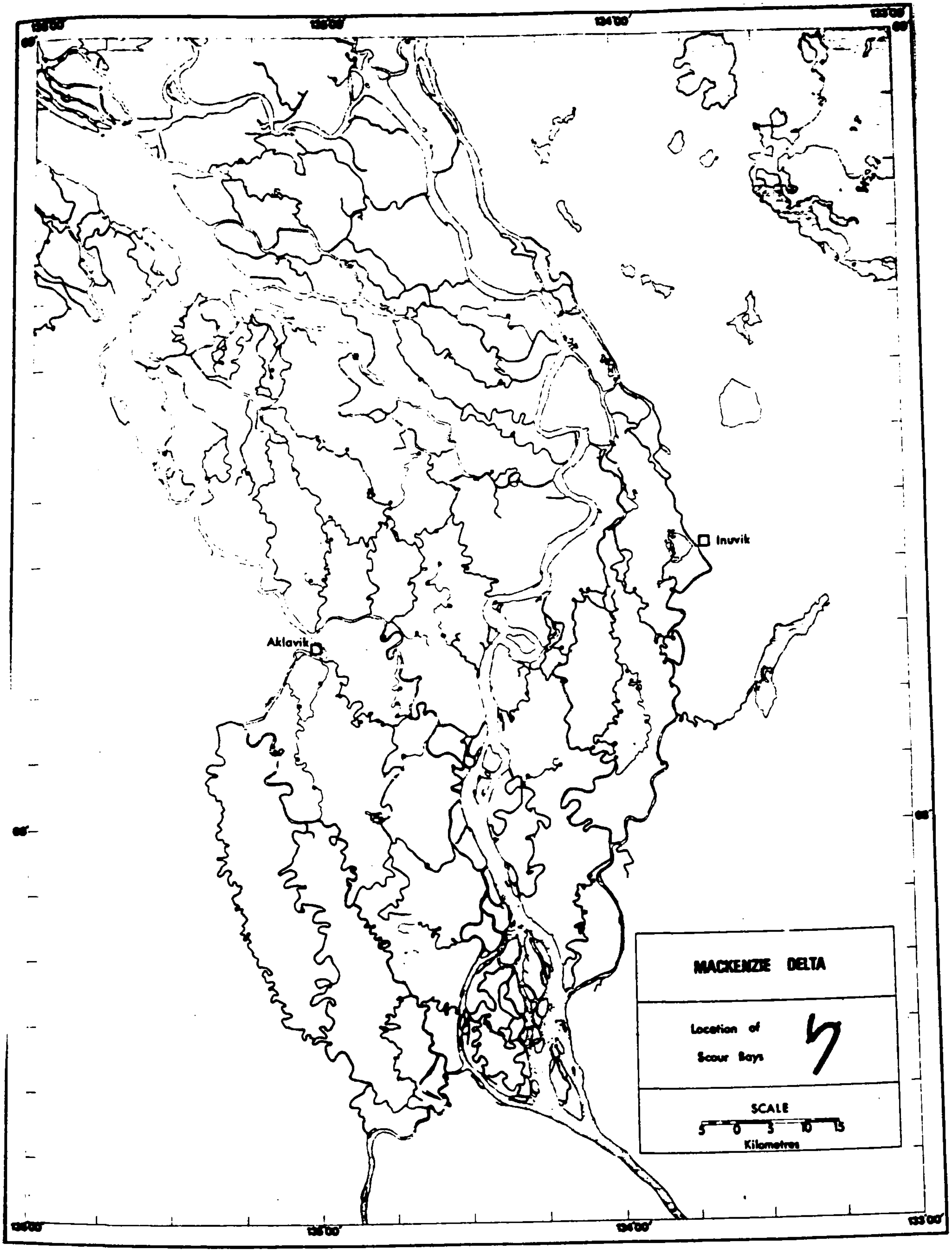


FIGURE 2.9

(from Lapointe, 1986a)

FIGURE 2.10 The style of meandering in Mackenzie Delta channels. Notice the contrast between the rather regular meanders of Peel Channel at the left, and the irregular "contorted" style of two smaller channels to the right.

Dept.of E.M.R. photo A21583-131.Near 67°50'N, 134°45'W.

(from Lapointe, 1984)

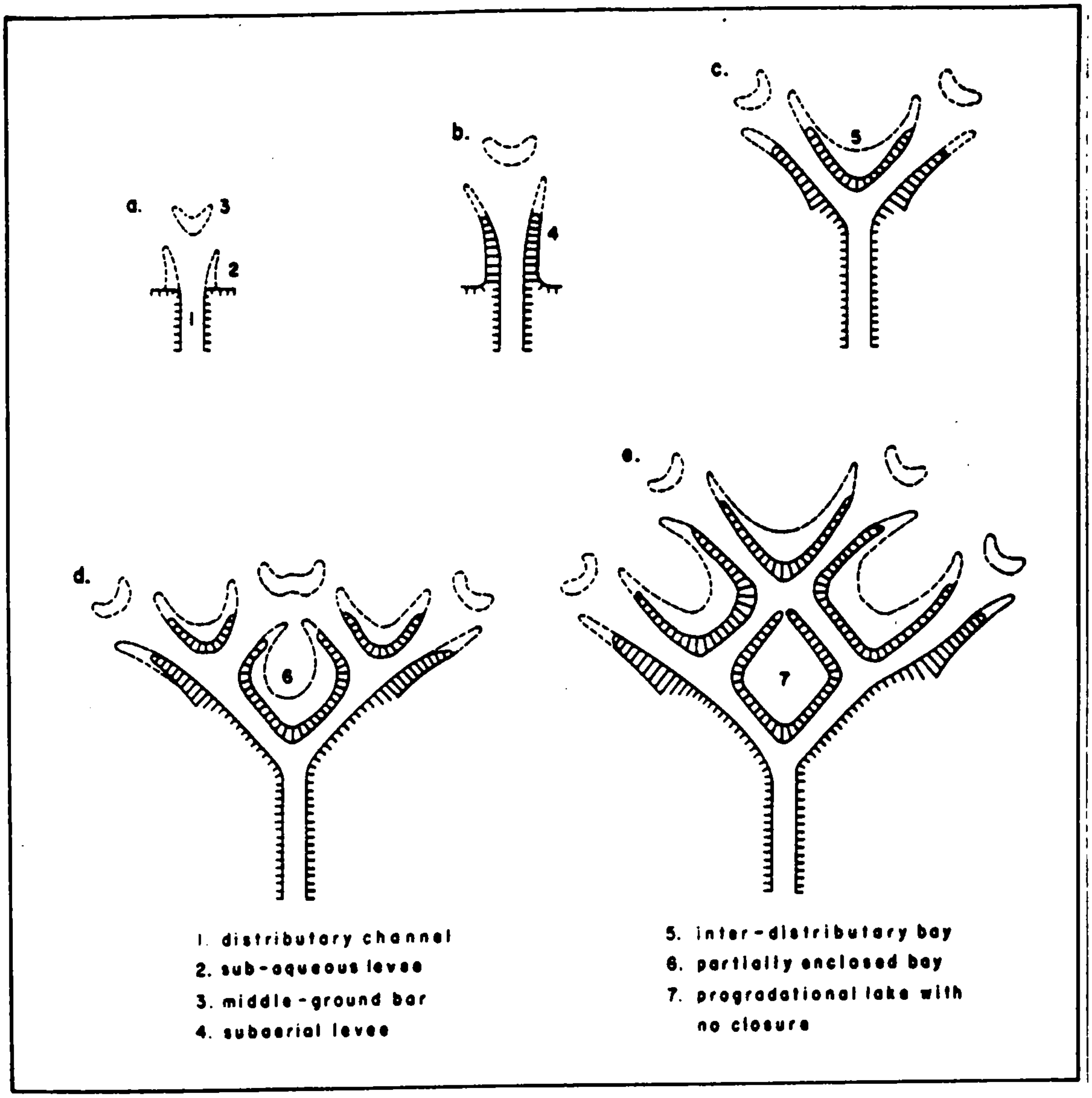


FIGURE 2.11 Deltaic advance in the absence of stratified flow: the traditional model.

a. Initial state - subaqueous levees and middle-ground bar
b. Distributary extension by levee progradation
c. Channel bifurcation, inter-distributary bay formation
d. Continued bifurcation and channel convergence, isolation of inter-distributary bay
e. Completed bay isolation, formation of a progradational lake basin with no closure

(from Lewis, 1988)

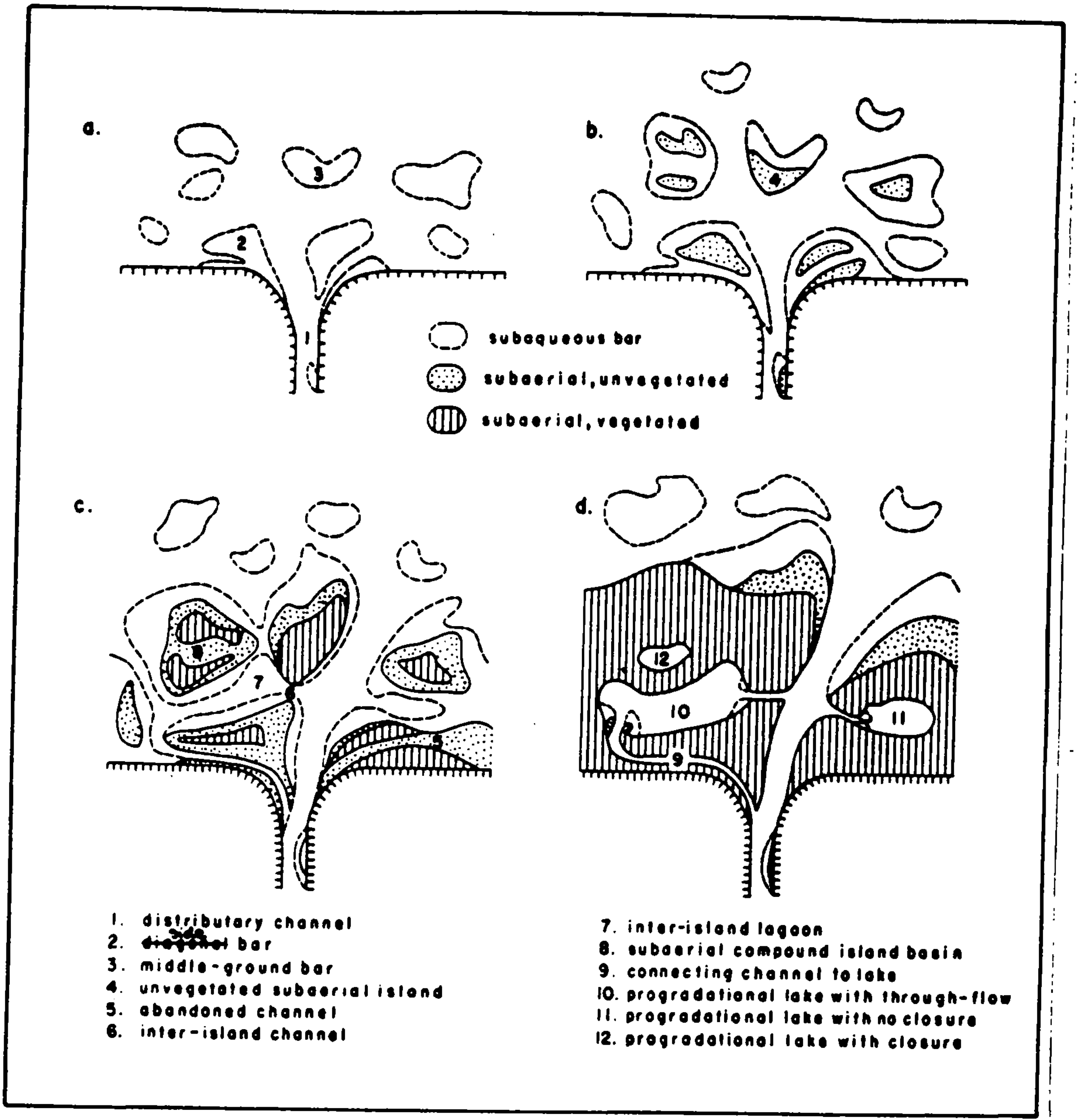


FIGURE 2.12 Deltaic advance in the absence of stratified flow: the Mackenzie situation.

a. Initial state - broad, low-relief subaqueous bars
b. Bar expansion, formation of unvegetated subaerial islands
c. Island expansion and colonization by vegetation, definition of compound island basin and inter-island lagoon and channels
d. Island coalescence, extension of distributary channel and inter-distributary flats, isolation of progradational lakes with and without closure

(from Lewis, 1988)

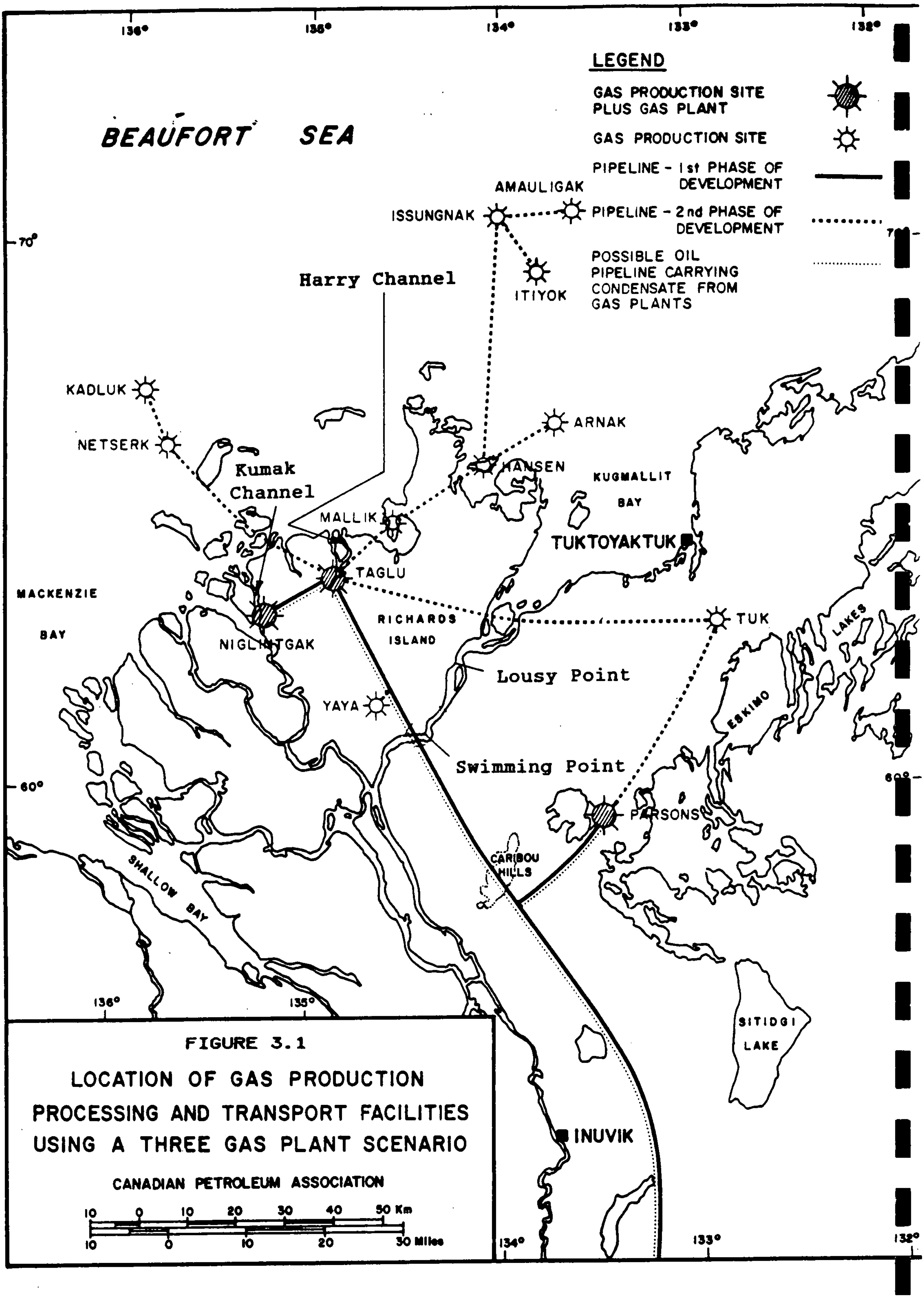


FIGURE 3.1

LOCATION OF GAS PRODUCTION PROCESSING AND TRANSPORT FACILITIES USING A THREE GAS PLANT SCENARIO

CANADIAN PETROLEUM ASSOCIATION

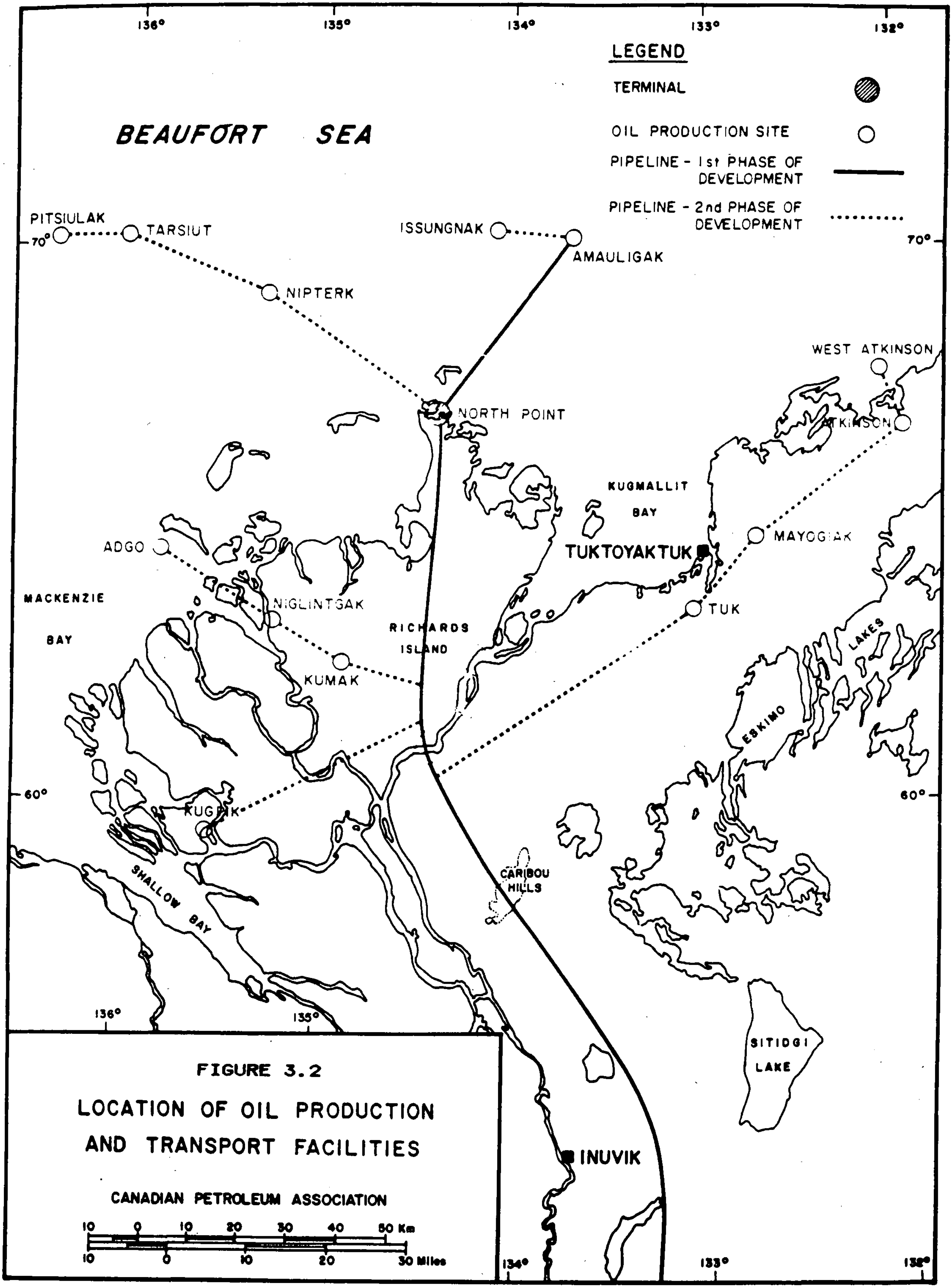
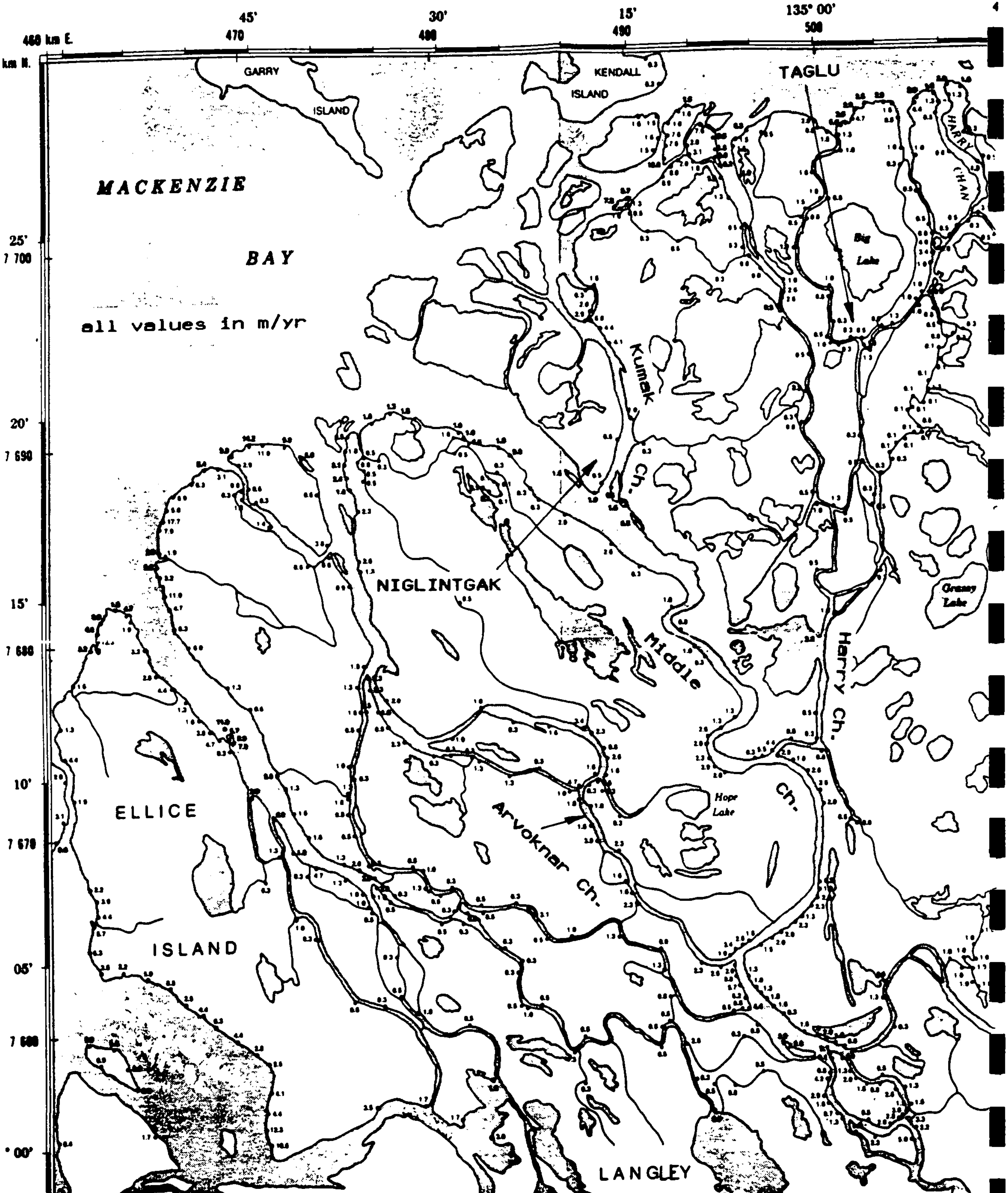


FIGURE 3.2

LOCATION OF OIL PRODUCTION AND TRANSPORT FACILITIES

CANADIAN PETROLEUM ASSOCIATION

FIGURE 3.3 BANK EROSION RATES IN WESTERN OUTER DELTA



(from Lapointe, 1986b)

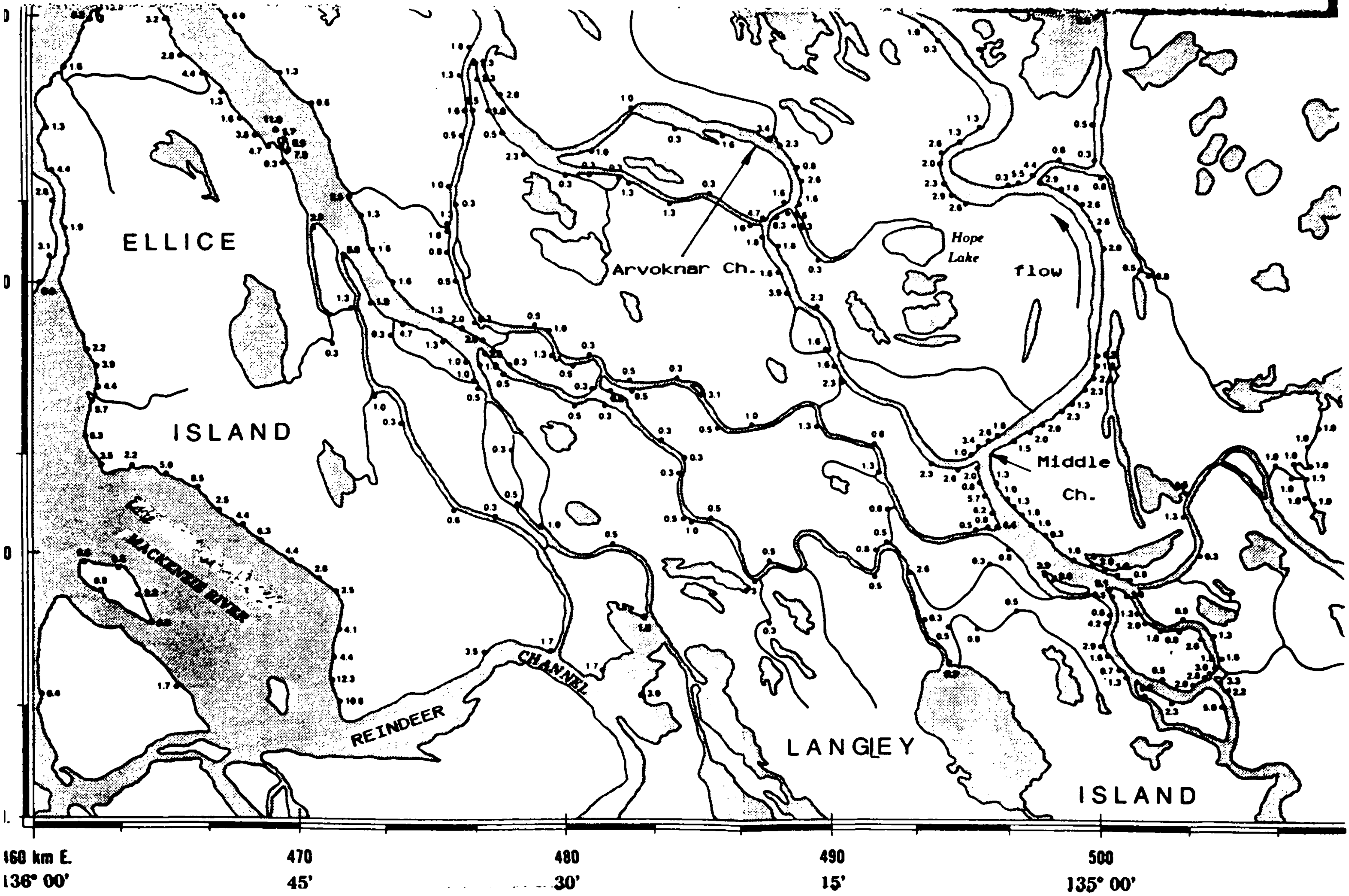


FIGURE 3.4 BANK EROSION RATES, ELLICE AND LANGLEY ISLAND AREAS (m/yr) (from Lapointe, 1986b)

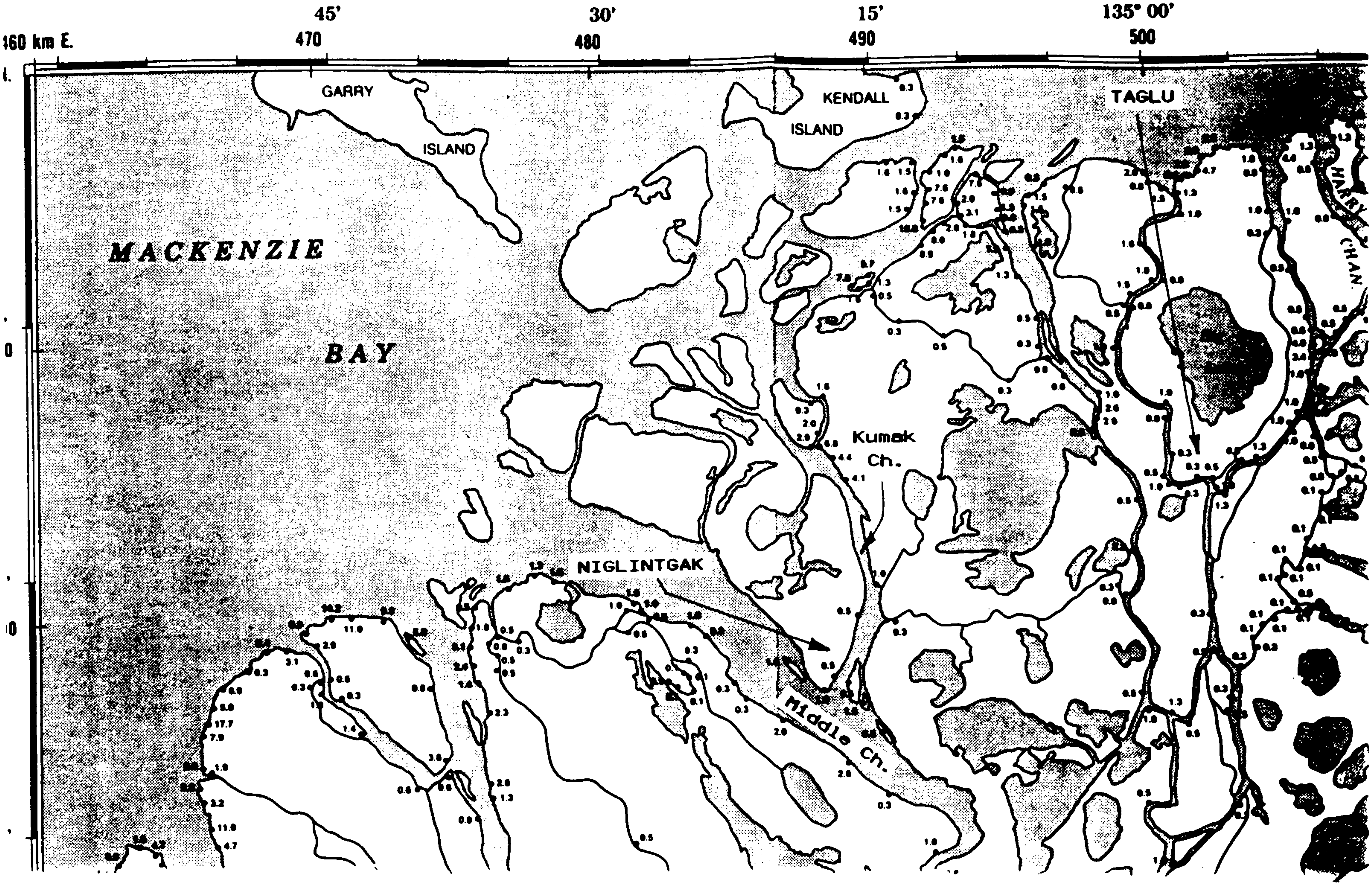


FIGURE 3.5 BANK EROSION RATES, NIGLINTGAK - TAGLU AREA

(m/yr) (from Lapointe, 1986b)

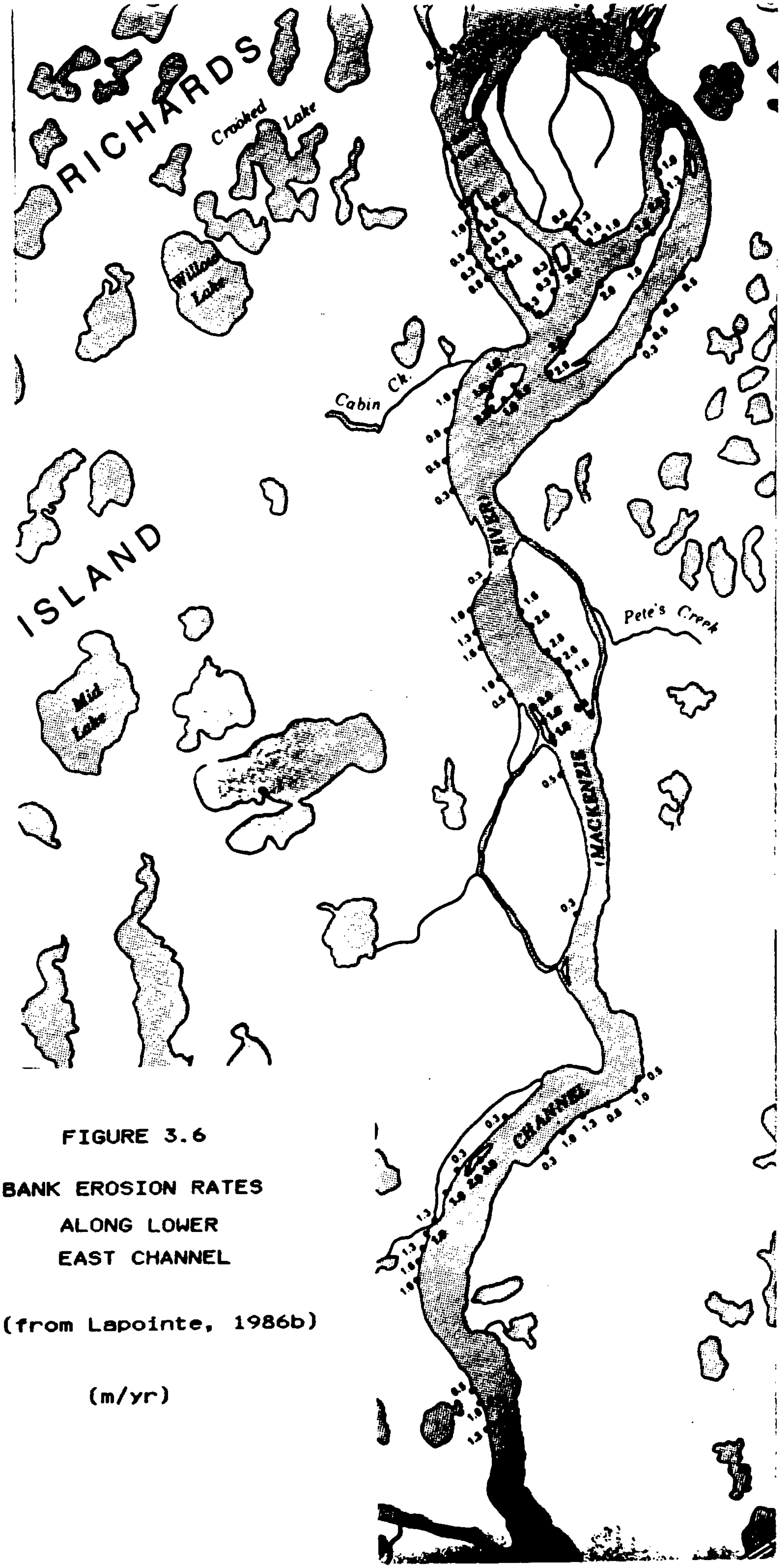


FIGURE 3.6

BANK EROSION RATES
ALONG LOWER
EAST CHANNEL

(from Lapointe, 1986b)

(m/yr)

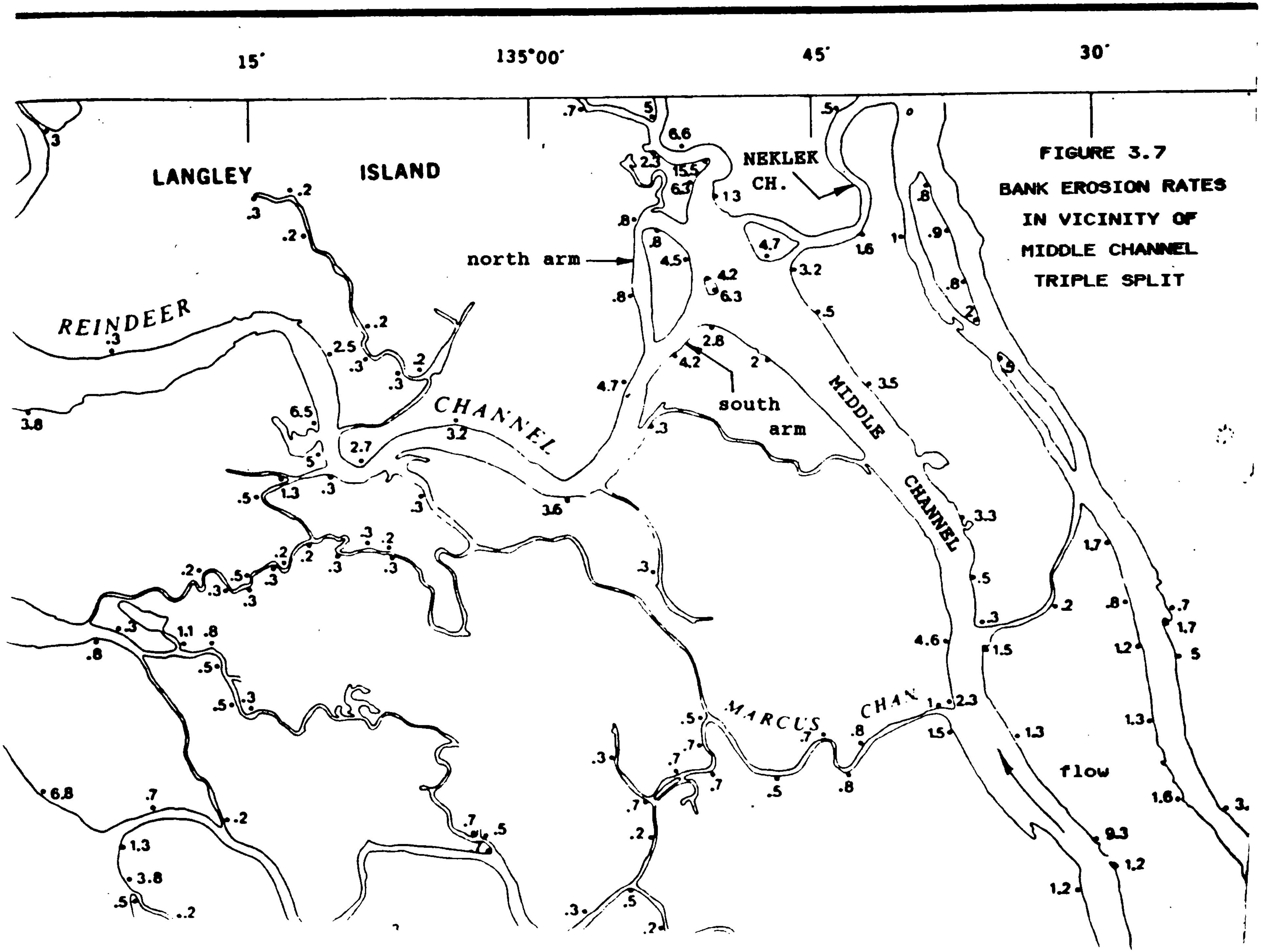


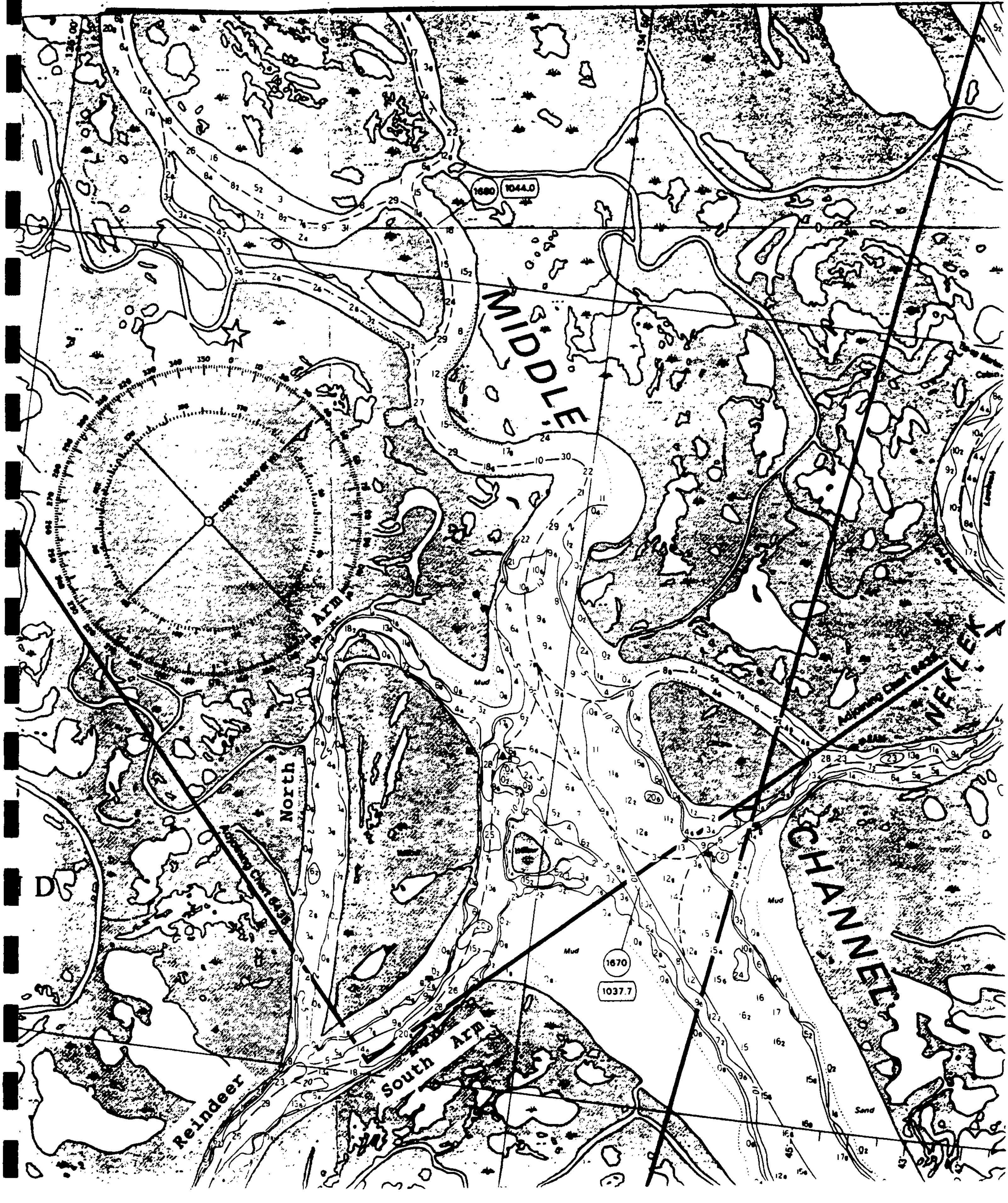
FIGURE 3.7
BANK EROSION RATES
IN VICINITY OF
MIDDLE CHANNEL
TRIPLE SPLIT

(from Lapointe, 1986b)

FIGURE 3.8

BATHYMETRY OF TRIPLE-SPLIT AREA OF MIDDLE CHANNEL

(from CHS chart 6434 ; depths in m below LWD)



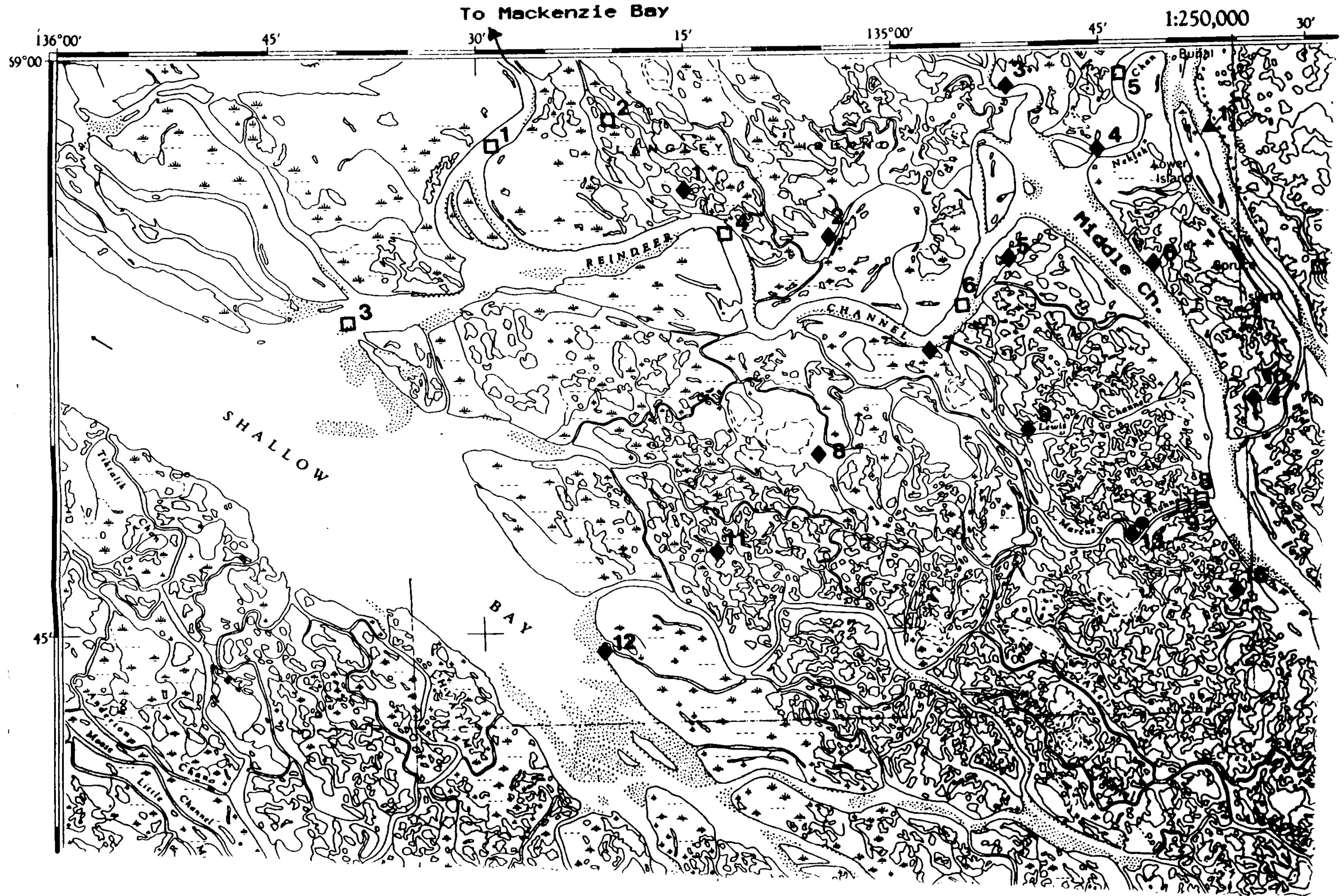


FIGURE 3.9

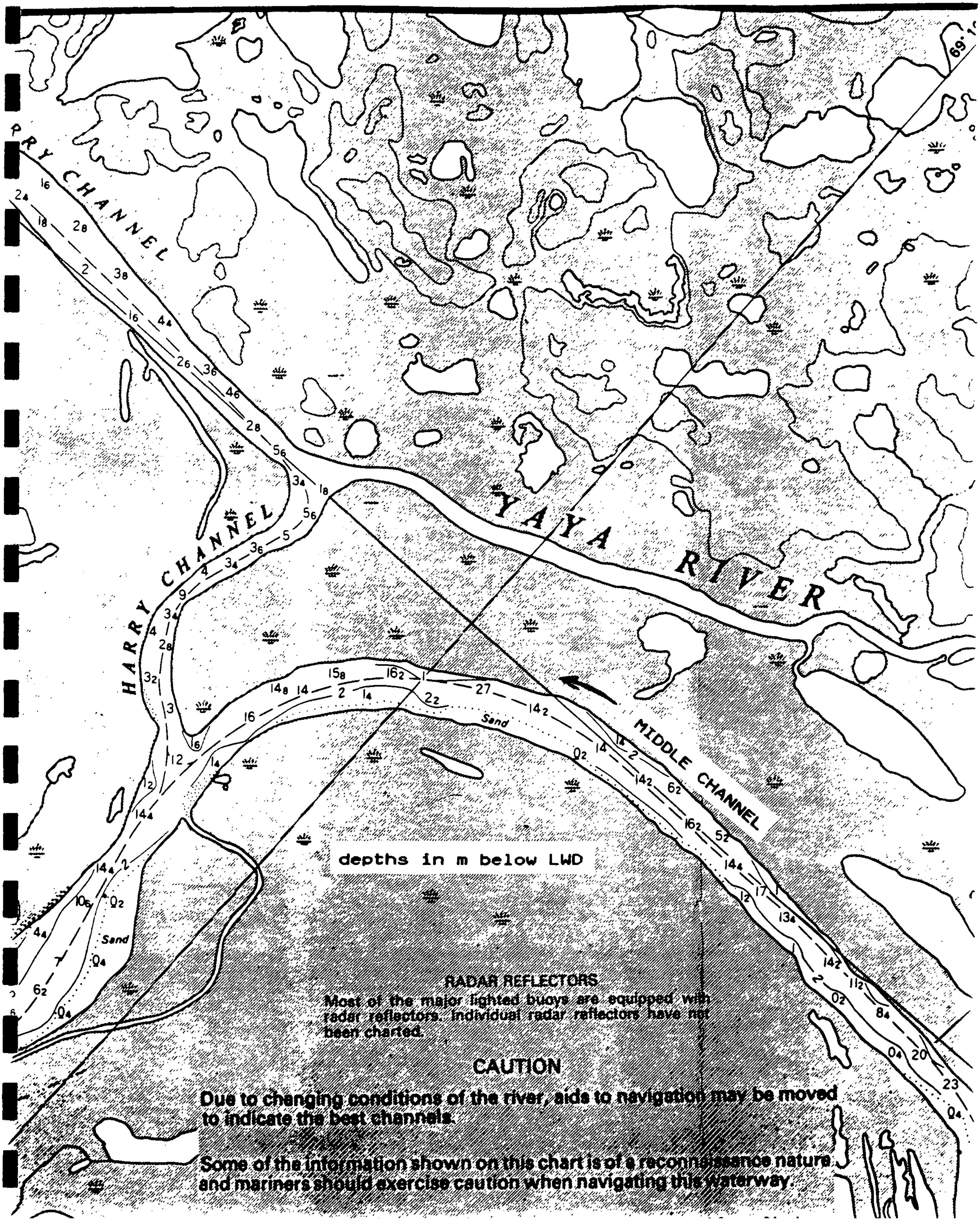
MAP OF REINDEER CHANNEL AREA

(from IWD Hydrologic Information series map, Aklavik)

FIGURE 3.10

(from CHS chart 6435)

MAP OF HARRY CHANNEL BRANCH-OFF FROM MIDDLE CHANNEL



depths in m below LWD

RADAR REFLECTORS
Most of the major lighted buoys are equipped with radar reflectors. Individual radar reflectors have not been charted.

CAUTION
Due to changing conditions of the river, aids to navigation may be moved to indicate the best channels.

Some of the information shown on this chart is of a reconnaissance nature and mariners should exercise caution when navigating this waterway.

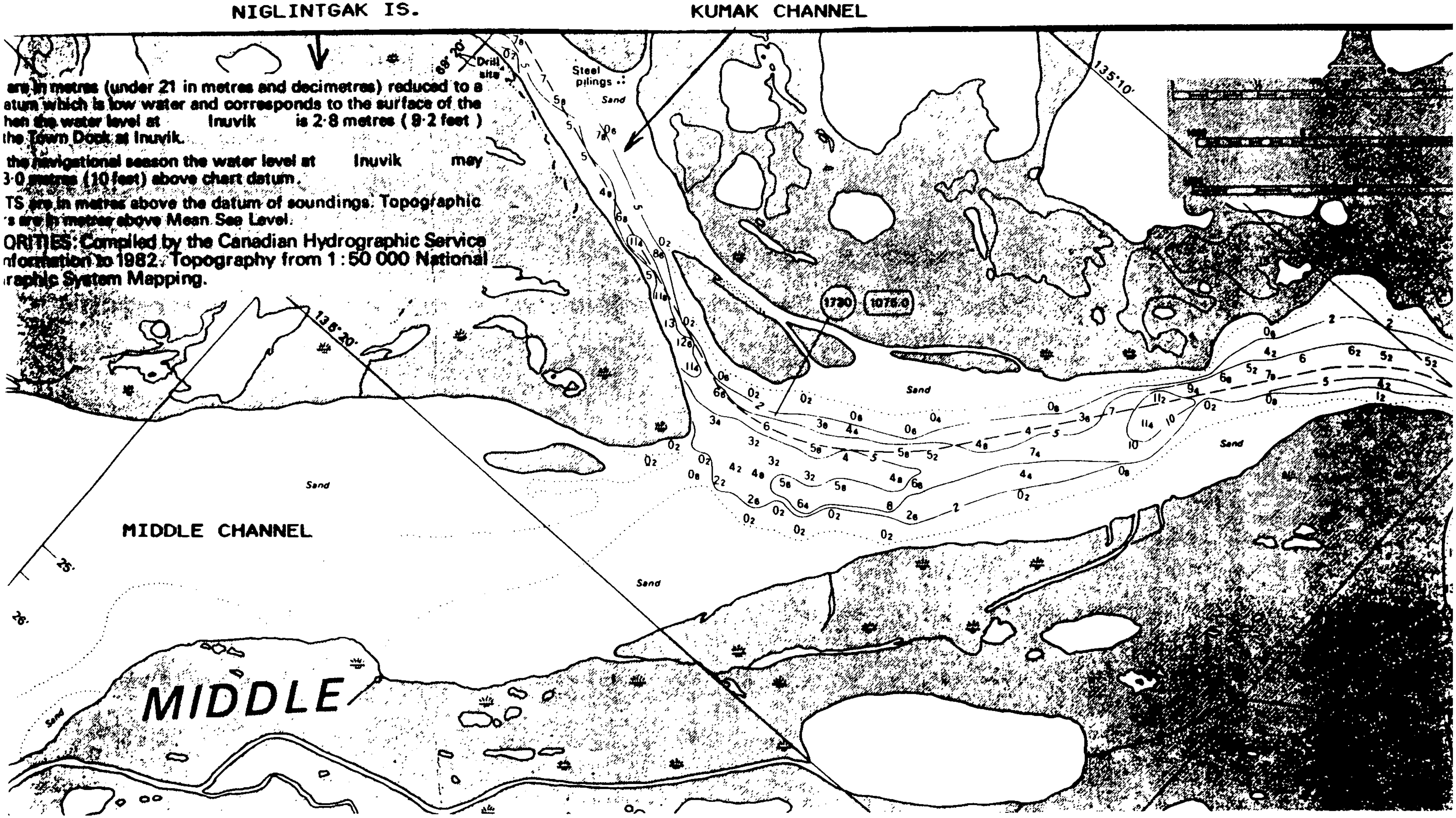


FIGURE 3.11

BATHYMETRIC MAP OF BRANCH-OFF OF KUMAK CHANNEL FROM MIDDLE CHANNEL

(from CHS chart 6435)

flow is towards left

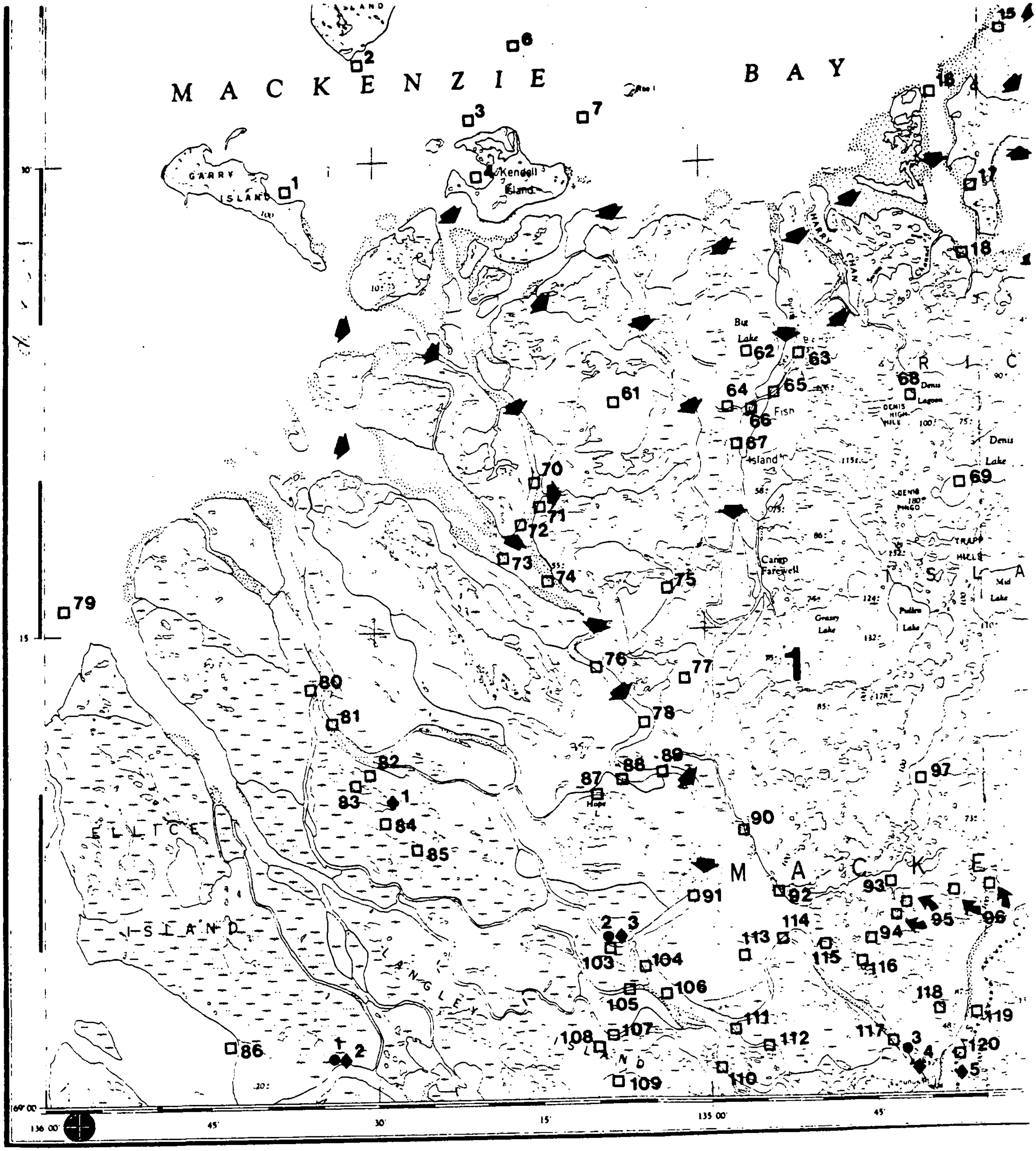


FIGURE 3.12

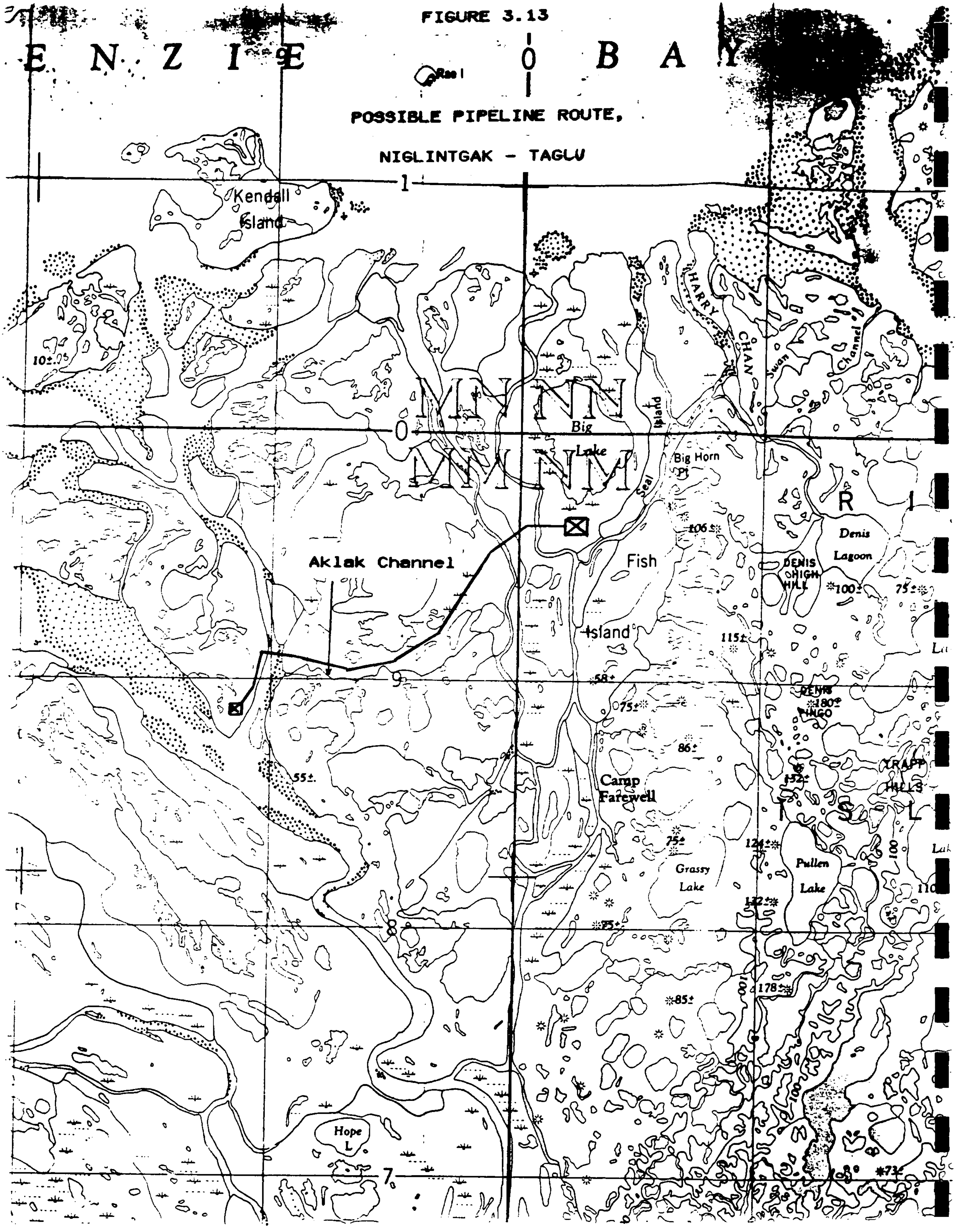
ESTUARINE INLETS OF THE NORTHWEST PART OF THE OUTER DELTA

(from IWD, Hydrologic Information Series map, Mackenzie Delta)

FIGURE 3.13

POSSIBLE PIPELINE ROUTE,

NIGLINTGAK - TAGLU



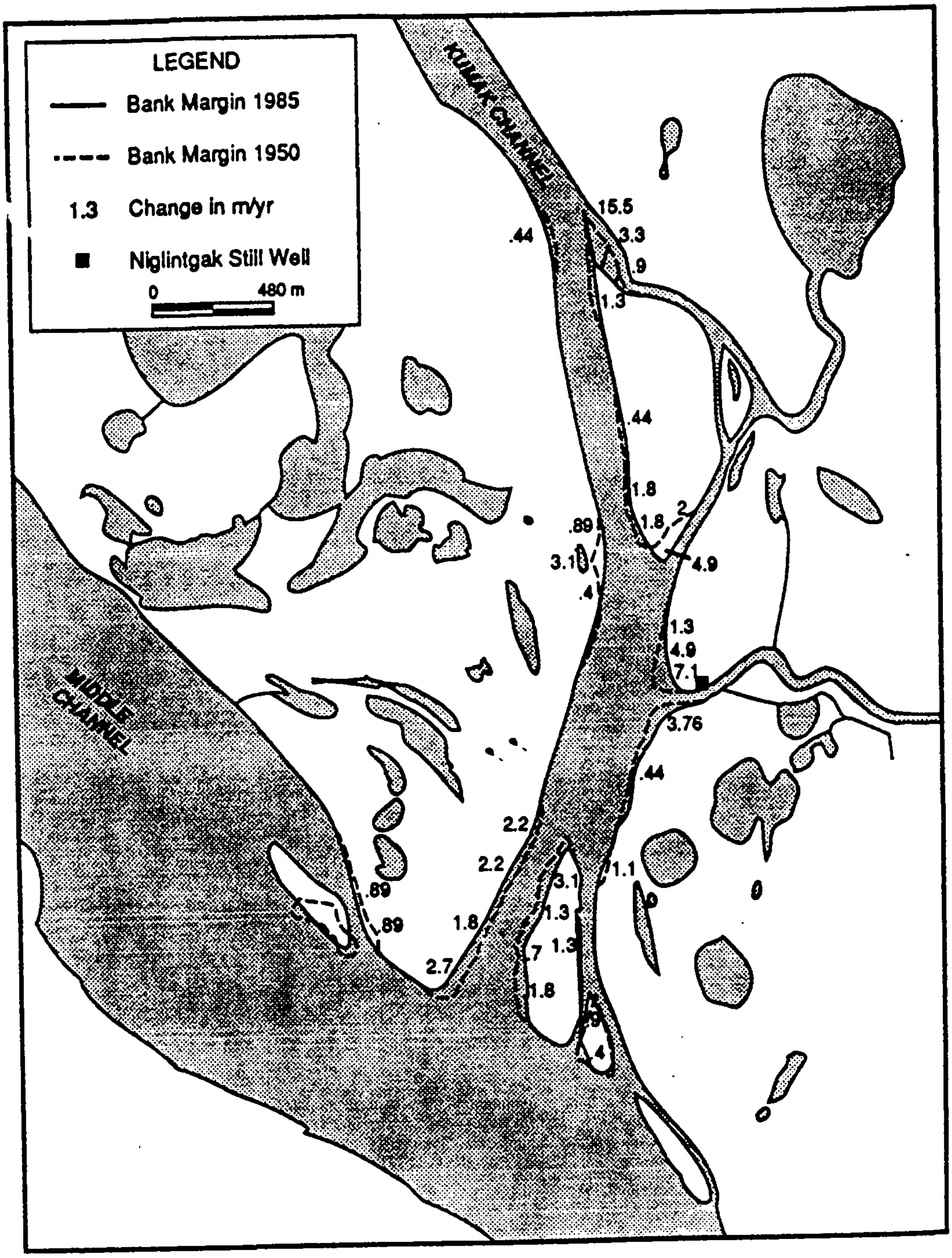


Figure 3.14: Niglintgak Island Area Bank Stability from 1950 to 1985

(from Traynor and Dallimore, in prep.)

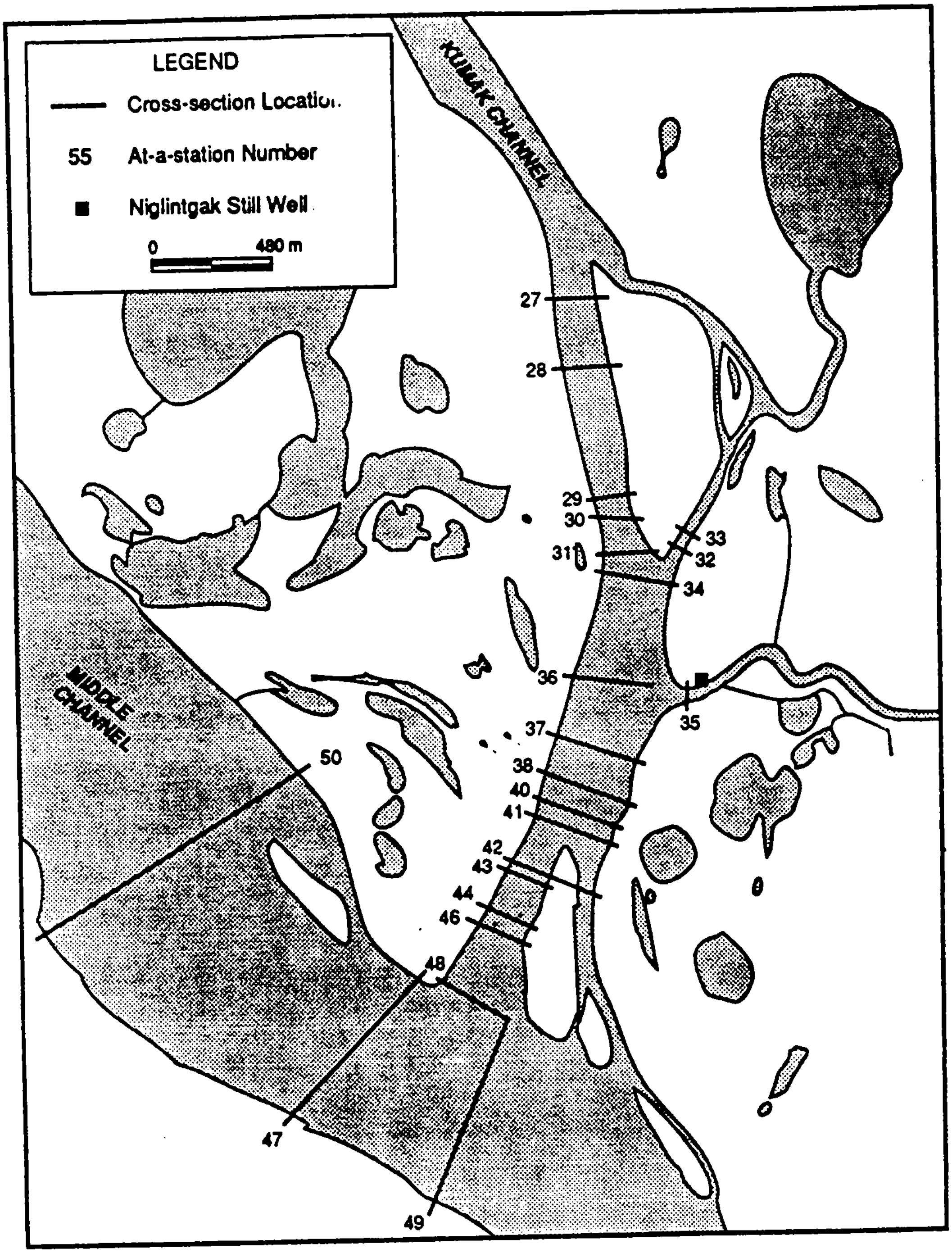


Figure 3.15 : Niglintgak Island Area Cross-Section Locations

(from Traynor and Dallimore, in prep.)

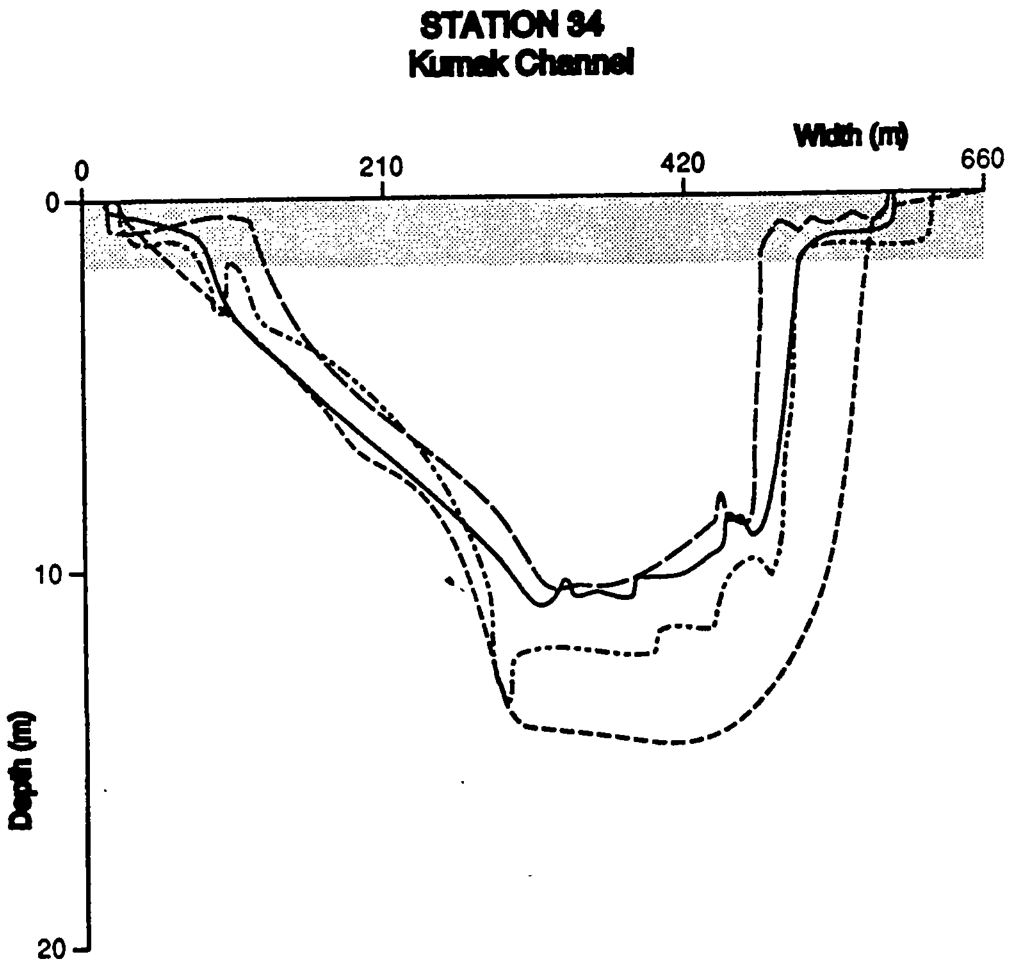


FIGURE 3.16

(from Traynor and Dallimore, in prep.)

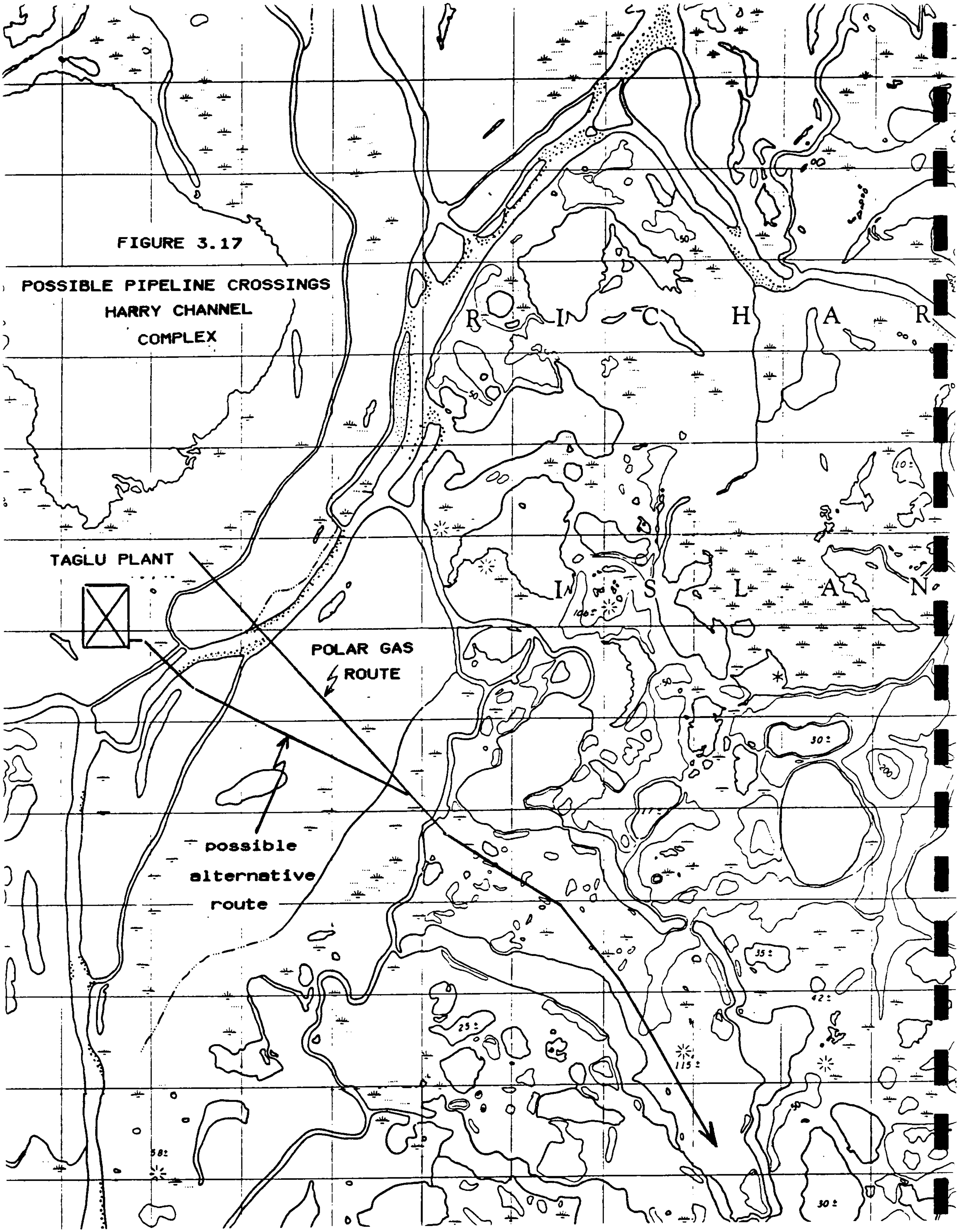


FIGURE 3.17

POSSIBLE PIPELINE CROSSINGS HARRY CHANNEL COMPLEX

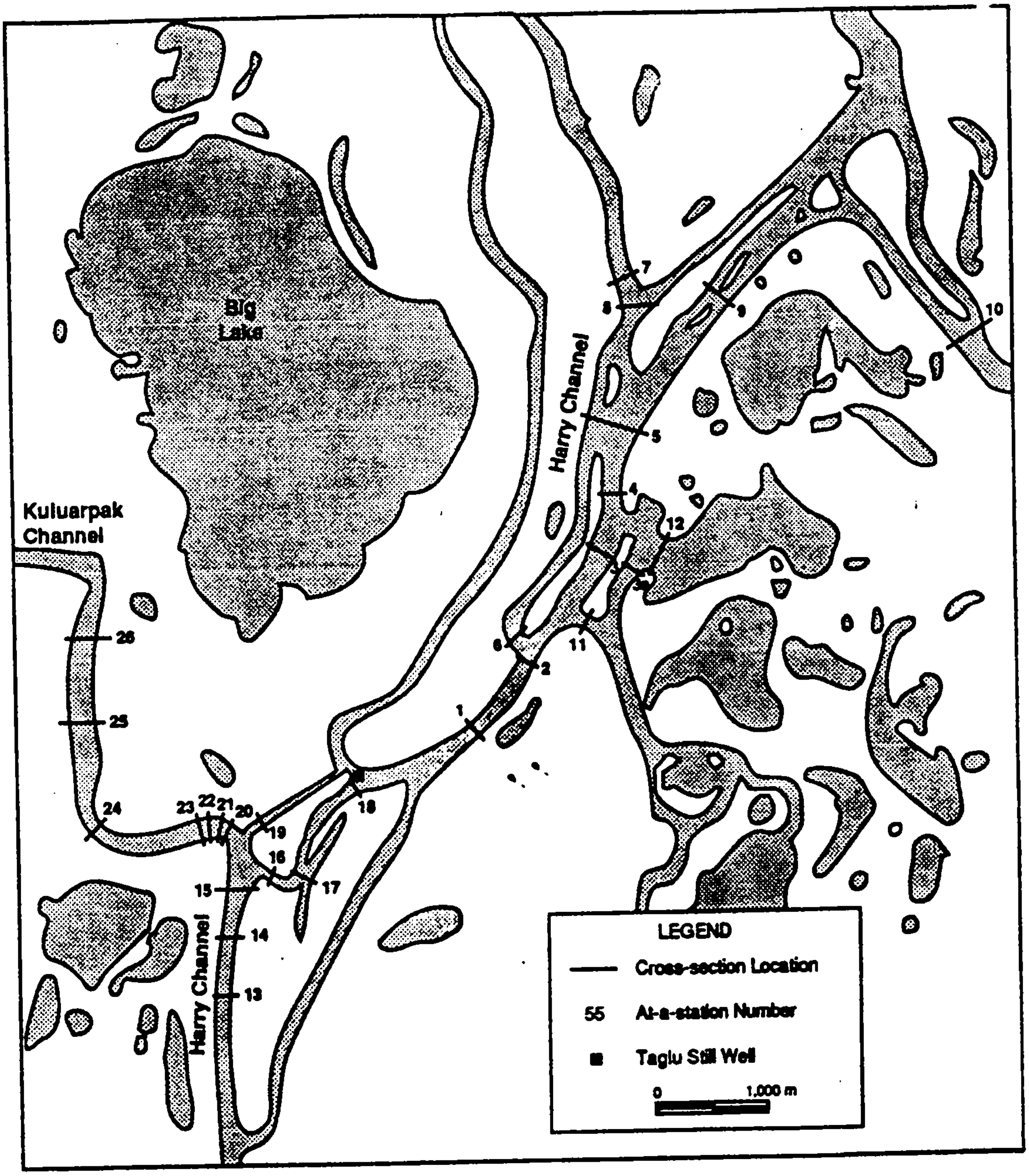


FIGURE 3.18 TAGLU ISLAND AREA CROSS-SECTION LOCATIONS

(from Traynor and Dallimore, in prep.)

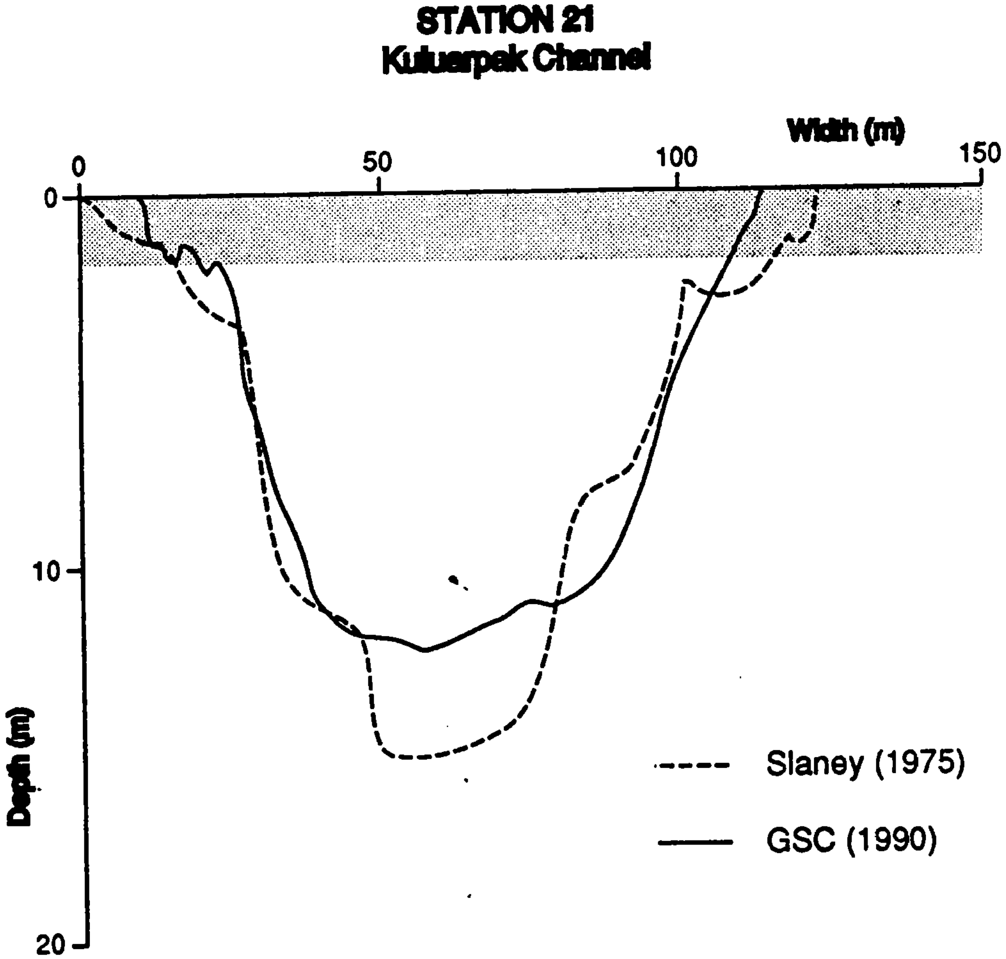


FIGURE 3.19

CROSS-SECTIONS AT STATION 21, KULUARPAK CHANNEL

(from Traynor and Dallimore, in prep.)

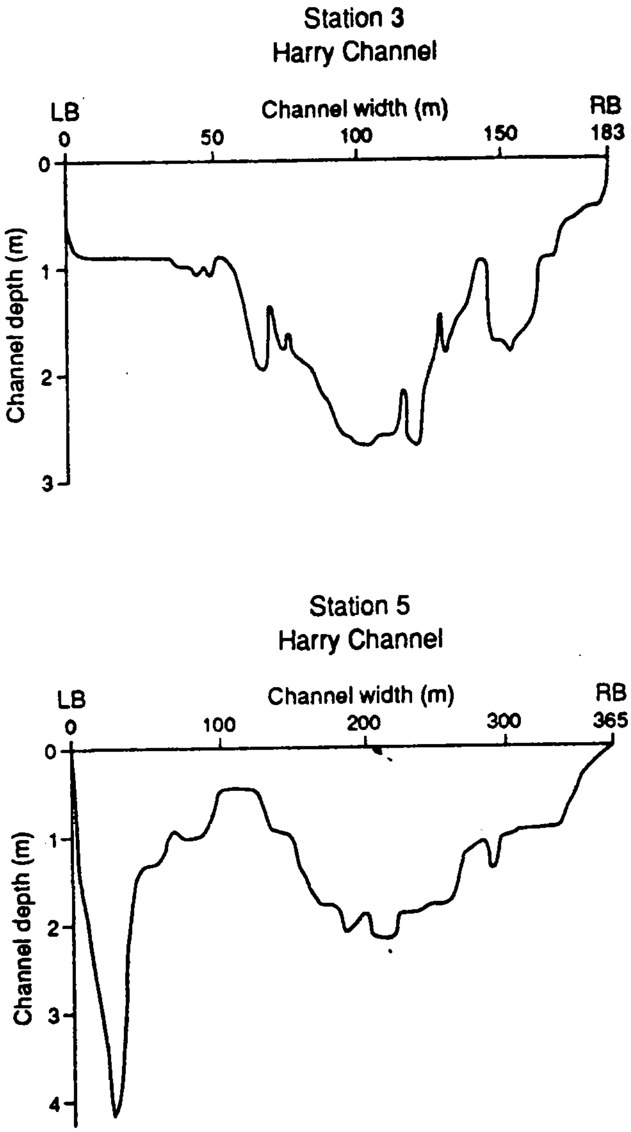


FIGURE 3.20

CROSS-SECTIONAL SURVEYS OF HARRY CHANNEL

(from Traynor and Dallimore, in prep.)

FIGURE 3.21

SURFICIAL DEPOSITS OF OUTER DELTA (from Rampton, 1988, GSC Map 1647a)

HOLOCENE

Ap alluvium (floodplain)
C colluvium
L lacustrine
cross-hatch thermokarst topography
Wr marine beaches, bars, spits

Bar denotes underlying unit:

$\overline{\text{KZ}}$ Kittigazuit Formation
$\overline{\text{UD}}$ undifferentiated
$\overline{\text{PL}}$ Pleistocene sands

PLEISTOCENE

L lacustrine
G glaciofluvial Gp outwash plains Gx ice-contact
M moraine Mm hummocky Mb blanket Mv veneer

Superscripts S T F B M denote glacial stade or period

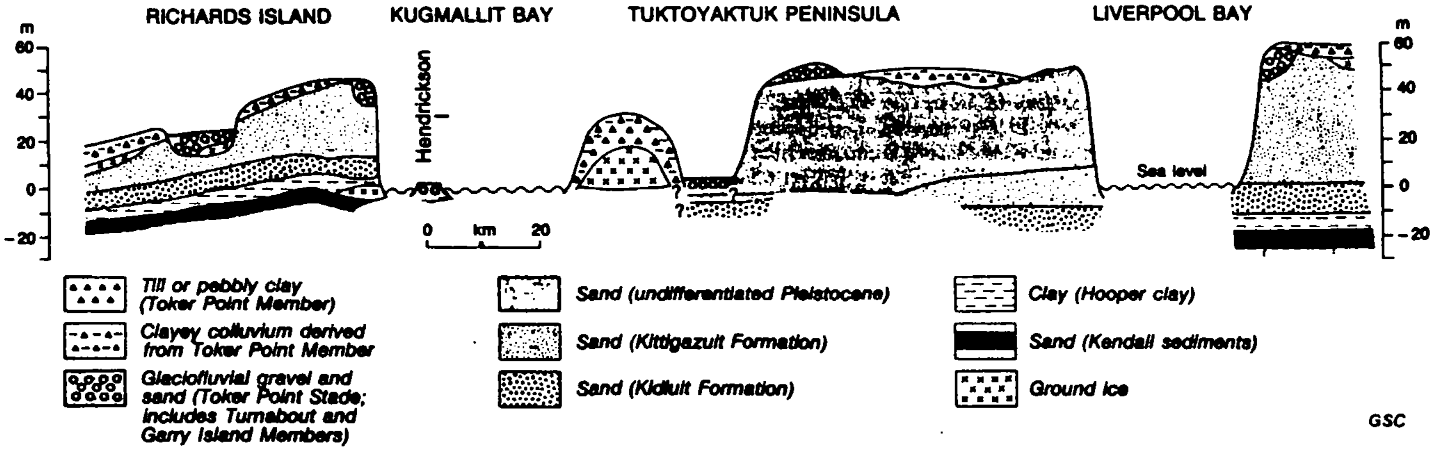


FIGURE 3.22 Diagrammatic representation of the stratigraphic succession, Tuktoyaktuk Coastlands (modified from Rampton, 1972c).

FIGURE 3.23 Stratigraphy at selected sections along East Channel, Mackenzie River

Thickness	Material
A. Composite section at site 67V	
18 m	Covered to crest of bank; mainly silt and sand in lower part, gravel in upper part
2.5 m	Sand, medium to fine grained, grey; many layers of organic detritus (finely disseminated to twig size) up to 15 cm thick
5 m	Sand, medium grained, grey, coarsens to gravel near top; finer grained sand is crossbedded
3.5 m	Covered
5 m	Sand, grey; organic laminae; small-scale crossbeds
0.5 m	Peat, medium to coarse plant detritus including wood fragments (67V7a)
1 m	Sand, fine and silt, grey
0.1 m	Peat; composed of plants; semi-autochtonous
2 m	Sand, fine, grey to greyish brown; some silty lenses; crossbedded; few pebbles
0.5 m	Gravel, iron stained; cobbles to 10 cm diameter
4 m	Covered to high water level
B. Stratigraphy at site 65V	
0.5 m	Interbedded turf, peat, silt, sand
1.5 m	Toker Point Stade? till, brownish grey
0.5 m	Gravel
13 m	Sand, grey; horizontal bedding up to 1 m thick; few beds of silt and coarse sand; upper 7 m partly covered
0.5 m	Sand, fine, brown; organic detrital lenses (65V9b, Table 17)
4.5 m	Covered
2.5 m	Sand, grey; thin beds of silt and organic detritus; crossbeds (65V7b at base)
1 m	Silt, brownish black; unit has lens-like configuration (65V6a, 6b)
1 m	Sand, fine, greyish brown; lenses and pods of sand (65V5a)
2 m	Sand, grey; locally iron stained; silt and organic detritus near top (65V3b, 3d)
6 m	Covered to mean water level
C. Stratigraphy at site 71V	
9.5 m	Covered
7.5 m	Silt and silty fine sand, brown; partly covered
9.5 m	Sand, fine, grey; iron stained; driftwood mats; few logs and pebbly layers; laminae of organic detritus near base
4.5 m	Covered to high water level

(from Rampton, 1988)

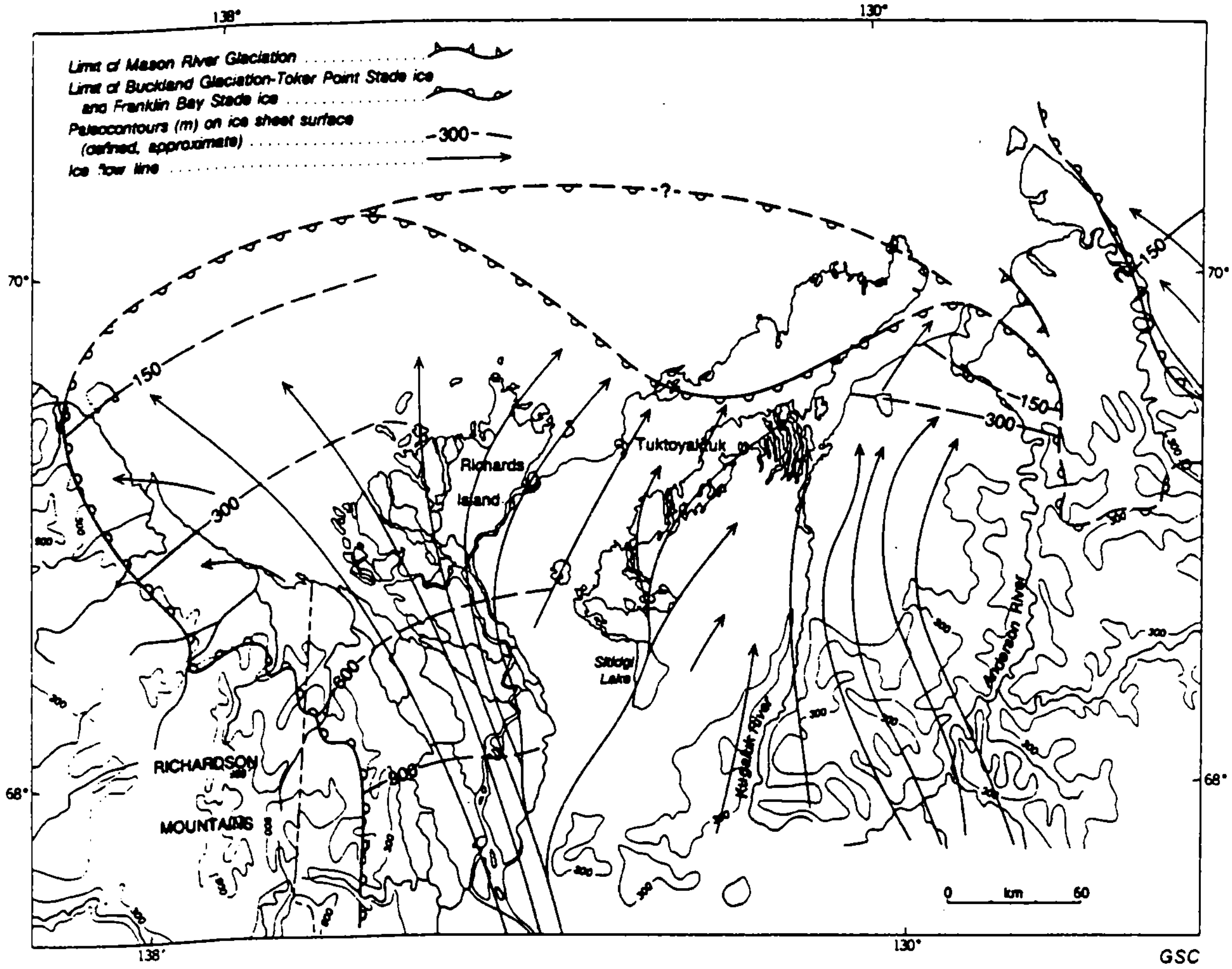


FIGURE 3.24 Ice flow and glacial limits during the Middle Pleistocene Mason River Glaciation, and the Early Wisconsinan Toker Point (Buckland Glaciation) and Franklin Bay stades.

(from Rampton, 1988)

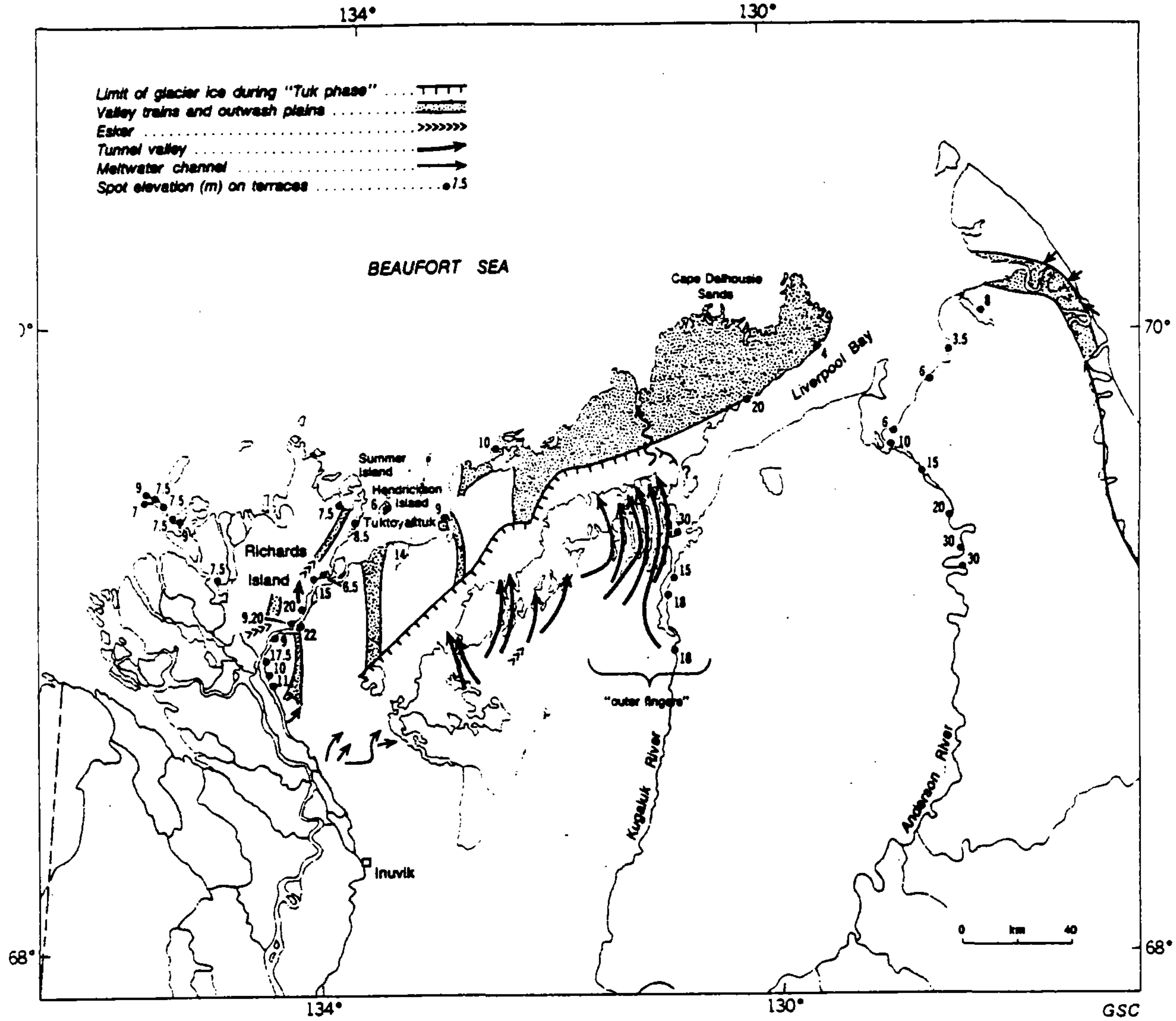


FIGURE 3.25 Glaciofluvial and glaciomarine features of Early Wisconsinan Toker Point and Franklin Bay stades.

(from Rampton, 1988)

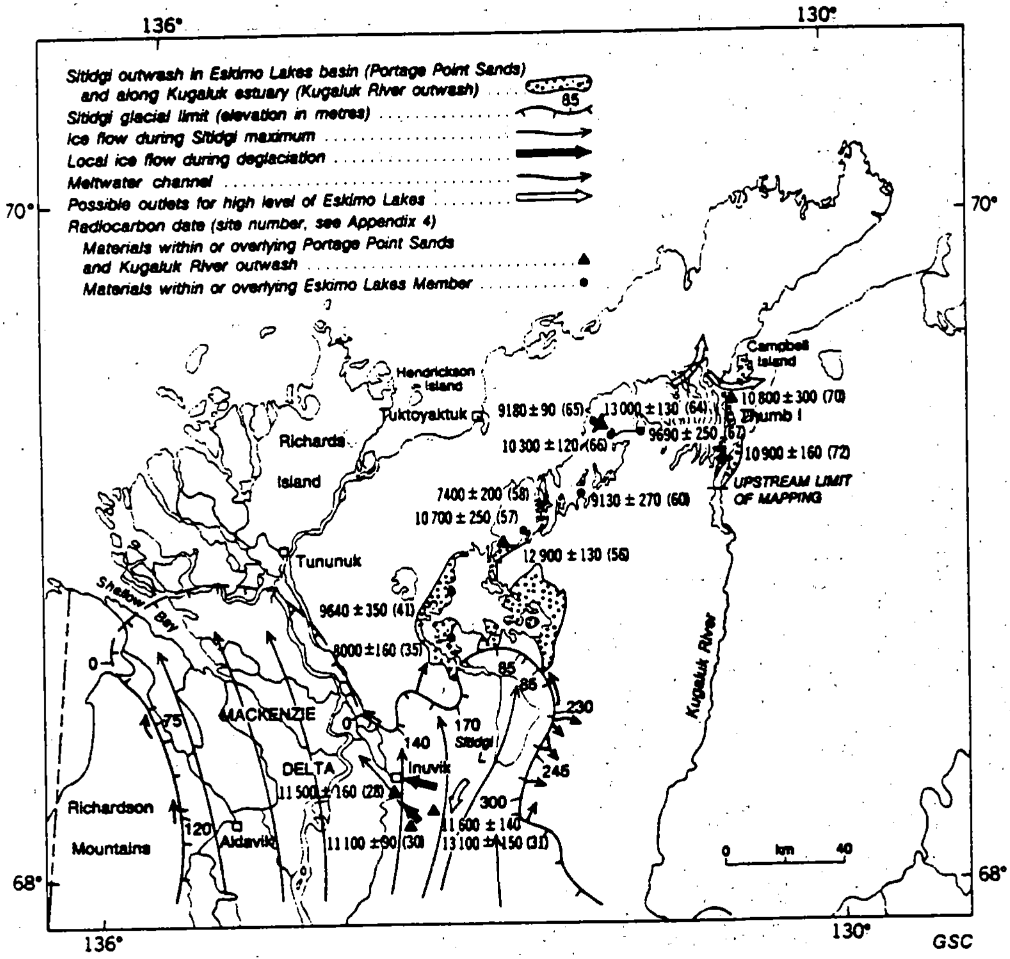


FIGURE 3.26 Glacial features and radiocarbon dates (Appendix 4) related to the Late Wisconsinan Sitidgi Stade.

(from Rampton, 1988)

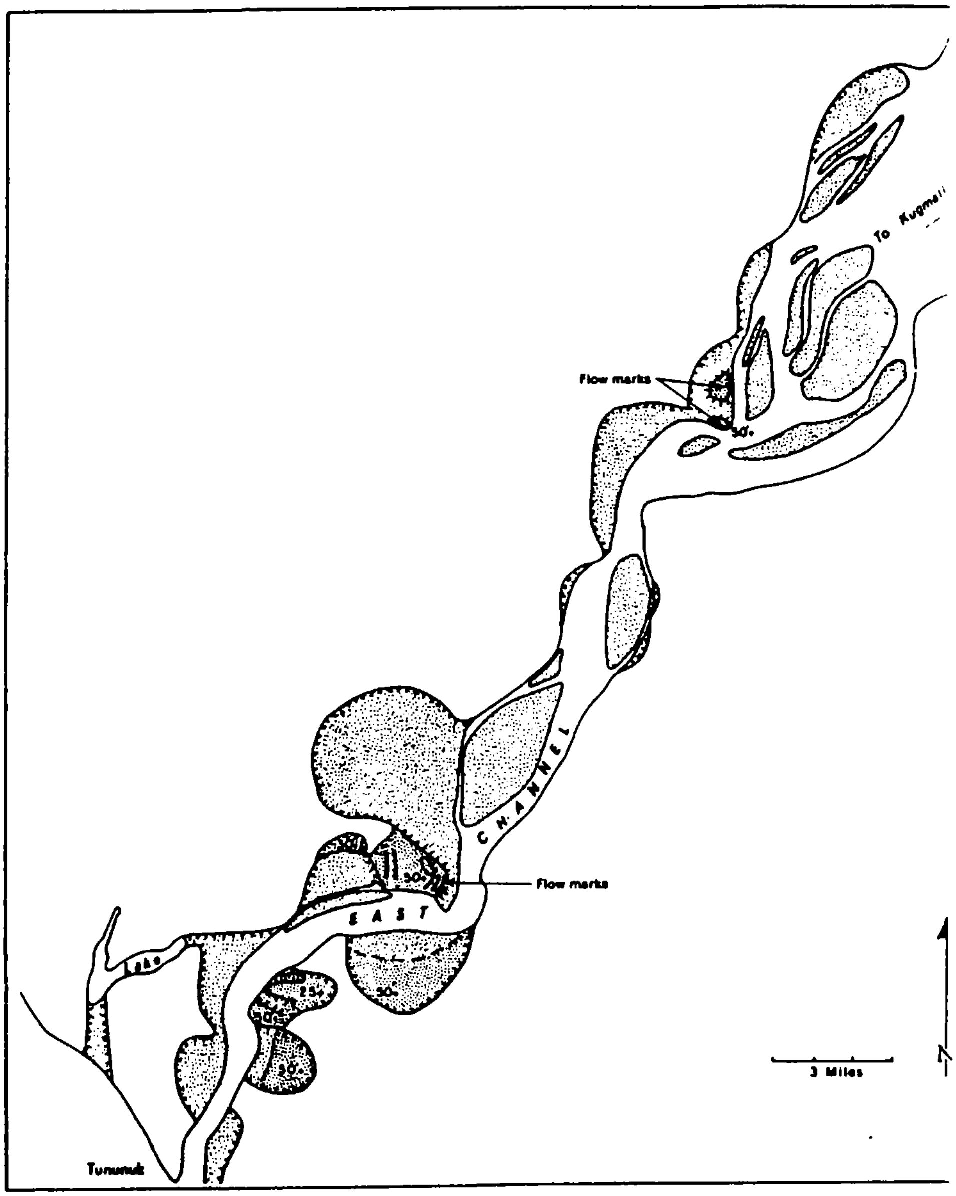


FIGURE 3.27 East Channel between Tununuk and Kugmallit Bay. The high-level meander scars, in the dark-stippled pattern, have smaller radii of curvature than the present channel.

(from MacKay, 1963)

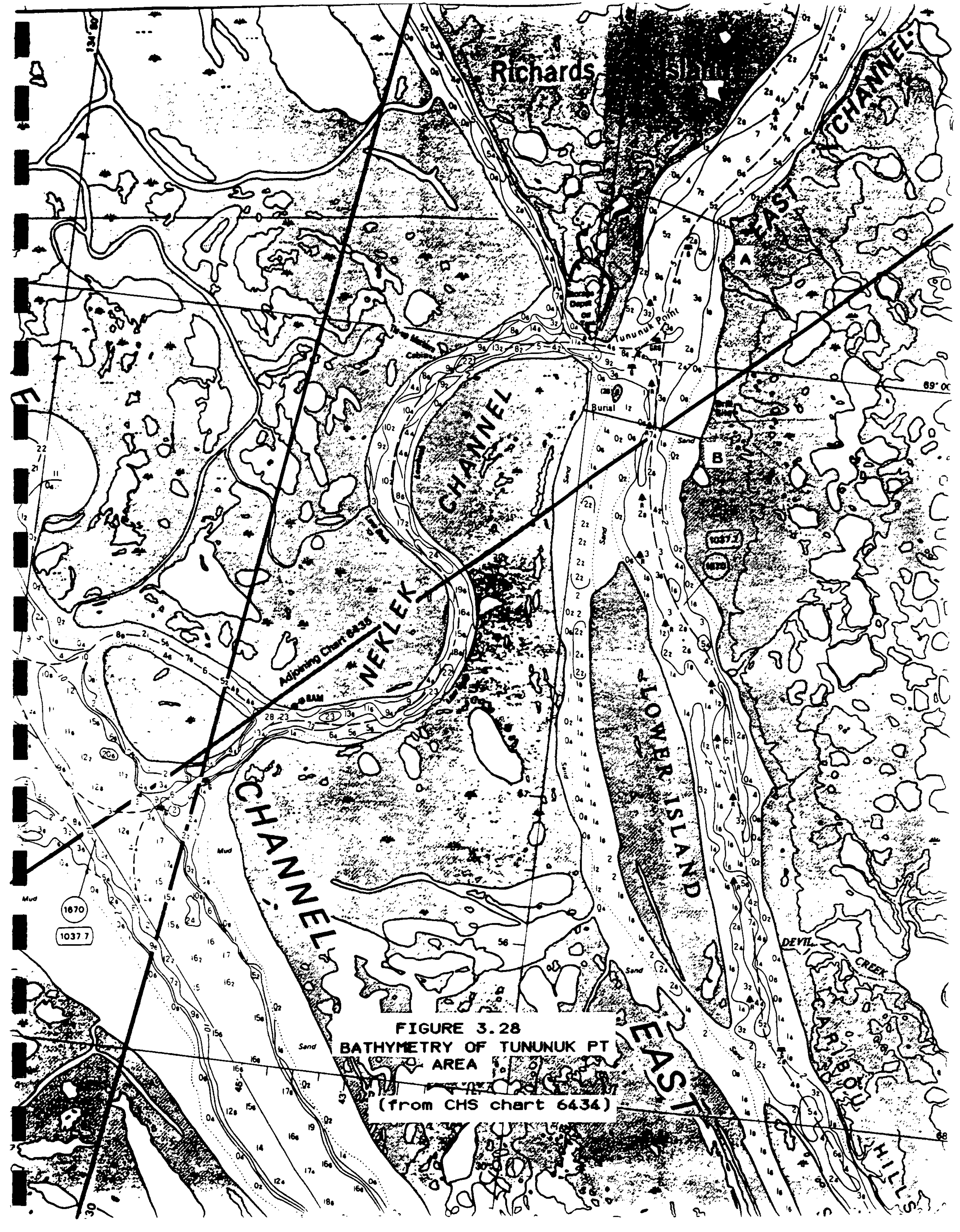
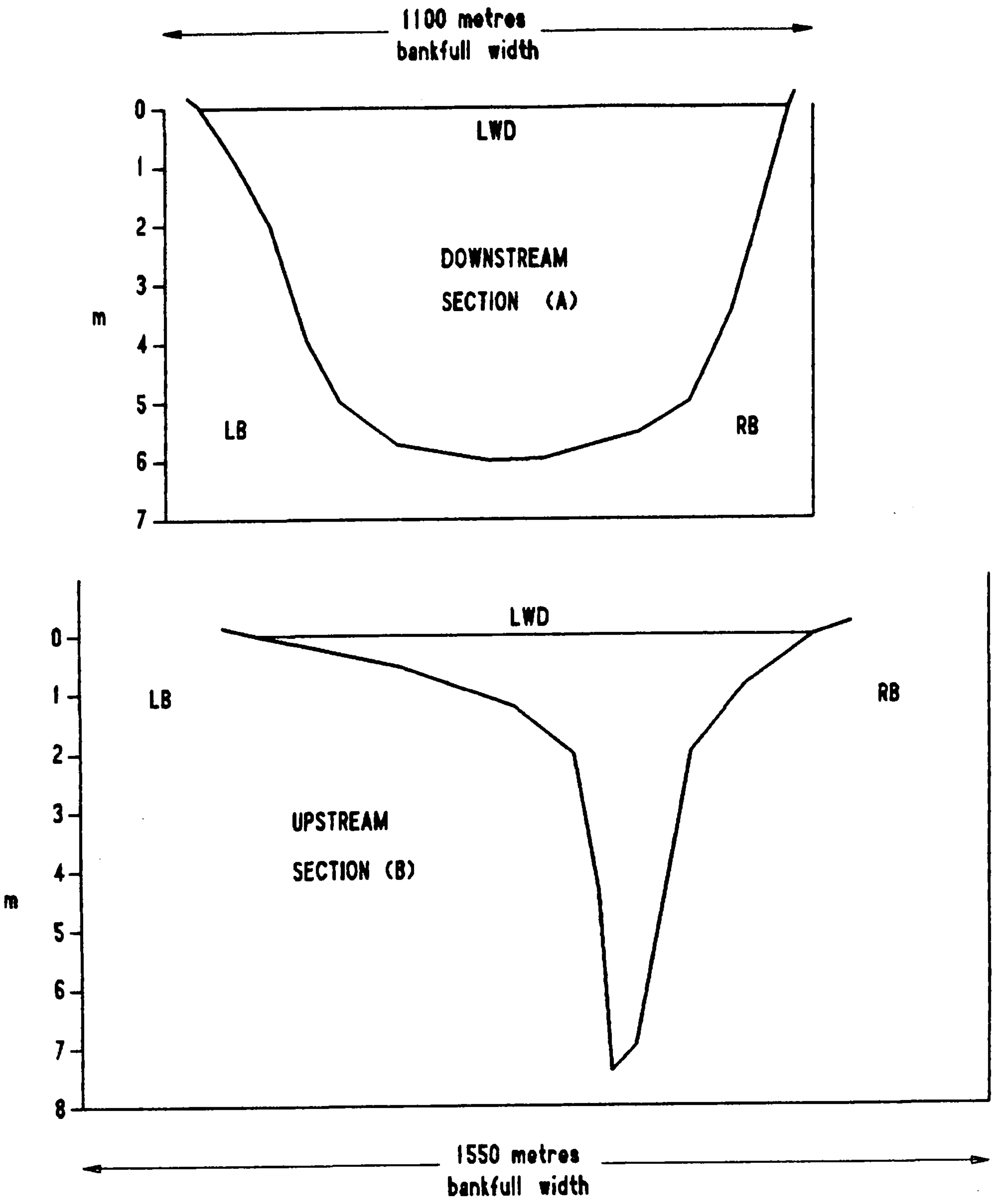


FIGURE 3.28
BATHYMETRY OF TUNUNUK PT
AREA
(from CHS chart 6434)

FIGURE 3.29

EAST CHANNEL UPSTREAM AND DOWNSTREAM OF TUNUNUK POINT
(from Chart 6430)



for locations of sections, see Fig. 3.28

APPENDIX I

CAGSL INFOBASE

This appendix contains 20 abstracts taken from the CAGSL INFOBASE prepared by Arctic Science and Technology Information System for the Arctic Institute of North America, University of Calgary.

The abstracts, dealing with channel stability, were extracted from the five subbases entitled Mackenzie Delta, River Crossings, River Ice Conditions, River Hydrology and Permafrost.

The reports listed represent work done by, or for, Canadian Arctic Gas Study Limited in the mid-1970s. In general, the database is based on CAGSL material, and only infrequently contains reports done for other companies. The locations of the main sites involved in the CAGSL studies in the Mackenzie Delta are given in Fig. 2.3.

The 20 abstracts are ordered alphabetically by author.

AG-GI-BLENCH 74-07-01
1974 river break-up and ice study : Mackenzie, Liard and Peel rivers : data report / T. Blench and Associates Ltd. Northern Engineering Services Company [Sponsor]
Edmonton, Alta. : T. Blench & Assoc. Ltd., 1974.
[94] leaves, [155] leaves of plates : ill., maps ; 29 cm.
Appendices.
References.

The engineering design of buried pipeline crossings of large northern rivers must take into consideration the effects of river ice phenomena. On the Mackenzie, Liard and Peel Rivers which are to be crossed by the proposed pipeline to Richards Island and Prudhoe Bay, the extreme occurrences of local scour and high water may be governed by river ice phenomena. These events generally occur due to major ice jams which cause high local velocities and high upstream water levels. The study presented herein provides a detailed description of the river ice conditions and break-up events that were observed prior to and during the 1974 break-up on the Liard, Mackenzie and Peel Rivers. ... The scope of this report is limited to presentation of results from field programs that were undertaken. The synthesis of these and other findings is the subject of a separate report (T. Blench and Associates, 1974). (Au)

Underwater pipelines - Environmental aspects
Underwater pipelines - Design and construction
Mackenzie Valley Pipeline - Environmental aspects
Mackenzie Valley Pipelines - Design and construction
River ice - Break-up
Ice scouring
Ice jams
Rivers

Mackenzie River, N.W.T.
Liard River, N.W.T.
Peel River, N.W.T.

AG-GI-BLENCH 75-04-01

Ice freeze-up study : Mackenzie Delta, 1974 / T. Blench and Associates Ltd. Nuttall, J.B. Northern Engineering Services Company [Sponsor] Canadian Arctic Gas Study Limited [Sponsor]
Edmonton, Alta. : T. Blench & Assoc. Ltd., 1975.
[14] leaves : ill., 2 folded maps : 29 cm.
References.

Several deep holes are known to exist in the channels of the Mackenzie Delta area. Break-up observations in 1973 and 1974, and b), indicated that development of these holes is not likely associated with ice break-up. However, the possibility of scour beneath hanging ice dams formed from frazil ice generated during late freezing or in ice free water areas upstream remained. The objective of the study reported herein was to observe ice conditions in the Mackenzie Delta area following freeze-up and to assess the possibility of hanging ice dams forming in the lower delta area. Observations of winter ice conditions were made from the air a few days after freeze-up on October 18, 1974 and again on December 9, 1974. (Au)

River ice - Break-up
Frazil ice
Rivers
Underwater pipelines - Design and construction
Underwater pipelines - Environmental aspects
Mackenzie Valley Pipeline - Design and construction
Mackenzie Valley Pipeline - Environmental aspects

Mackenzie Delta, N.W.T./Y.T.
Inuvik region, N.W.T.
Aklavik region, N.W.T.

AG-GH-BLENCH 75-07-01
April, 1975 flow distribution and hydraulic parameters : Mackenzie River - Lower Delta / T. Blench and Associates Ltd.
Northern Engineering Services Company [Sponsor] Canadian Arctic Gas Study Limited [Sponsor]
Edmonton, Alta. : T. Blench & Assoc. Ltd., 1975.
[40] leaves (3 folded) : ill. (some folded), maps ; 29 cm.
References.

The Mackenzie Delta possesses a maze of channels that distributes the Mackenzie River flow to the Beaufort Sea. With the possibility of the Canadian Arctic Gas Pipeline crossing the Lower Delta, a database describing the flow distribution and hydraulic parameters of the various channels is required to develop river design procedures for the proposed pipeline. ... The scope of this study is limited to the development of a data-base on the late-winter flow distribution and hydraulic parameters that exist under an ice cover in the Mackenzie River's Lower Delta. ... The specific objectives of this study are: (1) To measure the late-winter discharge of main, lower-delta channels that the proposed CAGSL pipeline may traverse. (2) To measure and compute the hydraulic parameters of each channel at the flow measurement stations. (3) To retrieve river-bed material samples and analyze grain sizes. (4) To investigate the velocity distribution in the deep holes at East Twin Channel and North Reindeer channel. (5) To measure ice thicknesses and observe the character of the Lower Delta ice cover. (6) To cross-section Shallow Bay at the proposed crossing location to determine the geometry and the portion that is susceptible to ice freezing fast to the bed. (Au)

Watersheds
Stream flow
River discharges
Gas pipelines - Design and construction
Mackenzie Valley Pipeline - Design and construction
Rivers
Bottom sediments
River ice - Thickness
Fast ice - Formation
Underwater pipelines - Design and construction
Storm surges
Tides
Winds

Mackenzie River, N.W.T.
Mackenzie Delta, N.W.T.
Peel River, N.W.T.

AG-GI-BLENCH 75-08-01
Analysis of maximum scour beneath an ice jam / T. Blench and Associates Ltd. Cooper, R.H. Mercer, A.G. Nuttall, J.B. Northern Engineering Services Company [Sponsor] Canadian Arctic Gas Study Limited [Sponsor]
Edmonton, Alta. : T. Blench & Assoc. Ltd., 1975.
[34] leaves : ill. ; 29 cm.
References.

... The purpose of the study presented herein was to examine the feasibility of constructing a buried pipeline crossing that would accommodate scour associated with a severe ice jamming event. The approach was to operate the current analytical model with the objective of establishing a conservative prediction of the maximum scour that could develop as a result of the most severe jamming conditions considered to be possible. River bed scour resulting from an ice jam is expected to be most severe on deep, incised rivers where all of the flow must pass underneath the jam. The Mackenzie River near its downstream end is particularly susceptible to this scour process because: (i) Extreme flood discharges can occur during river ice break-up. (ii) The river is deep and is incised within a single channel so that all flow must pass underneath an ice jam. (iii) The lower reach of the Mackenzie River has a sand bed which has a relatively low resistance to erosion and scour. For these reasons the study presented herein has been based on conditions that might occur in the reach of the Mackenzie River just upstream of Point Separation. (Au)

Underwater pipelines - Design and construction
Ice jams
Ice scouring
Floods
River ice - Break-up
Sedimentation and deposition
Mackenzie Valley Pipeline - Design and construction

Mackenzie River, N.W.T.

AG-GD-EBA 74-01-01

Preliminary geotechnical evaluation : Beaufort Gas Development, Richards Island, N.W.T. / EBA Engineering Consultants Limited
Imperial Oil Limited [Sponsor] Shell Canada Limited [Sponsor]
[S.l.] : EBA Engineering Consultants Ltd., [1974].
ca. 400 p. : ill. (some folded), maps ; 29 cm.
Cover title.
Appendices.
References.

This report presents the findings of a preliminary geotechnical site investigation for a proposed gas plant, an associated gathering system, a docksite, and a potential source of river bed borrow. The development is to be located in the Taglu Block on Richards Island, N.W.T. where ice rich, perennially frozen deltaic silt materials predominate. ... The stratigraphy and ground ice conditions were determined in the area of the plant site, drilling pad, airstrip and roadways. The stratigraphy consisted of non plastic silt over very fine sand while the excess ice contents in the surficial 20 feet averaged approximately 50 percent. Also the permafrost conditions and stratigraphy were investigated at two potential docksites. ... This report describes the drilling program undertaken and presents the data in a form suitable for preliminary design of soil supported structures. ... (Au)

Permafrost
Soil moisture
Soils - Physical properties
Foundations
Soil cores
Ground ice
Gravel mines and mining
Underwater pipelines
Petroleum industry - Plant facilities - Design and construction
Petroleum industry - Plant facilities - Location
Stratigraphy
Rivers
Soils - Classification
Soil texture
Wharves - Design and construction
Airports
Gas pipelines - Location
Physical geography
Stream flow
Current scouring
Granular materials

Richards Island, N.W.T.
Mackenzie River, N.W.T.
Mackenzie River region, N.W.T.
Mackenzie Delta, N.W.T.
Harry Channel, N.W.T.

AG-GC-HARDY 73-03-01 v.2 c.1 / Preliminary report : volume II : recommendations re: major river crossings & approaches. R.M. Hardy and Associates Northern Engineering Services Company [Sponsor] Canadian Arctic Gas Study Limited [Sponsor]
[S.l.] : R.M. Hardy and Assoc., 1973.
1 portfolio : [14] folded ill. ; 30 cm.
Cover title.
Contains only folded illustrations.

These folded illustrations show an aerial view of proposed pipeline river crossings. They delineate the water's edge, and plot the test hole locations on the Peel River, Liard River, Mackenzie River and Great Bear Rivers. (ASTIS)

Gas pipelines - Design and construction
Mackenzie Valley Pipeline - Design and construction
Rivers
Water level
River banks
River terraces
Underwater pipelines - Design and construction
Soil profiles
Soil cores

Mackenzie River region, N.W.T.
Mackenzie River, N.W.T.
Great Bear River, N.W.T.
Liard River, N.W.T.
Liard River region, N.W.T.
Peel River, N.W.T.
Peel River region, N.W.T.
Swimming Point, N.W.T.

AG-GC-Hardy 73-06-02
Reconnaissance of pipeline river crossings north of 60th parallel
/ R.M. Hardy and Associates   Northern Engineering Services
Company [Sponsor]   Canadian Arctic Gas Study Limited [Sponsor]
[S.l.] : R.M. Hardy and Assoc., 1973.
[273] leaves : ill., 1 folded map ; 29cm.
Contains many coloured photographs.
Contains folded map in pocket.

The reconnaissance study summarized in this report ... was undertaken in August, 1972 and was primarily directed at examining river crossings along the proposed pipeline route north of the 60th parallel. The purpose of the reconnaissance was: (a) Design of pipeline river crossings will require significant input from several disciplines, including pipeline engineering and construction, river engineering and geotechnical engineering. A representative from each of the three disciplines noted above undertook the reconnaissance to become familiar with the type of rivers, scope of work involved and in particular to observe special features characteristic of rivers in the Arctic and sub-Arctic region. The observations made would be of considerable benefit in undertaking subsequent designs. (b) Part of the field investigations undertaken for the pipeline in 1972 included obtaining data at selected river crossings. This work included profiling of the river banks, river bed soundings and drilling to determine the river bank conditions. The reconnaissance provided information which permitted better planning of the field investigation program. This data included information on potential base camps, accessibility to the various sites, type of equipment likely necessary, and availability of air and water transport. ... (Au)
H
Underwater pipelines - Design and construction
Mackenzie Valley Pipeline - Design and construction
Bottom sediments
Rivers
River banks
River terraces
Water levels
Soil cores
Mackenzie Valley Pipeline - Location
Gas pipelines - Location
Plant distribution
Permafrost
Slopes - (Soil mechanics)
Soil profiles
Erosion

Prudhoe Bay, Alaska
Y.T., Northern
Mackenzie Delta, N.W.T.
Mackenzie River region, N.W.T.
Mackenzie River, N.W.T.
Liard River, N.W.T.

AG-GC-HARDY 73-07-01
Major pipeline river crossings : test hole logs / R.M. Hardy and Associates   Northern Engineering Services Company [Sponsor]
Canadian Arctic Gas Study Limited [Sponsor]
[S.l.] : R.M. Hardy and Assoc., 1974.
[62] leaves : ill. ; 29 cm.
Mostly charts and tables.

This report includes an explanation of terms and symbols used on test hole logs, and a physical description of the test holes drilled at the Mackenzie River Crossings, Peel River crossing, and Liard River crossing. This report provides back-up data for "Recommendations Re Major River Crossings and Approaches, Canadian Arctic Gas Study Ltd, for Canadian Section North of 60th Parallel". Information provided for each test hole includes: soil description, soil temperature, soil moisture, ice content, frozen ground and soil profiles. (Au)

Underwater pipelines - Design and construction
Rivers
Soils - Classification
Soils - Physical properties
Geology
Soil cores
Soil texture
Soil moisture
Frozen ground
Soil temperature
Soil permeability
Mackenzie Valley Pipeline - Design and construction
Gas pipelines - Design and construction

Mackenzie River, N.W.T.
Mackenzie River region, N.W.T.
Peel River, N.W.T.
Peel River region, N.W.T.
Swimming Point, N.W.T.
Liard River region, N.W.T.
Liard River, N.W.T.

AG-GC-HARDY 73-08-01 v.2 c.1
Geotechnical report : major river crossings : proposed Arctic Gas Pipeline route : Canadian section north of 60th parallel : volume 2 / R.M. Hardy and Associates   Northern Engineering Services Company [Sponsor]   Canadian Arctic Gas Study Limited [Sponsor]
[S.1.] : R.M. Hardy and Assoc., 1973.
[154] leaves. [33] leaves of plates : ill., maps (1 folded) ; 29 cm.
Appendices.

(1) ... The primary purpose of the site investigations was to provide sufficient data to undertake preliminary designs of the pipeline crossings of the selected rivers. ... (2) Drilling and soil sampling was undertaken at crossing sites of the following five rivers: 1. Liard River 2. Mackenzie River - near Burnt Island 3. Mackenzie River - downstream of Arctic Red River 4. Mackenzie River - Swimming Point 5. Peel River .... (3) [This work included: profiling the centreline of the proposed pipeline at the river banks above the river water level, surficial investigation of soil and ground ice, estimations of depth of permafrost, mapping of bedrock exposures, and vegetation mapping.] (Au)

Underwater pipelines - Design and construction
Mackenzie Valley Pipeline - Design and construction
Rivers
Soils - Classification
Soils - Physical properties
Meteorology
Plant distribution
Physical geography
Frozen ground - Thawing
Water level
Soil cores - Location
Soil texture
Soil moisture
Permafrost
Soil temperature
Soil permeability
Gas pipelines - Design and construction

Liard River, N.W.T.
Liard River region, N.W.T.
Mackenzie River region, N.W.T.
Mackenzie River, N.W.T.
Peel River, N.W.T.
Peel River region, N.W.T.

AG-GC-HARDY 74-06-02

Geotechnical data report : proposed Arctic Gas pipeline : major river crossings : drilling program / R.M. Hardy and Associates
Northern Engineering Services Company [Sponsor] Canadian Arctic Gas Study Limited [Sponsor]
[S.l.] : R.M. Hardy and Assoc., 1974.
[212] leaves, [14] leaves of plates : ill. (some folded), maps : 29 cm.
Appendices.
References.
Contains many tables and charts.

... Preliminary geotechnical studies had been conducted at, or near, all of the river crossings included in this investigation. The primary objectives of this drilling program were: (i) To provide information on the composition and properties of the river beds. (ii) To investigate the soil conditions along minor location changes in the proposed alignment. (iii) To provide additional detail in selected areas. (iv) To determine the characteristics of the subsurface materials to depths greater than previously examined at these locations. Proceeding from south to north the following proposed crossings were drilled: (i) The Liard River Crossing (ii) The Burnt Island Crossing of the Mackenzie River (iii) The Great Bear River Crossing (iv) The Point Separation Crossing of the Mackenzie River (v) The Peel River Crossing (vi) The Swimming Point Crossing of the East Channel of the Mackenzie River. ... (Au)

Geology
Physical geography
Soil cores - Location
Plant distribution
Soil moisture
Permafrost
Underwater pipelines - Design and construction
Gas pipelines - Design and construction
Mackenzie Valley Pipeline - Design and construction
Soil texture
Soils - Classification
Soils - Physical properties
Frozen ground
Water level
Rivers
Bottom sediments
Soil temperature
River banks
Hydrography

Liard River, N.W.T.
Liard River region, N.W.T.
Mackenzie River, N.W.T.
Mackenzie River region, N.W.T.
Great Bear River, N.W.T.
Great Bear River region, N.W.T.

AG-GD-HARDY 74-10-02

Geotechnical data report : proposed Arctic Gas Pipeline : Cross Delta Alternative Route : ground truth drilling program, Mackenzie Delta region / R.M. Hardy and Associates   Northern Engineering Services Company [Sponsor]   Canadian Arctic Gas Study Limited [Sponsor]

[S.l.] : R.M. Hardy & Assoc., 1974.

1 v. (various pagings) : ill. (some folded), maps (some folded) ; 29 cm.

Appendices.

References.

In April of 1974 a sub-surface investigation along the proposed alternative pipeline route across the mouth of the Mackenzie Delta was undertaken for Northern Engineering Services Company Limited (NESCL), engineers for Canadian Arctic Gas Study Limited. ... The objectives of the investigation were to provide verification of terrain classification performed by NESCL, to provide data on site conditions along the alternative Delta Route, and to sound and collect information on soil and permafrost conditions at major water crossings along the route. The objectives were achieved by a three-part field program which consisted of land drilling, channel drilling and channel sounding. Proceeding in a westerly direction, the following proposed channel crossings were investigated: East Mackenzie Channel, West Tununuk Channel, East Twin Channel, West Twin Channel, Middle Channel and Shallow Bay. All of these channel crossings were sounded but drilling was limited to the East Mackenzie Channel, West Tununuk Channel, East Twin Channel and Shallow Bay. The land drilling provided ground truth data on the proposed route between the major crossings. Location information is given in Appendix I. ... The geology and terrain along the route covered by this investigation are discussed in detail in the NESCL report "Proposed Cross Delta Alternative Route Terrain Typing, Mackenzie Delta from the Yukon Coastal Plain and from Big Lake, Richards Island to the Mackenzie River East Channel", December, 1974. The geology section of the report is included in Appendix E of this volume. The results of a related study on the vegetation of the Mackenzie Delta, which was carried out by NESCL botanists, are included in Appendix F. ... (Au)

Bathymetry
Geology
Physical geography
Underwater pipelines
Gas pipelines - Location
Gas pipelines - Design and construction
Mackenzie Valley Pipeline - Location
Mackenzie Valley Pipeline - Design and construction
Plant distribution
Soil cores
Frozen ground
Rivers
Meteorology

Soils - Drainage
Soils - Physical properties
Soil texture
Soil temperature

Beaufort Sea region
Mackenzie Delta, N.W.T.
Shallow Bay (68 50 N, 135 40 W), N.W.T.
Mackenzie River region, N.W.T.
Mackenzie River, N.W.T.
D.M.

AG-PG-HARDY 76-11-03
Information Data Bank permafrost distribution at river crossings : literature review, volume I / R.M. Hardy and Associates
Beaufort-Delta Oil Project Limited [Sponsor]
Edmonton [Alta.] : R.M. Hardy & Assoc., 1976.
1 v. (various pagings) : ill., maps ; 29 cm.
References.
Five published reports from various journals and proceedings are bound in this report.

The objective of the subtask is to provide an information databank on geological, geotechnical and geothermal properties of terrain along pipeline corridors. The following comprises information concerning river crossings, and incorporates data on permafrost distribution, sediment type, ice and water content, and slope characteristics for river crossings for which data are available. A brief review is given of literature on permafrost distribution adjacent to water bodies. River crossings and boreholes are listed; floodplain boreholes are listed separately. Slope information is provided in the form of a list of boreholes on slopes at river crossings, and other slopes for which borehole data are available. Also listed are unfrozen zones or taliks associated with rivers and slopes. For each river crossing, the following information is included: large-scale map; 1:50,000 map; airphotograph; cross section of river, which incorporates frozen ground distribution, sediment distribution, slope angle and height; cross-section displaying major slopes on approaches to river crossings. Xerox copies of papers on effects of water bodies on permafrost distribution are enclosed. An assessment is made of the representativeness of river crossing data for the Beaufort-Delta Corridor. This incorporates terrain units traversed by the river in the corridor and potential stability of crossings in those units. (Au)

Mackenzie Valley Pipeline - Location
Gas pipelines - Location
Slopes (Physical geography)
Permafrost - Distribution
Soils - Thermal properties
Rivers
Erosion
Sediment transport
Ground water - Flow
Underwater pipelines - Design and construction
Ground ice - Distribution
Permafrost - Coring

D.M.

AG-GD-MVPL 72-11-01
Report 17-1 : boring logs & laboratory test results, Mackenzie Delta section / Mackenzie Valley Pipe Line Research Limited
Blackwell, J.M. Watson, G.H. Northern Engineering Services Company [Sponsor}
Calgary, Alta. : Mackenzie Valley Pipe Line Research Limited, 1972.
1 v. (various pagings) : ill., maps ; 28 cm.
Cover title.
Appendices.
References.

During early 1972, Mackenzie Valley Pipe Line Research Limited (MVPLR) undertook a program of drilling, sampling and laboratory testing along a corridor extending from Hanna River to Tuktoyaktuk, N.W.T. The purpose of the program was to obtain regional reconnaissance-level subsurface information in support of a warm-oil pipeline feasibility study. This report presents the data obtained from the program. The report is divided into two sections: (1) Boring Logs and supplementary information and (2) laboratory test results and description of test methods. (Au)

Soils - Classification
Petroleum pipelines - Location
Petroleum pipelines - Design and construction
Soil moisture
Frozen ground - Thawing
Soil cores
Soil profiles
Soils - Density
Soils - Physical properties
Soil temperature
Permafrost - Thawing
Soil mechanics
Soils - Testing
Mackenzie Valley Pipeline - Location
Mackenzie Valley Pipeline - Design and construction

Mackenzie River region, N.W.T
Mackenzie Delta, N.W.T.
Travaillant Lake region, N.W.T.
Mackenzie Delta, N.W.T.
Hanna River region, N.W.T.
Tuktoyaktuk region, N.W.T.
Hanna River, N.W.T.

AG-GD-NESCL 74-11-04

Geotechnical data report : proposed Arctic Gas Pipeline: Cross Delta Alternative Route, supplementary ground truth drilling program, Yukon North Slope to Thunder River, N.W.T. / Northern Engineering Services Company R.M. Hardy and Associates
Canadian Arctic Gas Study Limited [Sponsor]
[S.l.] : R.M. Hardy & Assoc., 1974.
4 v. (various pagings) : ill., maps (some folded) ; 29 cm.
Appendices.
References.
Contents: Geotechnical data report - Cross Delta Drilling Program : Photographs, v.1 & v.2 - Photo negatives : Cross Delta Drilling Program, Fall 1974.
Photographs and slides are stored in three-ring binders.

This drilling and sampling program, conducted in September, 1974, was undertaken for Canadian Arctic Gas Study Limited (CAGSL) by Northern Engineering Services Company Limited (NESCL). ... The objective of this program was to obtain ground truth and subsurface information along portions of the proposed Cross Delta Alternative pipeline route which were not investigated during the field program completed in the Spring of 1974. The program consisted of drilling holes at an approximate spacing of five miles to a target depth of 20 feet along three segments of the proposed alternative pipeline route. The three segments of the proposed route were as follows: (i) Conglomerate Creek, Y.T. (14 miles west of Shingle Point) to the west side of Shallow Bay, N.W.T. (ii) Northern tip of Richard's Island, N.W.T. to Parson's Lake, N.W.T. (iii) Noel Lake, N.W.T. to Thunder River, N.W.T. After the completion of the drilling for the ground truth phase of the program, additional drillhole locations were selected adjacent to the banks of several major channels in the Mackenzie Delta. These holes were drilled to establish the presence of unfrozen soil in the area. ... The sites, selected by NESCL geological staff, on the basis of airphoto interpretation, were intended to verify the preliminary terrain typing, to evaluate the limited number of potential granular borrow sources, and to supplement the ground truth data obtained from the spring 1974 drilling program. ... (Au)

Soil texture
Soil cores
Rivers
Gravel mines and mining
Physical geography
Plant distribution
Frozen ground - Distribution
Soil moisture
Soils - Physical properties
Meteorology
Frozen ground - Thawing
Topography
Soils - Drainage
Gas pipelines - Location

Gas pipelines - Design and construction
Soils - Classification
Mackenzie Valley Pipeline - Location
Mackenzie Valley Pipeline - Design and construction

Conglomerate Creek (68 54 N, 137 47 W), Y.T.
Thunder River region, N.W.T.
Richards Island, N.W.T.
Parsons Lake region, N.W.T.
Noell Lake region, N.W.T.
Thunder River, N.W.T.
Noell Lake, N.W.T.
Parsons Lake, N.W.T.

AG-GD-NESCL 75-01-03
Geotechnical data report : proposed Arctic Gas Pipeline : Cross Delta Alternative route : Channel depth anomaly drilling and sampling program / Northern Engineering Services Company
Canadian Arctic Gas Study Limited [Sponsor]
Calgary, Alta. : Northern Engineering Services Co., 1975.
2 v. (various pagings) : ill., maps, 29 cm.
Appendices.
References.
Contents: Negatives for: Cross Delta Alternative route channel depth anomaly drilling and sampling program is related to this main report, but bound separately in a 3-ring binder.

... This data report describes the field operation and presents the results of the laboratory classification and thaw consolidation testing. ... The objective of the field program was to collect samples of permafrost adjacent to a typical channel depth anomaly. A selection of these samples from various depths were to be tested for thaw strain unless significant variations in ice content were found adjacent to the deep and shallow portions of the river channel. On the basis of the results of a detailed channel sounding program, a suitable reach was identified in the East Twin Channel area as being suitable for the field drilling and sampling program. In addition, a single test hole was drilled at the proposed Langley Island channel crossing. (Au)

Soils - Classification
Soil cores
Bottom sediments
Soil temperature
Soils - Classification
Soils - Physical properties
Gas pipelines - Design and construction
Underwater pipelines - Design and construction
Rivers
Hydrography
Mackenzie Valley Pipeline - Design and construction
Frozen ground - Thawing
Permafrost - Thawing
Meteorology
Soil texture

Mackenzie Delta, N.W.T.
Mackenzie River region, N.W.T.
D.M.

AG-GD-NESCL 75-11-04 V.1

Synopsis of data from soils investigations to August 1975, Cross Delta Route of the proposed Arctic Gas Pipeline / Northern Engineering Services Company   Canadian Arctic Gas Study Limited [Sponsor]

Calgary, Alta. : Northern Engineering Services Co., 1975.
2 v. (various pagings) : ill. (some folded), folded maps ; 28 cm.
References.

This report contains a summary of data from all field soils investigations carried out over the past three years along, or near, the Cross Delta Route of the proposed arctic gas pipeline. ... The first of these soils investigations was done in the Travaillant Lake area by R.M. Hardy and Associates Limited for Northern Engineering Services Company Limited during May and June of 1973. This field investigation was done in order to provide the necessary subsurface soils data to assist in verifying the airphoto interpretation, performed by J.D. Mollard & Associates along a newly relocated section of the then proposed pipeline route. ... The next subsurface investigation carried out in the Mackenzie Delta was done by R.M. Hardy & Associates Limited for Northern Engineering Services Company Limited in April of 1974. ... A secondary objective of this field investigation was to sound and collect information on soil and permafrost conditions at major water crossings along the proposed Cross Delta route. ... In the fall of 1974 two additional subsurface field investigations were undertaken along the then proposed Cross Delta Route. ... The first took place during September of 1974 and was done ... along those portions of the proposed Cross Delta Route not investigated in the Spring of 1974. ... The second subsurface field investigation was carried out during late September, and early October 1974 in the area of the East Twin Channel in the Mackenzie Delta. The objective of this investigation was to drill deep test holes adjacent to a deep section in the channel and adjacent to a shallow section in order to detect any variation in soil ice-content, and to obtain intact frozen soil samples for thaw settlement testing. ... [In] The most recent subsurface soils investigation .... Three test holes were drilled at the quarter points along the proposed route across Shallow Bay. A track-mounted drill working from a landing craft was used to obtain unfrozen, undisturbed samples of fine grained soil from the bottom of the bay. ... (Au)

Soils - Classification
Soil cores
Soils - Physical properties
Soil texture
Soils - Drainage
Soil moisture
Frozen ground - Thawing
Meteorology
Plant distribution
Topography
Underwater pipelines - Design and construction

Rivers
Permafrost
Gas pipelines - Location
Granular materials
Bottom sediments
Mackenzie Valley Pipeline - Location

Travaillant Lake region, N.W.T.
Mackenzie Delta, N.W.T.
Shallow Bay region (68 50 N, 135 40 W), N.W.T.
Shallow Bay (68 50 N, 135 40 W), N.W.T.

AG-GH-NESCL 76-03-02
Channel geometry and flow distribution : Mackenzie River - Lower Delta : Summer 1975 / Northern Engineering Service Company
Canadian Arctic Gas Study Limited [Sponsor]
Calgary, Alta. : Northern Engineering Service Co., 1976.
iv, [60] leaves (33 folded) : ill. (some folded), maps (some folded) ; 29 cm.
Appendices.

... The present study was undertaken to better define conditions of channel geometry and flow distribution. The specific objectives of this study were: (1) To provide detailed surveys of the bottom topography of three major Lower Delta channels in the vicinity of proposed CAGSL pipeline crossings, namely the East Channel, Langley Island Channel, and North Reindeer Channel, in order that any major changes since the 1974 report could be determined. (2) To define the channel geometry with more precise horizontal control than that used in the 1974 study, in order that possible future channel shifting or movement of scour holes could be monitored. (3) To measure the discharge in each of the three channels under conditions of relatively high summer flow. (4) To measure the discharge in the Reindeer Channel and Middle Channel upstream of Neklek Channel in order to better define the summer flow distribution. (5) To observe and measure variations in water level during the study period due to the effects of tides and storm surges. No attempt has been made in this study to quantify the effect of tides and storm surges on the summer flow distribution and stream velocities. The variation in water levels during the survey period was documented to the extent possible in order to permit the calculation of these effects at some later date if required. (Au)

Underwater pipelines - Design and construction
Submarine topography
River discharges
Storm surges
Stream flow

Mackenzie River, N.W.T
Mackenzie Delta, N.W.T.
Kugmallit Bay, N.W.T.
Shallow Bay (68 50 N, 135 40 W), N.W.T.

AG-GC-NESCL 76-03-04
Geotechnical data report : proposed Arctic Gas pipeline : Shallow Bay drilling and sampling program, 1975 / Northern Engineering Services Company   Canadian Arctic Gas Study Limited [Sponsor]
[Calgary, Alta.] : Northern Engineering Services Co., 1976.
1 v. (various pagings) : ill, 1 folded map ; 29 cm.
Appendices.
References.
Mostly tables and charts.

The objective of this field investigation was to obtain undisturbed samples of unfrozen fine-grained soil from the bottom of Shallow Bay along the proposed Cross Delta pipeline route. These samples were to be used in laboratory studies conducted to evaluate their susceptibility to frost heave and liquefaction. (Au)

Soil cores
Bottom sediments
Underwater pipelines - Design and construction
Mackenzie Valley Pipeline - Design and construction
Soils - Physical properties
Gas pipelines - Design and construction
Soil moisture
Soil texture
Frozen ground
Liquefaction (Soil mechanics)
Frost heaving
Ground ice
Dictionaries and glossaries

Mackenzie Delta, N.W.T.
Shallow Bay, N.W.T.

AG-GI-NESCL 76-10-01

Summary report on channel sounding data and river ice break-up on the Mackenzie River, 1976 / Northern Engineering Services Company
Canadian Arctic Gas Study Limited [Sponsor]
Calgary, Alta. : Northern Engineering Services Co., 1976.
[26] leaves (9 folded), [17] p. : ill, maps (some folded) : 29 cm.
Appendices.
References.

The specific objectives of the study were: 1. To obtain a bed profile at each of the two crossings at East Channel, Langley Island Channel, North Reindeer Channel and the Mackenzie River east of Fort Simpson. 2. To obtain a bed profile at the upstream pipeline crossing at Shallow Bay. (Because of the small separation of 200 ft. between the two lines across the Bay, one profile was considered to be representative of both.) 3. To measure the thickness of ice across the channels. 4. To lay out a base line on the west shore of Shallow Bay in order to monitor the erosion of the left bank upstream and downstream of the crossings. 5. To obtain a photographic record of the ice break-up. 6. To identify possible locations of ice jams near the crossings. 7. To observe the extent of flooding at the crossings in the delta and the increase in water level at the Mackenzie crossings east of Fort Simpson. (Au)

River ice - Break-up
Underwater pipelines - Design and construction
Underwater pipelines - Environmental aspects
Ice scouring
Erosion
Deposition and sedimentation
Ice jams
Mackenzie Valley Pipeline - Environmental aspects
Mackenzie Valley Pipeline - Design and construction
Submarine topography
Stream flow
Ice - Thickness
Floods

Mackenzie River, N.W.T.
Shallow Bay (68 50 N, 135 40 W). N.W.T.

AG-GI-NESCL 77-08-01
Summary report on Channel sounding data and river ice breakup on the Mackenzie River, 1977 / Northern Engineering Services Company
Canadian Arctic Gas Study Limited [Sponsor]
Calgary, Alta. : Northern Engineering Services Co., 1977.
19 p., [4] folded leaves, [22] p. : ill., maps : 29 cm.
Project 12091.
Appendices.
References.

The proposed Arctic Gas pipeline crosses the Mackenzie River at two locations; in the lower delta, and approximately 9.6 km upstream of Fort Simpson (Figures 1 and 2). This study is part of the continuing effort to collect the data required to refine the preliminary river crossing designs at these locations. The specific objectives of the study were: 1. To obtain a bathymetric map of the upstream end of the deep channel (17-18 m deep vs. a general 3-7 m throughout), approximately 2 km off the west shore of Shallow Bay. 2. To obtain a photographic record of the ice breakup. 3. To identify possible locations of ice jams near the crossings. 4. To observe the extent of flooding at the crossings in the delta, and the increase in water level at the Mackenzie crossings east of Fort Simpson. (Au)

River ice - Break-up
Submarine topography
Erosion
Sedimentation and deposition
Ice scouring
Stream flow
Water level
Underwater pipelines - Environmental aspects
Underwater pipelines - Design and construction
Mackenzie Valley Pipeline - Environmental aspects
Mackenzie Valley Pipeline - Design and construction

Mackenzie River, N.W.T.
Shallow Bay (68 50 N, 135 40 W), N.W.T.

PROPOSALS FOR HYDRAULIC AND MORPHOLOGIC SURVEYS IN THE MACKENZIE DELTA, NORTHWEST TERRITORIES

by

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for

Inland Waters Directorate
Environment Canada
Yellowknife, NWT

under contract
KE521-1-0085/01-XSG
Supply & Services Canada, Edmonton

November, 1991

Preface

This report was prepared as one part of Contract KE521-1-0085/01-XSG administered by Supply and Services Canada with F. M. Conly of Inland Waters Directorate, Yellowknife, NWT as Scientific Authority. The assistance provided by Malcolm Conly and Jesse Jasper is duly acknowledged.

The report builds upon three prior reports on the Mackenzie Delta, prepared under the same contract, dealing with the suspended sediment sampling program, proposed overbank sedimentation studies, and channel stability with special reference to proposed pipeline crossings in the outer delta area.
Special thanks are due to Henry Hudson, IWD Winnipeg, for provision of a draft report on hydraulic and morphologic surveys; to John Kerr, IWD Yellowknife, for provision of material dealing with the one-dimensional flow model and for comments on a draft version of the report; to Scott Dallimore, GSC Ottawa, for provision of material dealing with GSC's recent and current work in the outer delta; and to Mike Deyell, Esso Resources Canada, Calgary, for provision of information regarding likely pipeline routes in the outer delta.

1. HYDRAULIC AND MORPHOLOGIC SURVEYS: INTRODUCTION

1.1 Background

IWD's NOGAP-funded project entitled "Sediment-related aspects of northern hydrocarbon development" involves a series of separate but related subprograms (Jasper, 1991). Subproject C11-6 deals with "Mackenzie Delta Channel Stability". Its objectives are "to document hydraulic and morphologic characteristics, and evaluate stability of outer delta channels, near potential pipeline crossings". The study description reads:

> "A sequential descriptive and predictive approach will be used to investigate delta channel stability. Existing delta bathymetric and bank erosion data and studies will be examined in 1991/92 to assess historical channel stability near likely pipeline channel crossings. Intensive hydraulic and morphological characterizations will be carried out in 1992/93 and 1993/94 at highest priority sites." The present report deals with the second of these two components, the hydraulic and morphologic surveys.

The project description continues: "The surveys will define hydraulic geometry, bed materials and other factors used in estimating scour depths and channel stability for oil and gas infrastructure design (peak discharge, ice jam and other conditions). Recommendations will also be made on further specific information needs in order to resolve any persistent design factors."

The terms of reference for the present report are: "In consultation with IWD personnel, identify potential sites for intensive Hydraulic and Morphologic surveys within the Mackenzie Delta. Compile and organize data from previous tasks outlined on this statement of work for all potential H&M survey sites."

The present report is not, however, to be restricted to possible pipeline crossing sites (Jasper, 1991, pers. comm.). Hydraulic and morphologic surveys would be useful in other IWD-NOGAP study components, including the study of overbank sedimentation, the location and monitoring of suspended sediment sampling sites, and calibration of the 1-dimensional flow model. These four components of the broad IWD-NOGAP program are described more fully in the next chapter. The final chapter provides recommendations for the location of specific hydraulic and morphologic work.

The concluding part of this introduction briefly summarizes the nature and purpose of hydraulic and morphologic surveys.

1.2 Hydraulic and morphologic surveys

The pioneering work in hydraulic and morphologic surveys of river channels in Canada was undertaken by the Alberta Research Council. More recently, Northwest Hydraulics Consultants Limited (NHCL, 1986) has provided an overview of the approach, together with advice to Inland Waters Directorate on the operation of such surveys.

NHCL (1986) defined hydraulic and morphologic data as follows:

> "an assemblage of numerical and descriptive items that, taken together, more or less establish the character or "regime" of a river with respect to flow phenomena and velocities, hydraulic resistance, stability and movement of bed material, planform and cross-sectional dimensions, relationship to valley and floodplain, composition and erosion of banks and deposition and migration of bars."

They go on:

> "Just as compiled hydrometeorlogical data at discrete stations are used in hydrologic studies to make inferences about conditions at intermediate points, so can hydraulic/morphologic data be used by specialists to make reasonable inferences on channel behaviour and response at locations other than the compiled sites. It may be objected that hydraulic/morphologic characteristics do not vary in a smooth manner along rivers, which is certainly sometimes the case; nevertheless, there are many rivers which retain a characteristic 'signature' over long distances, as seen for example on aerial photographs."

Fig. 1.1 indicates typical uses of hydraulic and morphologic data, the kind of data collected and typical hydraulic-morphologic attributes derived. The NHCL (1986) report provides several specific examples of the approach, including pipeline river crossing sites. Fig. 1.2 outlines the data collected for the M'Clintock River crossing in the Yukon and the hydraulic-morphologic attributes determined. Ideally all such surveys are done reasonably close to existing WSC hydrometric stations in order that survey results can be extrapolated to a longer time period.

One of the first hydraulic/morphologic surveys done by Inland Waters Directorate was for Qu'Appelle River below Loon Creek in Saskatchewan. The survey bulletin included:

1. description of WSC station;
2. description of basin, reach and gauge site;
3. description of channel form;

4. morphologic summary of study reach:
    - aerial photograph
    - summary of survey work
    - water and stream bed long profiles
    - cross-sections
    - bed and bank material grain size curves
5. hydrologic summary of study reach:
    - ice information
    - flow duration curve
    - stage-discharge curve
    - mean and extreme discharge data
    - mean annual hydrograph
    - flood frequency curve
6. hydraulic summary of study reach:
    - hydraulic geometry relations
    - channel data (width etc.) for survey day, mean summer flow, 2-year and 5-year floods
    - hydraulic data (shear stress, roughness etc.) for survey day, mean summer flow, 2-year and 5-year floods
7. environmental summary: climate and water temperature

These two examples provide some indication of the kind of data collected in hydraulic and morphologic studies. Two additional points should perhaps be emphasized.

- The hydraulic and morphologic surveys should not be regarded as "static". Ultimately their purpose is to assist in the assessment of river behaviour in the study reach. To this end, a qualitative record of river channel change over historic time from successive aerial photographs must be regarded as an essential accompaniment to the data collection.

- The characterization of channel reaches in terms of statistical means (shear stress etc.), while clearly necessary, must not be used to mask internal variation within the reach, both laterally and longitudinally. The movement of bed material through a reach, for example, may be far better understood in terms of the varying bathymetry and bed material in the channel than in terms of mean attribute values.

1.3 River FPR (Form, Process and Response) surveys

Hudson (1991) has provided a detailed review document on hydraulic and morphologic surveys for IWD programs in the Western and Northern region, introducing the title "River Form Process and Response Surveys". In particular, he advocates a hierarchical classification of such surveys based on (a) length of river reach and (b) time-frame and purpose of work. The five levels of survey can be summarized as follows:

Level 1	Single cross-section. Data collected on bathymetry, velocity, discharge as in existing measurement section surveys.
Level 2	Short study reach. Several cross-sections in a reach about 10 to 15 river widths in length. Additional cross sections used to assist in documentation of bed morphology, channel stability, bed and bank sediment, water surface slope. Typical of level of detail required for a suspended sediment station.
Level 3	Short study reach. As in Level 2, but with more detail, comparable with the "traditional" river regime information (e.g. Kellerhals et al., 1972). "Snapshot" of reach at one moment in time.
Level 4	Multiple study reaches. Level 3 surveys undertaken at different reaches along a watercourse, indicating contrasts among reaches in hydraulics and morphology, and reference to evolution of reaches (through study of historical aerial photographs).
Level 5	As in Level 4, but with explicit intention of repetition of surveys in the future, i.e. this is the "monitoring" level.

Though there may well be refinement of these levels in future drafts of the report, the recognition of variable levels of geographic scope, survey detail and past (and future) interpretative behaviour is an important point. The scale of such surveys will thus depend on the level of investigation.

The scale of hydraulic-morphologic surveys will also depend on the scale of the river. A study reach must be fully representative of the river area in which it is located. The Qu'Appelle River reach, for example, was about 650 m long, this being the along-channel length over a full meander wavelength. The survey work involved surveys of 11 cross-sections, and the acquisition of 24 bed material samples and 9 bank material samples.

The number of cross-sections and samples will depend more on the internal variability within the reach than simply reach length. Thus availability of existing bathymetric charts (or construction of such charts) should be regarded as a prelude to bed sediment sampling. The importance of this point was demonstrated on the Peace River near Fort Vermilion by Alberta Research Council (McLean and Anderson, 1980) and on river channels in South Island, New Zealand by Carson (1986).

A final important point needs emphasis. Hydraulic and morphologic surveys involve a great deal of routine field survey work. They must, not, however, be done in a rigid, routine manner: they require the supervision of someone trained with a fluvial geomorphic perspective.

2. AIMS OF HYDRAULIC-MORPHOLOGIC SURVEYS IN MACKENZIE DELTA

IWD's plans for hydraulic and morphologic work in the delta are related to four main studies: channel stability near likely pipeline crossings; overbank sedimentation patterns across the delta; suspended sediment sampling at various delta stations; and calibration of its one-dimensional flow model.

2.1 Channel stability in areas of possible pipeline crossings

Areas currently earmarked for hydrocarbon development in the delta are indicated in Figs. 2.1 and 2.2, based on the 1990-91 final report of the Beaufort Region Environmental Assessment and Monitoring Program of Indian and Northern Affairs Canada (Deyell, 1991, pers. comm.),

Two main areas of river crossings are involved in bringing oil or gas across to the east side of the Mackenzie River: the northwest area with crossings of relatively small distributaries such as Kumak and Harry channels; and the eastern area crossing of East Channel from Richards Island. The latter area has two proposed crossings, one at Swimming Point (Polar Gas) and one at Lousy Point (Gulf Canada), but the former seems more likely.

Appropriate hydraulic and morphologic work in these areas would include (a) assessment of channel bank migration from old and new air photographs; (b) assessment of channel bed scour and fill from resurvey of cross-sections previously surveyed; (c) sampling of bed material, including changes with depth below the surface at some sites; (d) description of bank stratigraphy (with special reference to ice contents) and sampling of bank material; (e) mapping of permafrost distribution along channel bed and banks; (f) measurement of discharge and velocity with the goal of developing a velocity-discharge rating diagram; (g) construction of % exceedance plot for discharge through use of one-dimensional flow model; (h) documentation of nature of ice breakup and implications for channel stability.

As indicated below, much of this work appears to have already been undertaken by consulting firms working for the petroleum and pipeline companies in the 1970s and, more recently, by Terrain Sciences Division of the Geological Survey of Canada.

North-west delta region

Potential crossing sites in this region were apparently documented by Slaney and Co. (1974), and few changes have been made since that time (Deyell, 1991, pers. comm.). The report by Slaney and Co. is the basis of ongoing research into channel stability by the Terrain Sciences Division (TSD) of the Geological Survey of Canada (Dallimore, 1991, pers. comm.).

During the summer of 1990, TSD resurveyed 20 proposed channel crossings established in the early 1970s in order to quantify recent changes in channel morphology (Figs. 2.3, 2.4). A summary of the work is given by Carson (1991a), but the full report (Traynor and Dallimore, in prep.) has not yet been released.

During the summer of 1991, TSD has been working in the vicinity of crossing sites at Middle, Kumak and Harry channels, mapping geology, ground ice and slope stability of channel banks, and ground-truthing LANDSAT vegetation mapping. A preliminary geological map of the Taglu and Niglingtak areas is planned for the end of the 1991/92 season. The final report is not expected until a year later.

TSD's main concerns relate to (a) pipeline stability (frost heave, thaw settlement) in the variable permafrost regime near the channels, and (b) the stability of the channels themselves, including rates of erosion and deposition. IWD's plans for hydraulic-morphologic surveys could provide valuable supplementary information in relation to the second of these areas, but (depending on the nature and scope of work already done) only partial surveys would be needed.

East Channel crossings

The description of the Swimming Point crossing by Polar Gas in its 1984 Application to the National Energy Board and the Department of Indian and Northern Affairs for a certificate to build the required crossing facilities is worth documenting in full because it provides some indication of the meagre extent of hydraulic information available.

> "The East Channel is one of the major outlets of the Mackenzie River to the Beaufort Sea via Kittigazuit and Kugmallit Bays. The proposed crossing at Swimming Point from Richards Island to the mainland just upstream of Holmes Creek was previously investigated for the Canadian Arctic Gas Study Ltd in 1972-74 and is considered the most logical crossing point for a number of reasons: directness of route, avoidance of additional water crossings on the north side, gentle approach on the south side and presence of an existing gravel airstrip and preparation area on the north side.
>
> Boreholes drilled for CAGSL show frozen sand nearly to the surface at the south (right) bank, and frozen silt underlain by sand beneath a broad shallow area of the low north (left) bank. Below the 500m wide by 21 m maximum deep main channel, located toward the south bank, the permafrost table is believed to lie well below practicable pipe burial depths. There has been no significant change in bank locations for many years.
>
> Discharges in the East Channel are not well defined as few flow measurements have been made. The design discharge adopted in previous studies for estimates of maximum channel scour was approximately 18,400 m3/s, based on half of the 100-year flood entering the Delta at Point Separation. Mean annual maximum flow is believed to be

> about 10,000 m3/s. Water levels are virtually constant under most conditions, being controlled by the Beaufort Sea which has a very small tidal range, but they can rise up to 2 m and 3 m on rare occasions as a result of ice jamming or storm surges. Velocities under likely construction conditions are believed to be in the range of 0.5 m/s to 1 m/s. Maximum design scour was previously estimated as 5 m below the lowest part of the cross-section.
>
> Field investigations of ice conditions at Swimming Point were conducted from 1973 to 1975 for CAGSL. The channel is usually ice-covered from mid-October to late May or early June, and late winter ice thicknesses average about 1.5 m. At break-up, water levels rise up to about 2 m and velocities rise to about 1 m/s. Ice push-up on banks of up to 6 m has been observed."

Abstracts of several reports done for CAGSL at this site were provided by Carson (1991a, Appendix I). None of these reports has been seen. Terrain Sciences Division of Geological Survey of Canada proposes to undertake work along East Channel in the summer of 1992, comparable with that undertaken in the northwest region in 1990 and 1991.

2.2 Overbank sedimentation studies

IWD has proposed studies to document the changing magnitude and pattern of overbank sedimentation along two transects of the delta, one at mid-delta and one in the outer delta (Jasper, 1991). The purpose of these studies is partly to assess the magnitude of overbank sedimentation in different parts of the delta, and partly to provide core samples which can be examined to determine background (pre-development) levels of hydrocarbon contamination.

Possible locations, methods and experimental design for this work have been outlined by Carson (1991b). It was suggested that a study area flanking Kumak Channel (downstream of the pipeline crossings from Niglintgak Island) and another downstream of the Taglu site would be logical areas for inclusion in this outer delta transect.

In-channel hydraulic and morphologic surveys may not have a great deal of direct relevance to these overbank sedimentation studies, but would provide useful indirect information. Since overbank sedimentation rates in different parts of the delta are partly a function of the frequency of overbank flooding, any data relating to flooding frequency is therefore useful. Thus documentation of breakup conditions and determination of the threshold discharge for flooding under ice-free conditions - information that would be gathered in a normal hydraulic and morphologic survey - would be useful supplementary information for any overbank sedimentation studies.

2.3 Suspended sediment sampling program

A crucial aspect of any suspended sediment sampling program at a station is knowledge of the cross-sectional variability in sediment concentration, and documentation of how that variability changes over time. In sand-bed rivers, suspended sediment concentrations in verticals that are above or immediately downstream of bars are frequently much greater than concentrations in the rest of the channel. Thus an understanding of the movement of such bars (and more generally the stability of the entire bed) is essential in any quality control program for a single vertical (SV) sampling program.

This point is not restricted to issues of sediment quantity (determination of loads), but also for sediment quality. Toxic compounds tend to adsorb preferentially to the finest particles; thus, even without any change in the degree of contamination of the clay fraction, fluctuations in the percentage of the suspended sediment belonging to the sand fraction would produce appreciable apparent changes in contaminant concentration for the total suspended sediment. If such changes in grain size composition occur only in the vicinity of the SV site, and not throughout the cross-section, this could produce a misleading impression of change in contaminant levels in a given river reach. An example of this problem has been documented for the Mackenzie River station just upstream of Arctic Red River (Carson, 1991c, Sect. 11.2).

Thus survey of any changes in bathymetry and bottom sediment pattern in the vicinity of suspended sediment sampling stations is an important component of such programs. To varying degrees, all such stations should have some hydraulic and morphologic work undertaken. Some stations in the delta would be expected to show more cross-sectional variance in sediment concentration than others, however, and more detailed work is required at some of these (Carson, 1991d).

2.4 Calibration of one-dimensional flow model

Wedel (1990, p. 5-9) has described IWD's development of the one-dimensional flow model and its application to the Mackenzie Delta. Its purpose is to simulate flows and water levels in the principal distributaries of the delta. Initially applied to ice-free conditions, it has recently been extended by IWD-Hull to flows confined by solid ice sheets (Kerr, 1992, pers. comm.).

The simulation is based on (a) known discharge inputs at the head of the delta, and (b) routing these inputs through the different reaches on the basis of channel bathymetry, reach slope and roughness. A series of water level stations at the downstream end of the network provides downstream boundary data on stage and water surface slope. Occasional water level and/or discharge gauging in the principal distributaries are needed for verification and/or calibration of the model.

In describing the relevance of the model to NOGAP work, Wedel (1990, p.6) comments:

> "The provision of accurate model estimates of velocity, water levels and streamflow in delta distributaries will contribute to safe, economical design of oil and gas pipeline channel crossings."
>
> "Reliable streamflow data as estuary inputs into Shallow Bay, Middle Channel around Langley Island and into Kittigazuit Bay will be of use to Fisheries and Oceans Canada's studies to define the freshwater plume in the nearshore environment of the Beaufort Sea."

The scale of application of the model is somewhat different, however, in the two cases. Fig. 2.5 shows the schematic distributary pattern (Configuration 2: 85 reaches) planned for the one-dimensional model of the delta, and Fig. 2.6 shows the location of cross-sections surveyed in 1987 (Kerr, 1991, pers. comm.). On the model schematic, there is good coverage of the distributary outlets into Shallow Bay, the water level boundary condition being represented by the gauge in the north arm of Reindeer Channel (10MC011); the number of cross-sections surveyed is, however, small, and many reaches currently lack data. To the north of this area, the network schematic does not extent past reach 39 (Middle Channel at Arvoknar Channel, Langley Island) (10MC010), though East Channel is continued to Kittigazuit Bay (10LC013). Kerr and Fassnacht (1991) and Kerr (1992) have previously emphasized the need to extent the network north of Langley Island.

The network schematic (even if not the number of cross-sections surveyed) in the outer delta seems adequate to address the general issue of plume inputs, identified in the second of Wedel's comments above. It is clearly not adequate, however, in the context of side channels in the northwest part of the delta (Harry Channel, Kumak Channel, etc.) downstream of reach 39. The situation here is complicated by the fact that station 10MC010 was discontinued after being undermined by erosion in 1986.

From the standpoint of oil and gas development, then, much more work seems necessary in order to extend the coverage downstream of reach 39, not only in terms of channel surveys (sections, slope, roughness), but also in terms of the provision of water level recorders near the outer delta north shore. More generally, specific aspects of hydraulic and morphologic work seem required on a fairly extensive regional basis in order to provide an overall assessment of the 1-d model in the delta.

2.5 Endnote

The above notes provide a brief overview of IWD's proposed NOGAP work in the delta, and the needs of the different components for hydraulic and morphologic data. The next chapter provides specific recommendations for the sites of such survey work.

3. RECOMMENDATIONS

This present work is charged with establishing priorities for Hydraulic and Morphologic Surveys (HMS) in the Mackenzie Delta, including identification of up to five sites for implementation during 1992/93 and 1993/94. Instead of simply identifying such sites for hydrologic and morphologic work, however, it seems more fruitful to adopt the position of Hudson (1991) that all IWD sites (hydrometric, sediment, water quality) should - to varying levels - include hydraulic-morphologic data (and interpretation) in their station files.

3.1 Hydrometric stations: routine data

Typical data format for current-metering at measurement sections is illustrated in Fig. 3.1: point velocities at 0.2 and 0.8 depth on verticals across the river. Such information is sufficient for hydrometric purposes. Only a small amount of extra time in the field, however, would be needed to provide additional velocity information that would be much more useful for hydraulic purposes. Bank erosion, for example, is related to shear stresses along the bank; such stresses can be determined through velocity gradients away from the bank, or at least correlated with a point velocity at a standard distance away from the bank. Bed sediment movement is related to bed shear stresses which can be determined through the velocity profile above the bed (e.g. Lapointe, 1984, p. 17-18; NESCL, 1975, Fig. 3.2 in this report) or at some fixed distance above the bed.

The existing velocity data collected by IWD could also be processed in a way that would make it far more useful in the context of hydraulic investigations. For example, isolated metering at different sites in the Delta show appreciable differences in mean cross-sectional velocity. Yet it is difficult to compare such sites, because metering are often done on different days. Thus a velocity-discharge rating curve for each site would be extremely useful, taking into account possible backwater effects. In turn (in conjunction with the flow record that would be built up by the one-dimensional flow model for the delta), this would allow determination of a plot, for each station, of velocity against percent of time exceeded. With this information comparison of sites in terms of a standard velocity (e.g. the two-year flood) would become possible.

3.2 Suspended sediment sampling stations: routine data

In the case of suspended sediment sampling stations (past and present) existing files include fragmentary data on bed material grain size and some cross-sections at measurement section (Carson, 1991d). The value of these data would be increased appreciably if hydrometric survey data were stored on diskette allowing graphical identification of cross-sectional change over time and easier interpretation of bed sediment data (Carson, 1991c, Sect. 11.1).

The importance of these repeated cross-sections in understanding year-to-year changes in the representativeness of the single vertical used for suspended sediment sampling has also been emphasized in the past. This point was made not only in connection with the mid- and lower-delta sediment stations (Carson, 1991d), but especially in connection with ongoing suspended sediment sampling on the Mackenzie River at Arctic Red River (Carson, 1988) and the Peel River (Carson, 1989). This routine work at existing stations is just as important to the overall NOGAP program as special hydraulic and morphologic work at new sites.

3.3 IWD sites: data from other agencies

It is clear from examination of the literature dealing with channel stability in the delta (Carson, 1991a) that some of the outer delta hydrometric sites used by IWD have been surveyed by other agencies in the past in connection with possible pipeline crossings. This is true of 10MC901 (Middle Channel at Langley Island) and 10LC901 (East Channel downstream of Tununuk Point) as indicated on Fig. 3.3. Air photographs and bathymetry of these two sites, as determined by NESCL (1975), are provided in Figs. 3.4 - 3.7. NESCL (1975) surveyed two sites on Reindeer Channel: one was in the north outlet, and the other in the main channel (prior to its outlet branching) at km 1700 (Chart 6434). The hydrometric data from the latter section may still be of value to IWD in connection with modelling of flows along Reindeer Channel. An aerial photograph of the section is given in Fig. 3.8; section data were previously given in Fig. 3.2.

Irrespective of whether these sites undergo new "HMS" work under the NOGAP C.11-6 program (and given the importance of other sites listed below, these two measurement sections may not be regarded as high priority), arrangements should be made to acquire these (often proprietary) data to supplement the existing hydraulic and morphologic information file for these stations.

3.4 New HMS fieldwork

The specific goals of the new NOGAP-funded program of IWD in the Mackenzie Delta require additional hydraulic and morphologic information at some existing IWD sites, and at some new sites. The goals of the NOGAP program have been outlined in Chapter 2. On the basis of the information summarized in that chapter, the following five reaches (Fig. 2.1) are identified as needing additional hydraulic and morphologic work:

- Kumak Channel: data are required in connection with channel stability, for calibrating and testing the one-dimensional flow model, and to provide background information for the proposed study of overbank sedimentation.

- Harry Channel at and downstream of Kuluarpak Channel branch off: channel stability, data-acquisition for the one-dimensional flow model, and background data for the proposed study of overbank sedimentation.

- Lower East Channel at Swimming Point: channel stability.

- Upper East Channel upstream of Inuvik: stability of deep scour hole.

- Mackenzie River at Arctic Red River: bed stability as it affects stage-discharge curve and suspended sediment sampling program.

These sites are not listed in order of priority. They are all important in the context of the NOGAP program. Moreover, the same level of work will not be needed in all reaches. In part, this statement reflects the comments of Hudson (1991) regarding different levels for different purposes. In part, it reflects the fact that in some cases (Kumak, Harry and lower East Channel) considerable work has already been done, is being done or is planned by other agencies. In these cases, IWD's work is primarily to supplement the other programs by attention to gaps in the program. In other cases a more extensive program, entirely within the domain of IWD, will be necessary.

The remainder of this chapter briefly discusses what is available and what is needed in these new reaches. It should be noted, however, that not all existing documentation for each reach has been seen. A detailed work program for each reach should be prepared prior to fieldwork, but only after an exhaustive investigation of existing databases has been completed.

3.5 Kumak Channel

Details of the work done at this site in the 1970s by consulting firms working for the petroleum companies, and in the last few years by GSC are not known. Reference will have to be made to the old reports, and to the GSC report (Traynor and Dallimore, 1991, in prep.) when it is ready. The synopsis of the GSC report provided by Dallimore (1991, pers. comm.) seems to indicate that the main thrust of the 1990 work was resurvey of old cross-sections to determine (a) scour, fill and bank migration, and (b) channel section properties at time of field survey (Fig. 3.9). Some 1970s surveys involved discharge measurements, but whether flows were also measured by GSC is not known.

The 1991 program of GSC has not yet been written up, but the project proposal (Dallimore, 1991, pers. comm.) highlights the following points:

- quantifying ground ice content of channel bank sediments;

- identification of areas of slumping and retrogressive thaw slide occurrence;
- ground truthing of Landsat vegetation mapping to assist in permafrost studies and interpretation of the geomorphology of crossing sites;
- extension of previous studies to investigate the shallow permafrost temperature regimes;
- review of existing geotechnical, hydrological and geophysical survey data.

Output will take the form of a preliminary geological map of Niglintgak and Taglu areas. The final report (which will also include East Channel) is not planned until the end of fiscal 1992/93.

The impression gained is that TSD has already embarked on the kind of HMS work envisaged by IWD, and that IWD's role would be primarily to supplement TSD's work. It appears that TSD has summarized its bathymetric data solely in terms of cross-sections. A more useful summary (from the standpoint of interpretation) would be as a bathymetric chart, and comparison with past bathymetric chart surveys (e.g. CHS 6435).

Areas in which IWD involvement appears to be desirable include:

(a) channel bed material sampling;
(b) additional discharge and water stage measurements; and
(c) additional cross-sectional surveys in Middle Channel at the branch-off of Kumak Channel.

(a) A program for sampling of channel bed material cannot be formulated until documentation of all existing bed material (located by site, depth and date) has been examined. Some information will be needed on changes in bed material with depth at key sites, but these data may exist from the drilling program done in the 1970s. Information regarding the temperature status of bed and submerged bank sediments (permafrost) is also needed, though, again, this may be available from past surveys.

(b) IWD's one-dimensional model has not yet been extended to the distributaries of the outer delta. Past discharge data on Kumak Channel may not be useful in the context of the 1-D model because of the lack of any water level recorder at the outlet of the channel. It seems likely that wind-tides and storm-surges, as well as the small normal tidal cycle, will affect any stage-discharge relationship in the reach. Thus, until a water level recorder is established at the outlet, to complement the existing stilling well near the entrance (Fig. 2.3), isolated discharge measurements may be of little use.

(c) A major control on the flows through Kumak Channel is the bathymetry of Middle Channel downstream of, and at the branch-off of Kumak Channel. Some surveys have been done in this region according to Fig. 2.3 (either by GSC or in the 1970s). Additional surveys would provide some insight into the pattern of sedimentation and bed scour through, firstly, comparison with CHS sounding (Chart 6435) in 1972/73, and secondly, providing a baseline for comparison with future surveys.

There is no direct linkage between this in-channel HMS work and studies of overbank sedimentation proposed for the region (Carson, 1991b, p. 19). However, overbank sedimentation through the delta is closely related to flooding frequency and duration. The existence of prior water-level data in this region (as represented by data from the Kumak stilling well) may therefore be useful in this regard.

3.6 Harry and Kuluarpak Channels

The comments directed at the Kumak Channel reach appear applicable also to the Taglu area. GSC's work and schedule is the same in both areas.

It is therefore assumed that IWD would make a threefold contribution similar to that outlined in 3.5. It seems likely (judging by channel morphology) that bank and bed sediments are much more variable in this area than in the Kumak reach. Attention should also be focused on bed stability of the two channels <u>relative to each other</u>: any preferential sedimentation in Kuluarpak Channel, for example, is likely to lead to increased flow through the Harry Channel complex.

The flow into these two channels is strongly controlled by conditions at the Harry Channel branch-off from Middle Channel (CHS Chart 6435). Examination of repeated aerial photographs of this juncture, together with a resurvey of channel bathymetry (for comparison with the 1972/73 CHS survey) would be useful in assessing changes in flow conditions in the branch-off.

3.7 Lower East Channel at Swimming Point

The morphology of East Channel is quite different from that of the Niglintgak and Taglu areas. In addition, bathymetric information is already available in Chart 6430 (surveyed in 1975). HMS studies will therefore be different in scale and scope.

Again, some information has already been collected by firms working for the petroleum companies in the 1970s. This information needs to be reviewed in detail before planning IWD's involvement in the reach. The Terrain Science Division plans to undertake work in this region during 1992 in a manner roughly comparable with work done in Niglintgak and Taglu in 1991. It is therefore essential that IWD liaise with TSD to ensure that their combined efforts complement rather than duplicate.

In view of the TSD program, it may be appropriate, again, that IWD focus its attention on bed material sampling, and determination of the temperature status of the bed sediment. It is assumed that little additional work is needed in terms of calibrating the 1-D model in this reach, given the existence of a gauge at the reach outlet (Kittigazuit Bay).

Some HMS work in the reach may be particularly useful to IWD in the context of its suspended sediment sampling program. It was previously noted that the existing measurement section and SV sampling site just downstream from Tununuk Point may not be entirely suitable for suspended sediment purposes (Carson, 1991d, p. 16), partly because of the angle of inflow from Neklek Channel and partly because of the limited mixing between flows from Neklek and East Channel upstream. The issue will become clearer with examination of the cross-sectional variance in concentrations available from the 1991 summer program. Depending upon these results, it may be desirable to move the sampling section (or at least the SV site) downstream. The Swimming Point reach may be a logical replacement.

3.8 Upper East Channel upstream of Inuvik

One aspect of channel stability that is clearly of concern to pipeline crossings is the origin and behaviour of the anomalous deep "scour holes" (Lapointe, 1986a).

Unfortunately, no examination of channels (in terms of scour holes or scour bays) was undertaken by Lapointe north of Shallow Bay. It is therefore not known whether these deep scour holes occur in the outer delta where hydrocarbon development is most likely. Given the time constraints of this program, however, it makes little sense to adopt a wait-and-see attitude. The recommendation is made here that resurveys be made of the one scour-hole site that was carefully documented by Lapointe (1986a, p. 29) in the expectation of future resurvey.

The location of the study site, on East Channel about 14 km SSW of Inuvik, is shown in Fig. 3.10. The survey lines and cross-sections are provided in the report by Lapointe (1986a). The interpolated bathymetry of the scour hole reach is given in Fig. 3.11. No comment was made by Lapointe regarding the transverse axis to the scour hole and its apparent relationship to the linear lakes southeast of the scour hole bend. This is a matter which warrants further investigation, possibly requiring on-land geomorphic and sediment study as well as hydraulic and morphologic survey of the river channel.

The river was surveyed by Lapointe on August 8, 1985. The six cross-sections were, in each case, tied in to a benchmark 20 to 30 m away from the water's edge. These benchmarks are nails set at less than one metre from the base of mature spruce trees located on, or less than 3 m laterally off, the section lines. In each case, orange-painted signs were nailed to spruce trees close to the bank to facilitate relocation of the lines.

Since the initial survey of this bend, there has been at least one substantial flood down East Channel (1988), and it would seem opportune to resurvey these lines in order to document bathymetric change. Whether the resurvey is done in 1992 or 1993 is perhaps not too important (but see comments below). What is important is that these benchmarks be relocated during the 1992 season, and, if necessary, additional markers established further from the channel margin. All Lapointe's markers were located on the cutbank side of the channel, and in view of ongoing bank erosion, they need to be relocated as soon as possible.

Resurvey of these sections should be accompanied by a detailed bed material sampling program on a grid dictated by the bathymetry (and indicated changes). Bed material sampling was undertaken by Lapointe (1986b) at three verticals on a cross-section upstream of the bend (E-E) and downstream (F-F), as indicated on Fig. 3.12. The upstream section was dominantly sand; this was also the largest fraction in mid-stream downstream of the bend; this raises questions regarding the origin of the sand, and its ability (if from upstream) to bypass the scour hole without infilling it.

Careful documentation of the exposed cut bank sediment and ice content should also be undertaken. All these observations are best made at relatively low flow. Assuming that the survey were undertaken in 1992, there is the possibility that follow-up "process" observations (velocities, upwelling, etc.) could be undertaken at high water in 1993.

Though the East Channel scour hole is remote from any likely pipeline crossing, the ability to resurvey this site after a period of 7 or 8 years (with at least one significant flood flow) is an opportunity that should not be missed. The work does not preclude monitoring of any scour holes found in other HMS work in the outer delta. It will, in fact, provide a good perspective for planning any such monitoring.

3.9 Mackenzie River at Arctic Red River

The locations of the gauge, measurement section and SV suspended sediment sampling site for this station are shown in Fig. 3.13, immediately upstream (1980s station) of the settlement of Arctic Red River. On the basis of the two surveys at the measurement section given in Fig. 3.14, it appears that the inner bank bar (at the bend upstream of the section) extended downstream towards and past the measurement section during the period 1980-86. The morphological changes in the reach were accentuated during the major floods of 1988. The morphological changes may have created problems for both the hydrometric program and the suspended sediment sampling program.

In terms of the hydrometric program, substantial infilling occurred along the left side of the measurement section, raising some concern at the time regarding continued usage of the section (Wedel, 1988, pers. comm.). Any massive change in mean bed levels in the gauge area or its downstream control area, as a result of the flood, may have had some effect on the stage-discharge rating curve. Of immediate concern (but not necessarily related to bathymetric changes) is the fact that the measured high flows in 1988 were consistently higher than predicted by the stage-discharge rating curve, casting doubt on the high-flow extension previously used (Fassnacht, 1991).

In terms of the suspended sediment program, there was, during the 1980s, a fairly strong increase in concentrations across the measurement section from right to left, this being attributed to downstream transport of sand along the left side of the channel from the left bank bar. Total suspended sediment concentrations at the SV site (downstream of the measurement section) in the early 1980s were less than the mean for the measurement section (on the four dates for which comparative data are available), whereas in 1984-1986, SV samples showed higher concentrations on two of the three days of comparative sampling. The maximum underestimate by the SV site in the early 1980s corresponded to a k-value of 1.73; the maximum overestimate in the mid-1980s was given by a k-value of 0.86 (Carson, 1988). The post-1986 data have not yet been reviewed.

Given the importance of both hydrometric and sediment data at this site to the entire Mackenzie Delta IWD program, monitoring of the stability of the stage-discharge curve and the sediment k-factor is essential. To aid in a better understanding of both problems, it is recommended that HMS work be undertaken in this reach. However, the two problems generally involve different aspects of the HMS work.

In terms of the hydrometric program, continued monitoring of water level at the old 10LA003 gauge site (Fig. 3.13) is needed to (a) verify the existing correlation between water levels at the old and new gauge sites and (b) provide information on water surface slope in connection with the 1-d flow model (Brumwell, 1991). It seems likely that slope could change appreciably on a seasonal basis, as well as during individual flood events. (The current status of the stage datum at both stations is included in the review by Fassnacht, 1991b).

In terms of the sediment program, the relationship between the k-factor for the SV site and the degree of extension of the left bank bar downstream of the measurement section needs further investigation. Whatever the outcome of that investigation, understanding the reasons for the substantial changes that have occurred in the k-factor in the past (and presumably likely in the future) is needed if reasonably accurate predictions of sediment load are to be made at this station (and if representative data for sediment quality are to be derived from SV samples). In the opinion of the present writer, these reasons probably relate to the ongoing changes in the bathymetric configuration of the channel. Documentation of these changes, through HMS work, is therefore needed.

3.10 Endnote

Additional examination of past work done at the likely outer- delta crossing sites (3.5, 3.6, 3.7) may indicate little, if any, fieldwork necessary by IWD staff. In this case, resources would be available for work at other sites. Two suggestions are made here. First, more effort might be made to assemble (and convert to a more useful format) existing hydraulic and morphologic data (from IWD and external agencies) at IWD sites, as outlined in Sections 3.1, 3.2 and 3.3. Second, HMS work previously recommended for Peel River above Fort McPherson (Section 3.2) might be increased. These additional hydrometric/sampling measurements (at high flows) would not only provide more information on the stability of the k-factor for the SV sediment site, but also provide more confidence in the stage-discharge rating curve.

Much hydraulic and morphologic information apparently exists at a few key sites in the Mackenzie Delta. Much more will be gathered as part of the NOGAP program. It is important that the final reports for each reach are not simply a compendium of data, but are synthesized from the standpoint of the geomorphic behaviour of the reach as well as the practical significance of the data.

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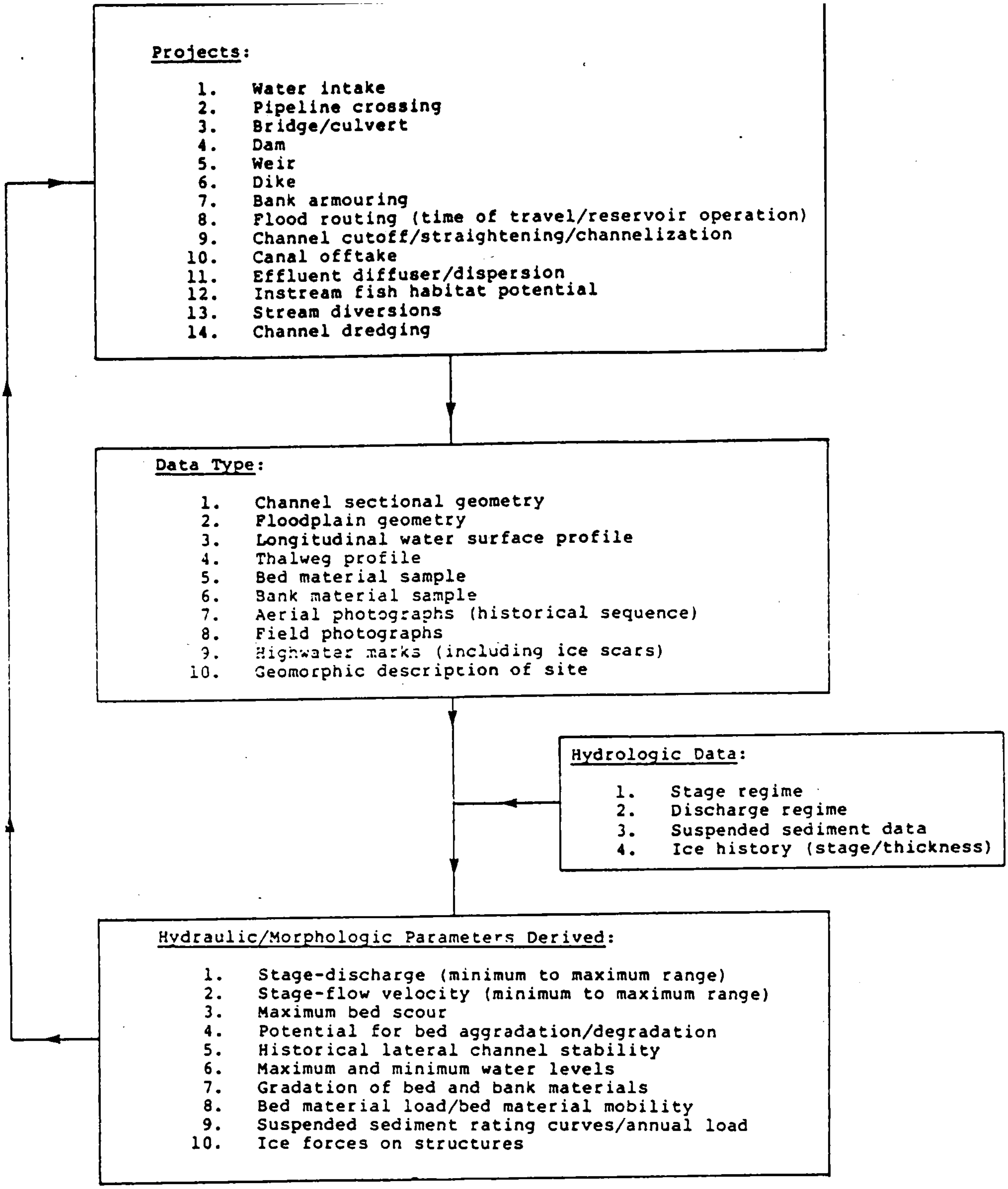
LIST OF FIGURES



Projects:

1. Water intake
2. Pipeline crossing
3. Bridge/culvert
4. Dam
5. Weir
6. Dike
7. Bank armouring
8. Flood routing (time of travel/reservoir operation)
9. Channel cutoff/straightening/channelization
10. Canal offtake
11. Effluent diffuser/dispersion
12. Instream fish habitat potential
13. Stream diversions
14. Channel dredging

Data Type:

1. Channel sectional geometry
2. Floodplain geometry
3. Longitudinal water surface profile
4. Thalweg profile
5. Bed material sample
6. Bank material sample
7. Aerial photographs (historical sequence)
8. Field photographs
9. Highwater marks (including ice scars)
10. Geomorphic description of site

Hydrologic Data:

1. Stage regime
2. Discharge regime
3. Suspended sediment data
4. Ice history (stage/thickness)

Hydraulic/Morphologic Parameters Derived:

1. Stage-discharge (minimum to maximum range)
2. Stage-flow velocity (minimum to maximum range)
3. Maximum bed scour
4. Potential for bed aggradation/degradation
5. Historical lateral channel stability
6. Maximum and minimum water levels
7. Gradation of bed and bank materials
8. Bed material load/bed material mobility
9. Suspended sediment rating curves/annual load
10. Ice forces on structures

Figure 1.1

Uses of hydraulic and morphological data

(from NHCL, 1986)

FIGURE 1.2

EXAMPLE OF HYDRAULIC-MORPHOLOGIC DATABASE

(from NHCL, 1986)

A1. Case 1

Project: Pipeline river crossing
Stream name: M'Clintock River
Location:: Yukon Territory

Data type collected:

- channel sectional geometry
- floodplain geometry
- longitudinal water surface profile
- thalweg profile
- aerial photographs (historical sequence)
- field photographs
- highwater marks
- geomorphic description of site

Hydraulic/Morphologic Parameters Derived:

- stage-discharge (minimum to maximum range)
- stage-flow velocity (minimum to maximum range)
- maximum bed scour
- potential for bed aggradation/degradation
- historical lateral channel stability
- maximum water level
- assumed bed and bank material gradation (based on visual observation that bed and bank material comprised of find sand)
- bed material load

Hydrology: **Water Survey of Canada hydrometric station No.9AB8 - located approximately 8.4 km upstream from mouth of Marsh Lake; pipeline crossing at mouth of Marsh Lake.**

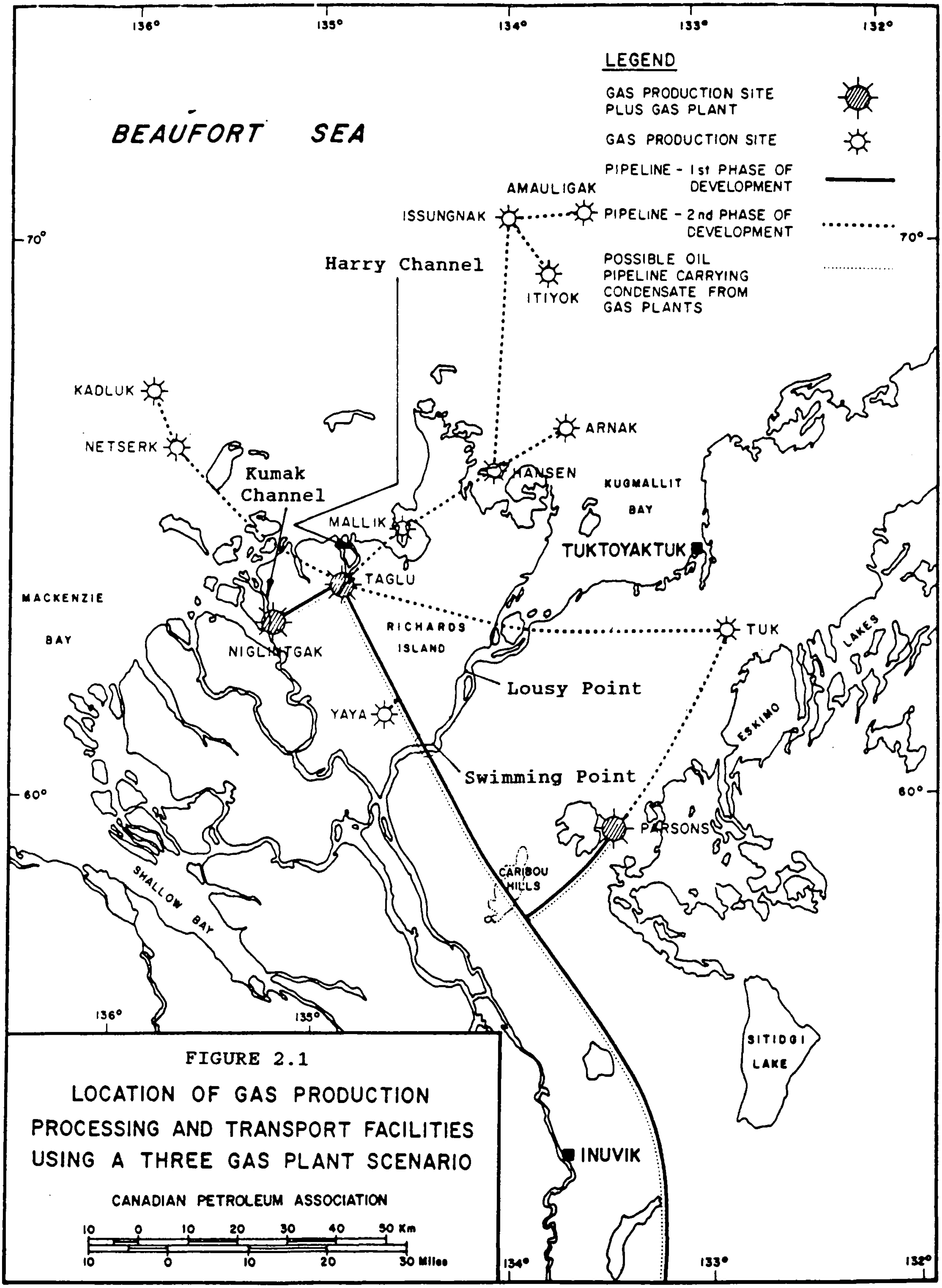


FIGURE 2.1

LOCATION OF GAS PRODUCTION PROCESSING AND TRANSPORT FACILITIES USING A THREE GAS PLANT SCENARIO

CANADIAN PETROLEUM ASSOCIATION

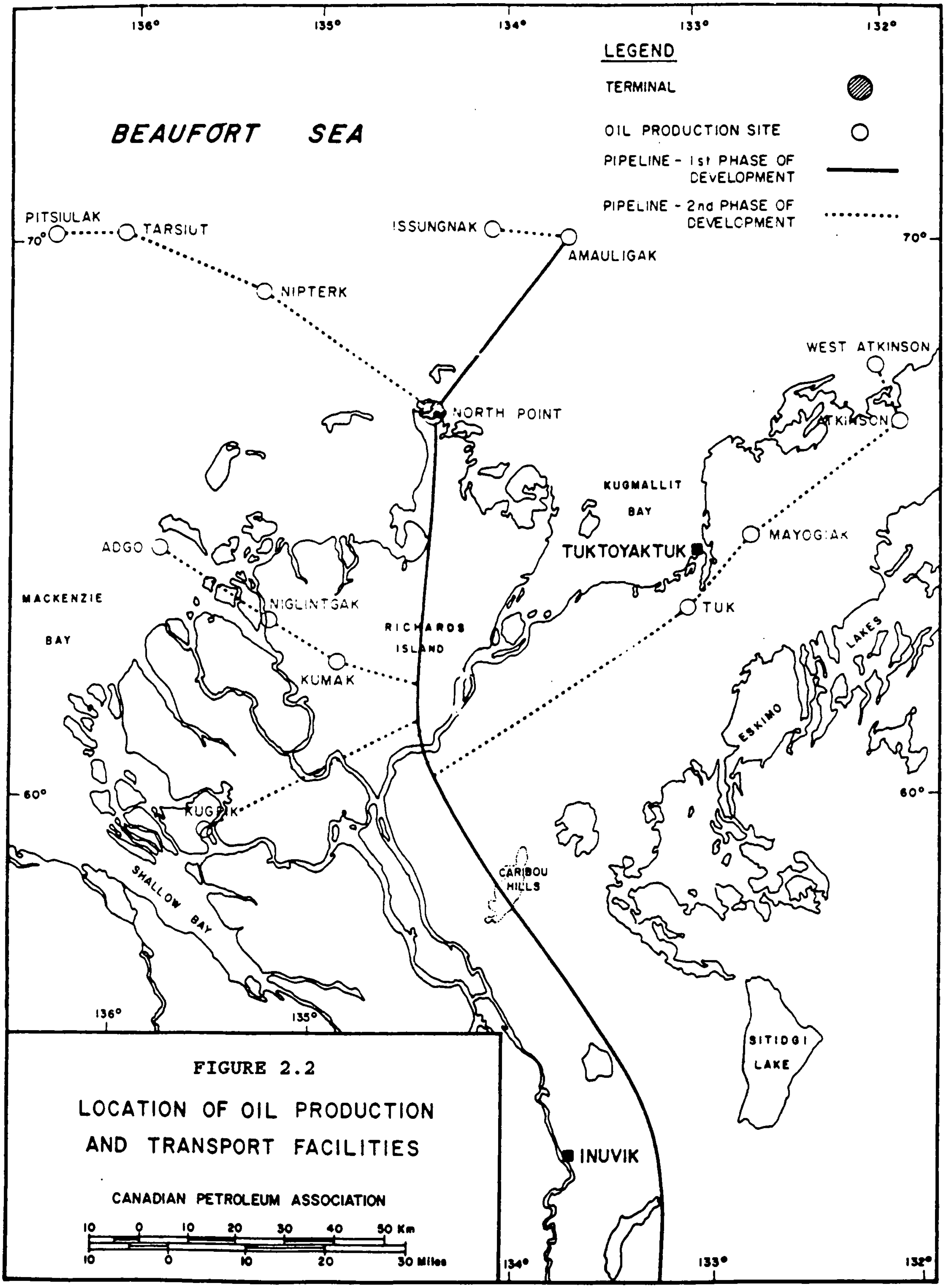


FIGURE 2.2

LOCATION OF OIL PRODUCTION AND TRANSPORT FACILITIES

CANADIAN PETROLEUM ASSOCIATION

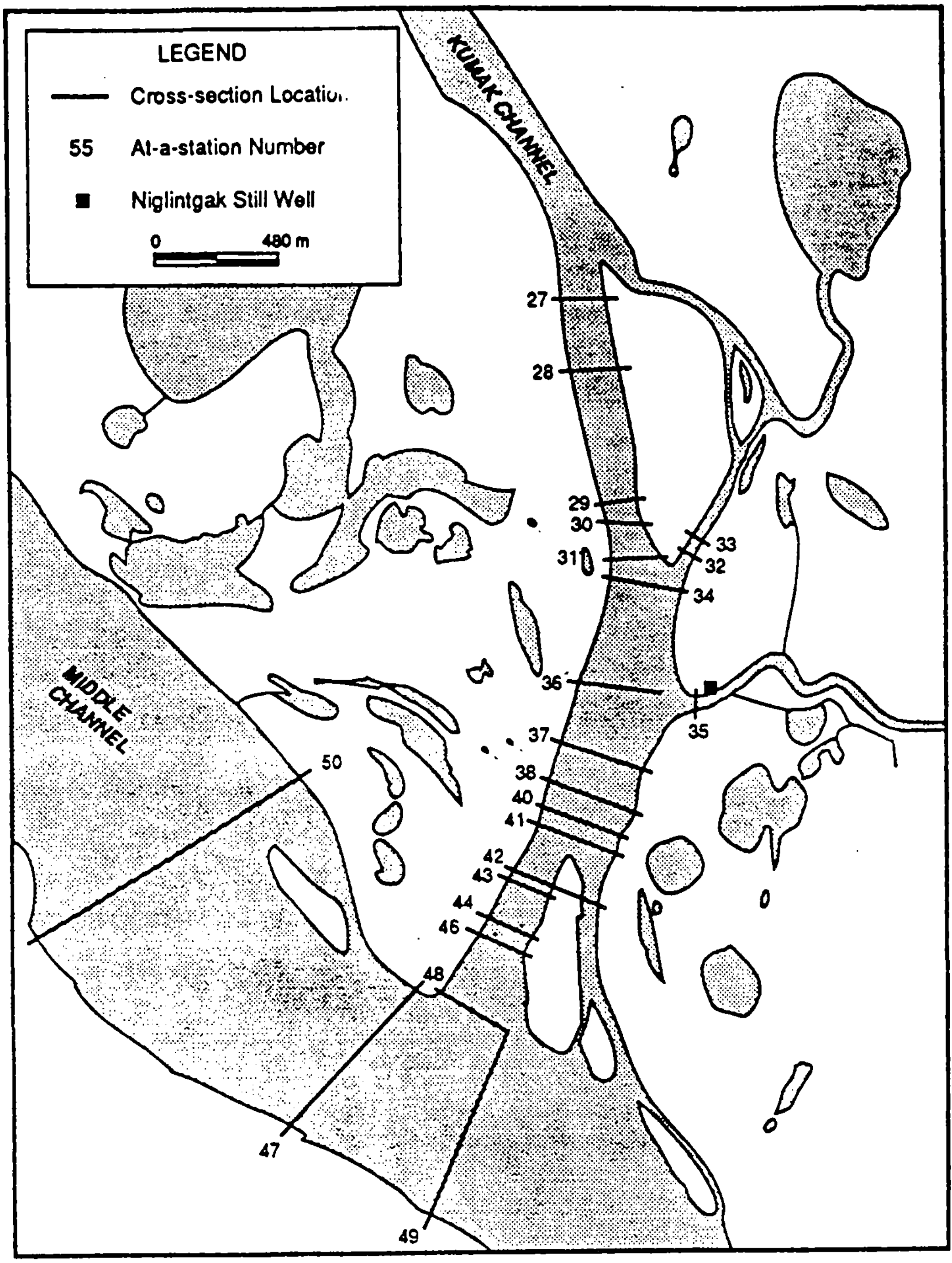


Figure 2.3

Niglintgak Island Area Cross-Section Locations

(from Traynor and Dallimore, in prep.)

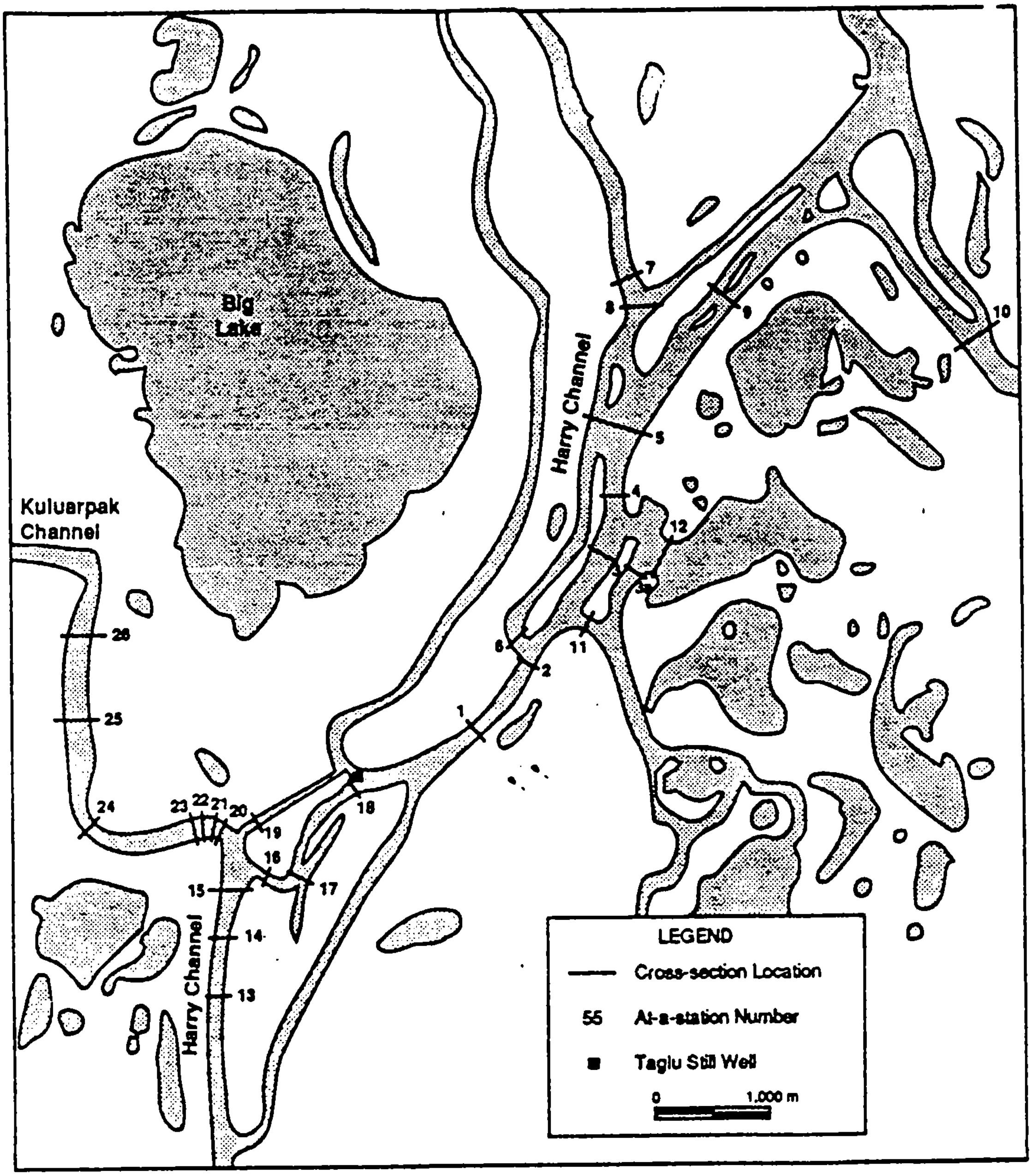
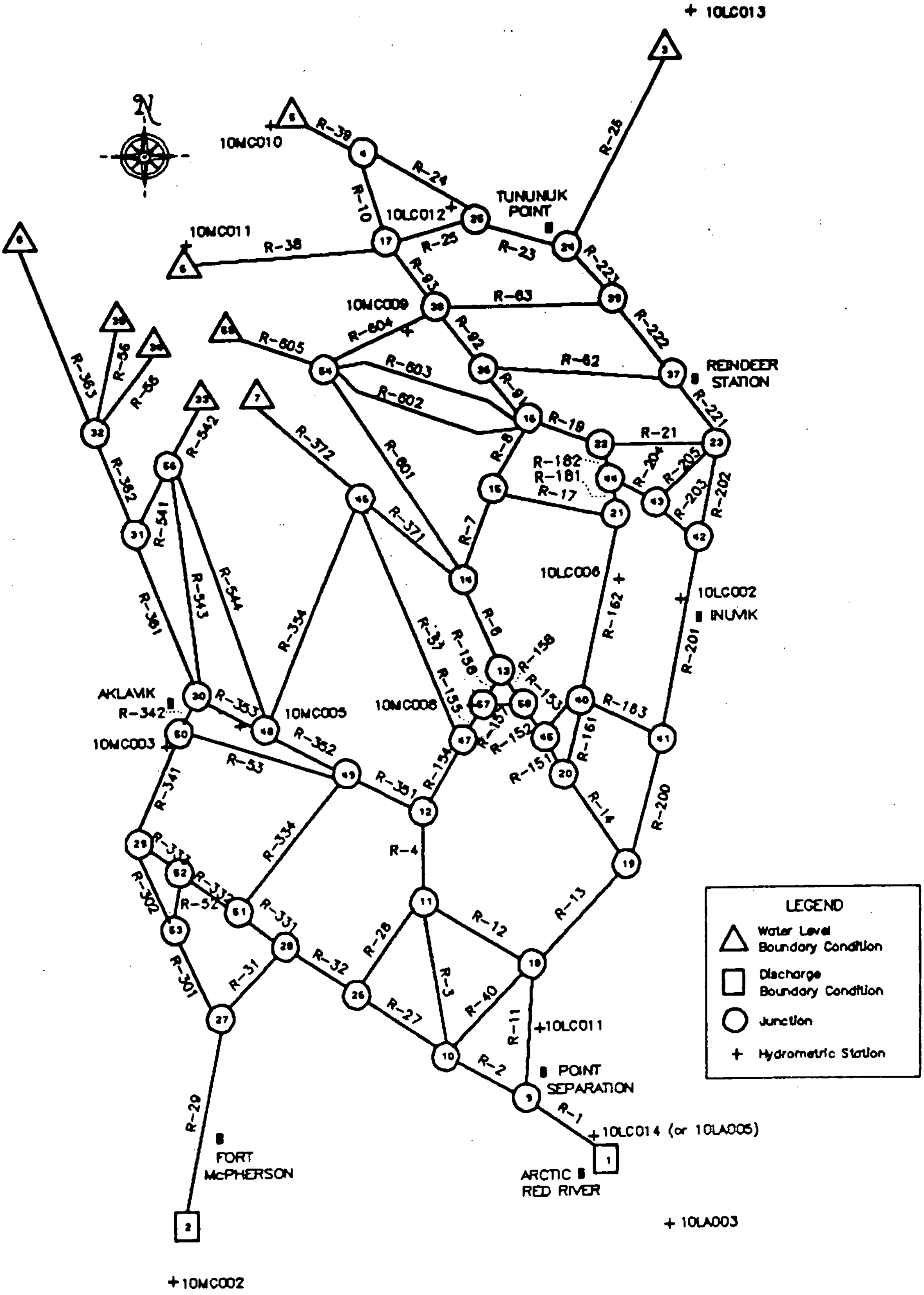


Figure 2.4

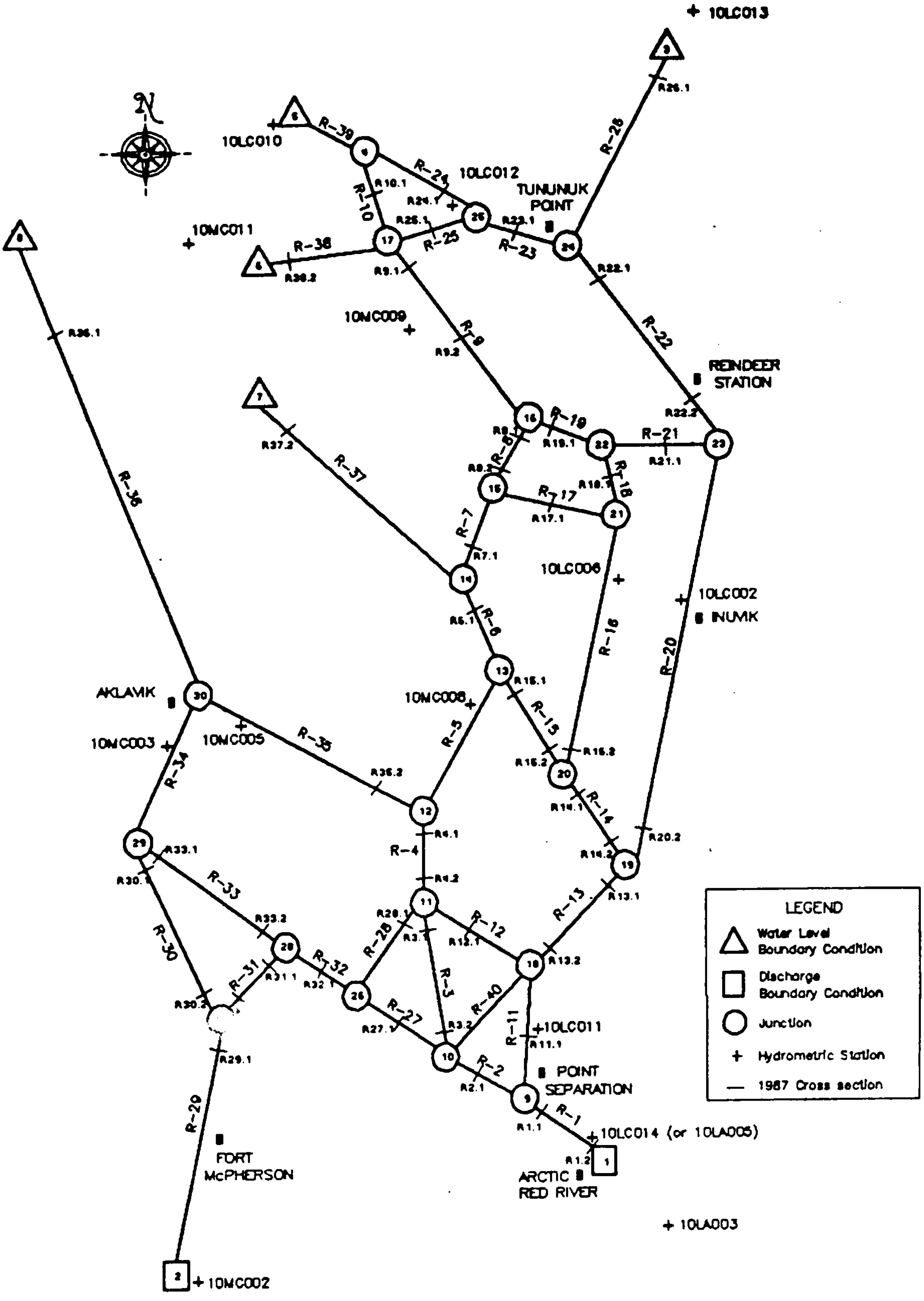
Taglu Island Area Cross-Section Locations

(from Traynor and Dallimore, in prep.)



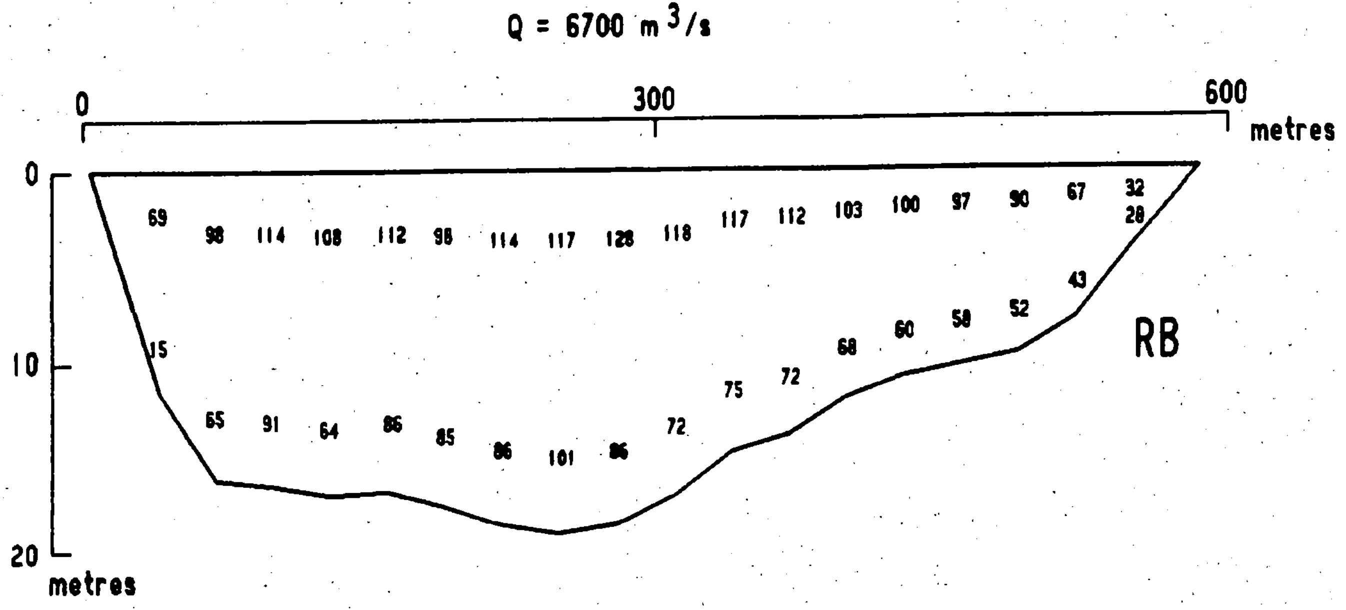
MACKENZIE DELTA PROJECT
MODEL SCHEMATIC

FIGURE 2.5 ONE-DIMENSIONAL FLOW MODEL



LOCATION OF CROSS SECTIONS
MEASURED IN 1987.

FIGURE 2.6 ONE-DIMENSIONAL FLOW MODEL



Point velocities in cm per second

FIGURE 3.1

REINDEER CHANNEL BELOW LEWIS CHANNEL: 1990 JUNE 20
CROSS-SECTIONAL VELOCITY DISTRIBUTION

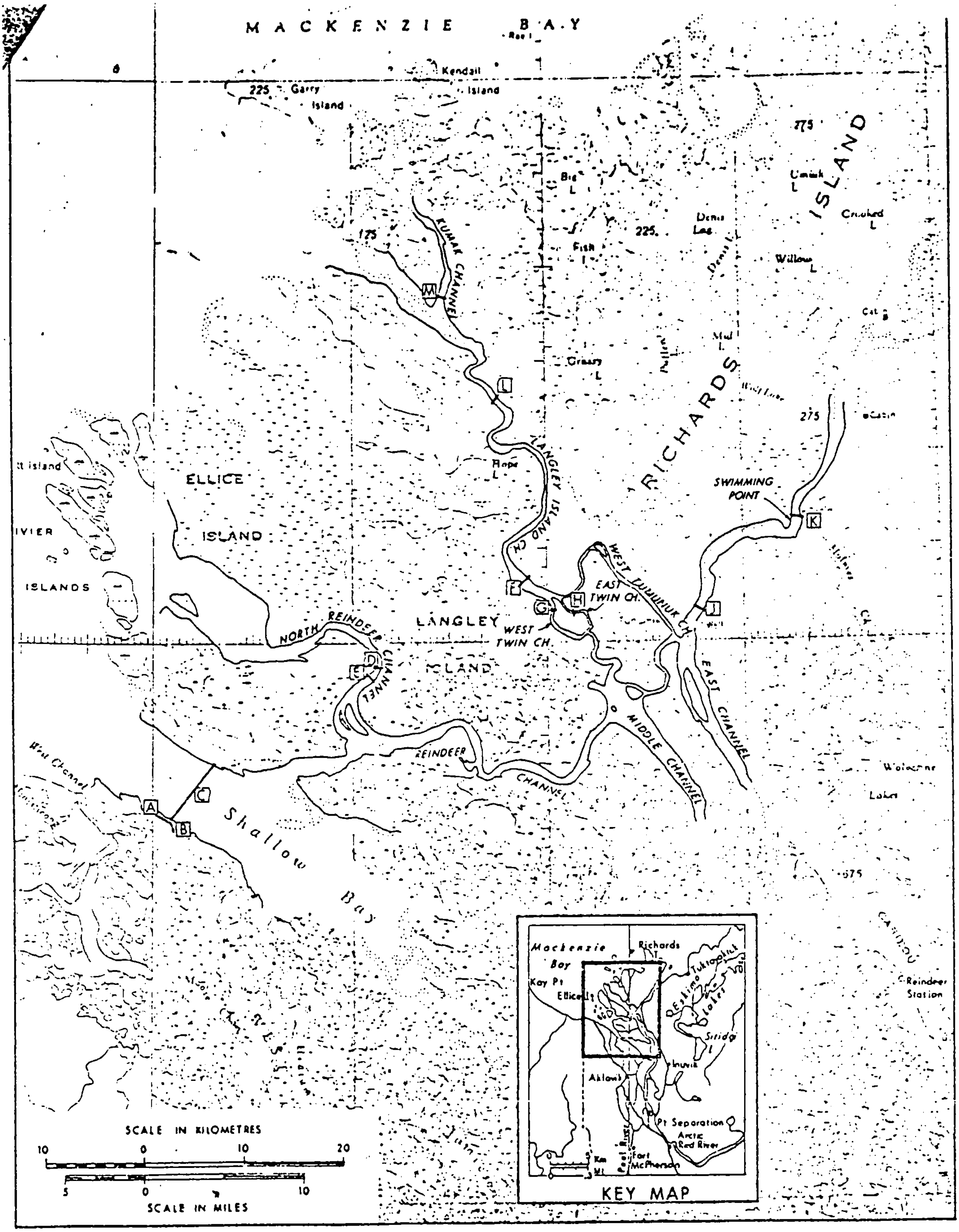


FIGURE 3.3 LOCATION MAP OF MACKENZIE RIVER - OUTER DELTA

(from Hollingshead and Rundquist, 1977)

LEGEND:

Ⓜ – FLOW MEASUREMENTS TAKEN AT THIS CROSS SECTION

○ A – SURVEY CONTROL POINT

NOTES:

1. DATE OF AERIAL PHOTOGRAPHY - AUGUST 24, 1974
2. DATE OF SURVEY - AUGUST 12, 1975

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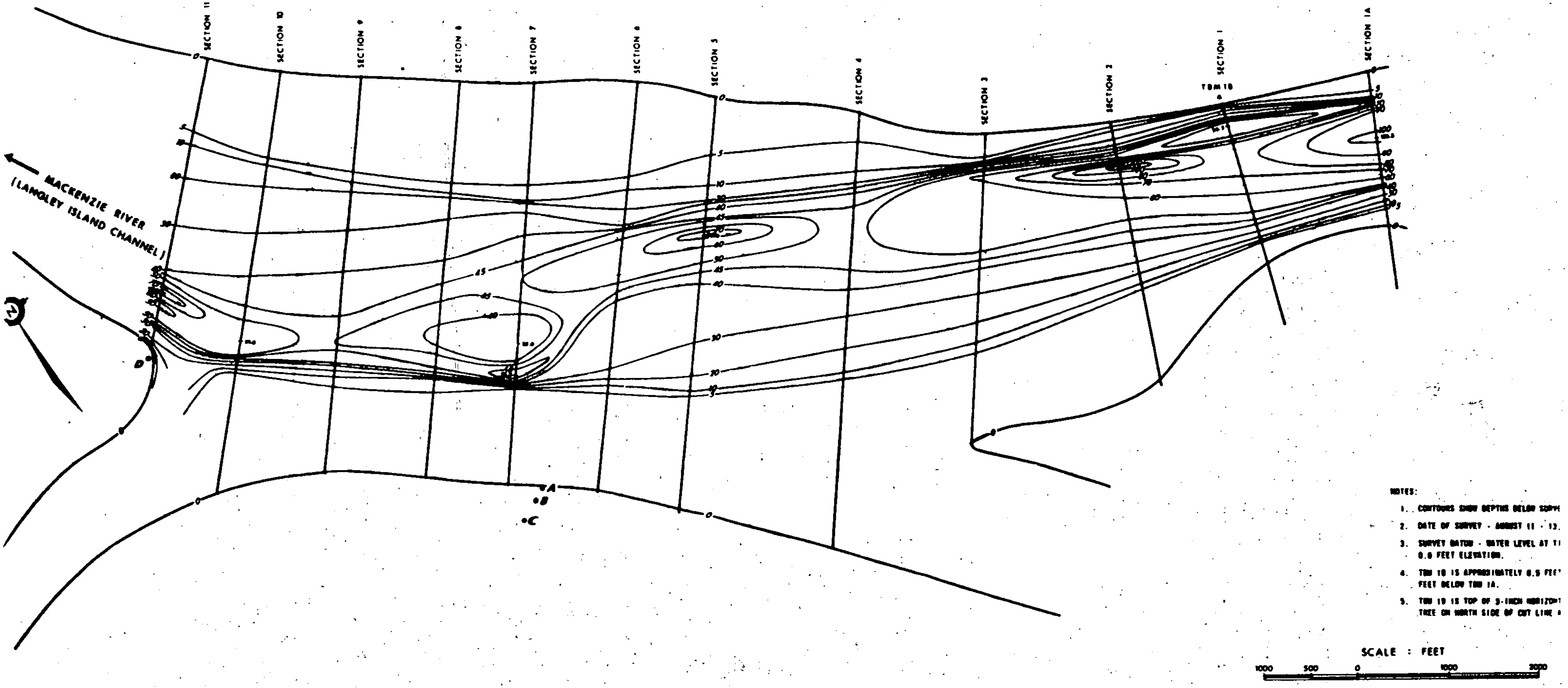
ENGINEERS FOR

CANADIAN ARCTIC GAS STUDY LIMITED

CROSS SECTION LOCATIONS
MACKENZIE RIVER - LANGLEY ISLAND CHANNEL
SUMMER 1975

FIGURE 3.4 MACKENZIE RIVER - LANGLEY ISLAND CHANNEL

(from NESCL, 1975)



NOTES:

1. CONTOURS SHOW DEPTHS BELOW SURV
2. DATE OF SURVEY - AUGUST 11 - 13,
3. SURVEY DATUM - WATER LEVEL AT T
   0.0 FEET ELEVATION.
4. TBM 1B IS APPROXIMATELY 0.5 FEE
   FEET BELOW TBM 1A.
5. TBM 1B IS TOP OF 3-INCH HORIZON
   TREE ON NORTH SIDE OF CUT LINE

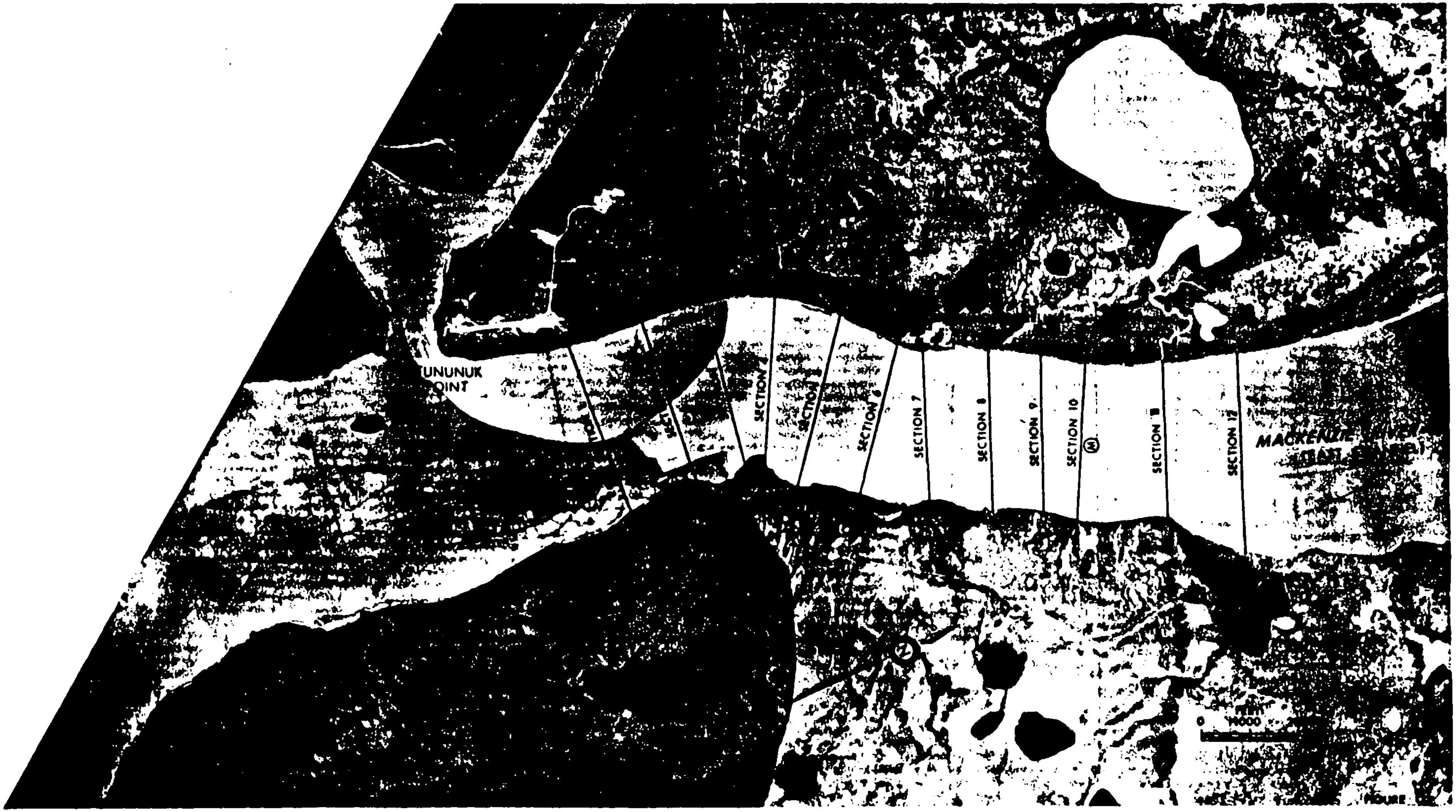
(from NESCL, 1975)

FIGURE 3.5

CHANNEL DEPTH CONTOURS

MACKENZIE RIVER - LANGLEY ISLAND CHANNEL

SUMMER, 1975



LEGEND:

Ⓜ – FLOW MEASUREMENTS TAKEN AT THIS CROSS SECTION

∘ A – SURVEY CONTROL POINT

NOTES:

1. DATE OF AERIAL PHOTOGRAPHY - JULY 27, 1970 AND AUGUST 24, 1974
2. DATE OF SURVEY - AUGUST 8 - 10, 1975

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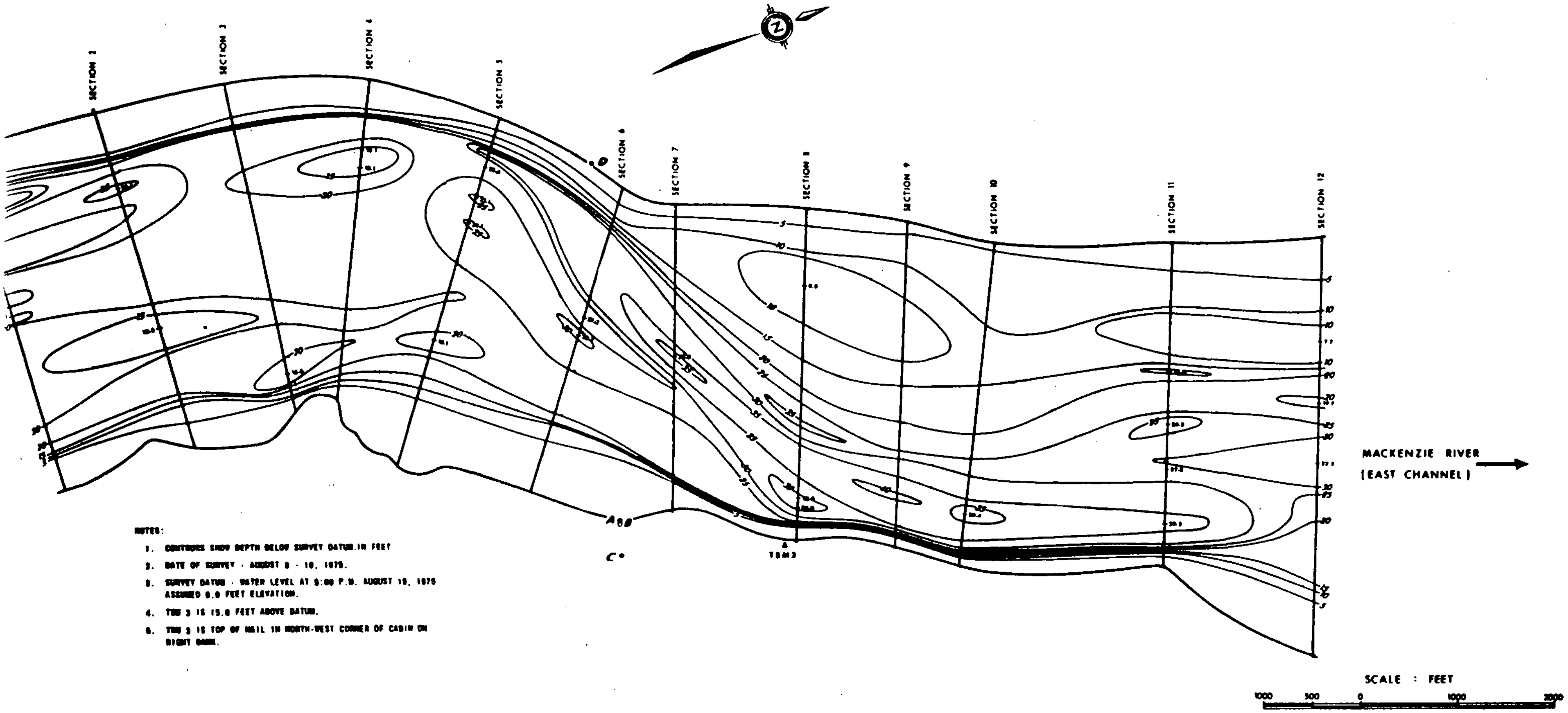
CANADIAN ARCTIC GAS STUDY LIMITED

CROSS SECTION LOCATIONS
MACKENZIE RIVER - EAST CHANNEL
SUMMER 1975

FIGURE 3.6 MACKENZIE RIVER - EAST CHANNEL

(from NESCL, 1975)



NOTES:

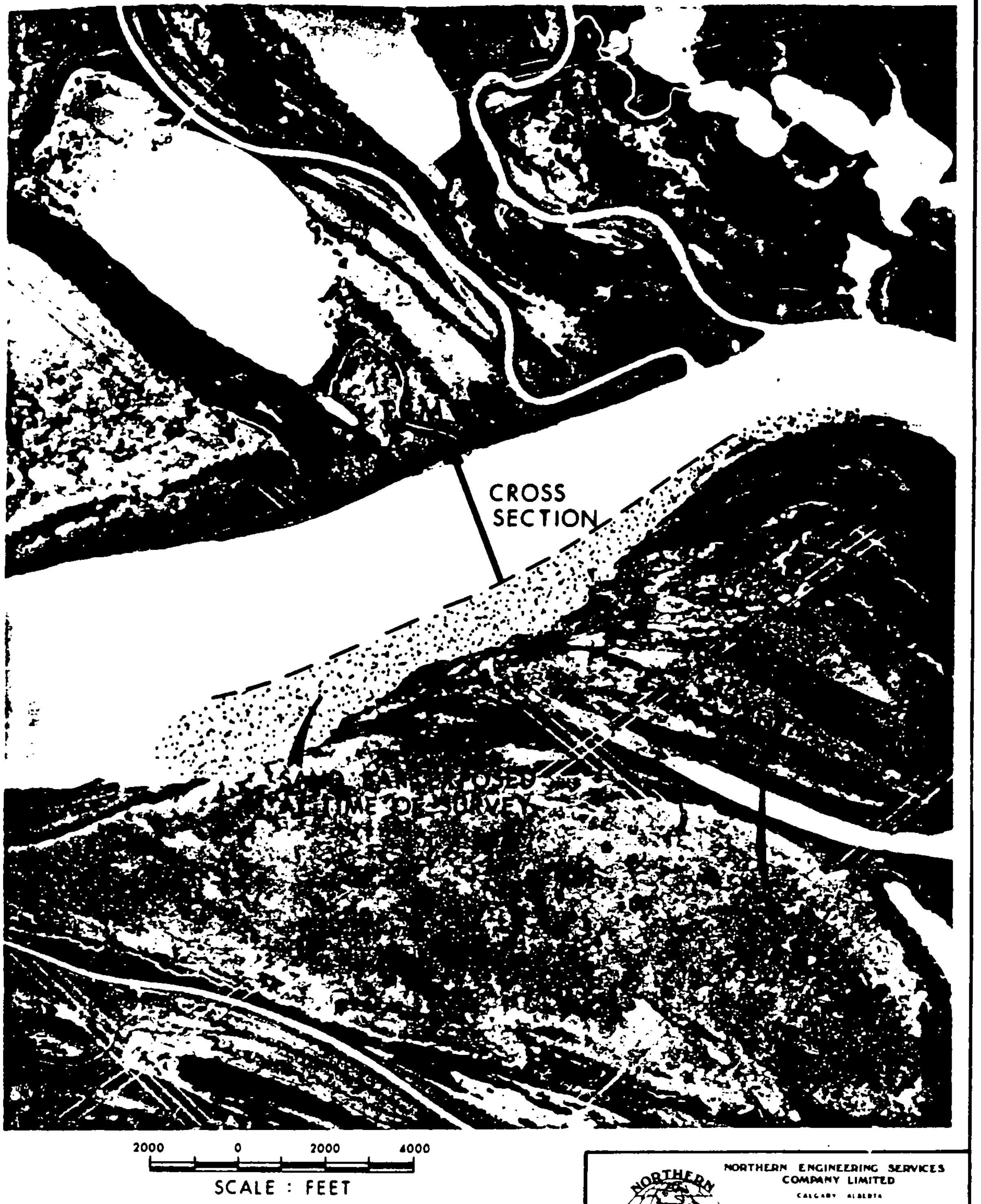
1. CONTOURS SHOW DEPTH BELOW SURVEY DATUM, IN FEET
2. DATE OF SURVEY - AUGUST 8 - 10, 1975.
3. SURVEY DATUM - WATER LEVEL AT 5:00 P.M. AUGUST 10, 1975 ASSUMED 0.0 FEET ELEVATION.
4. TBM 3 IS 15.0 FEET ABOVE DATUM.
5. TBM 3 IS TOP OF NAIL IN NORTH-WEST CORNER OF CABIN ON RIGHT BANK.

FIGURE 3.7 (from NESCL, 1975)

CHANNEL DEPTH CONTOURS

MACKENZIE RIVER - EAST CHANNEL

SUMMER, 1975



NOTES

1. DATE OF AERIAL PHOTOGRAPHY - JULY 27, 1973
2. DATE OF SURVEY - AUGUST 7, 1975
3. TBM R1 IS THE TOP OF A 2" × 2" WOODEN HUB AT EDGE OF WILLOWS AT THE BASE OF 7 FOOT HIGH RIGHT BANK.

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CROSS - SECTION LOCATION
MACKENZIE R.- REINDEER CHANNEL
SUMMER 1975

FIGURE 3.8

(from NESCL, 1975)

STATION 14 (GSC-90)

CHANNEL SIZE:	
Width (w)	141.00 (m)
Mean depth (Dm)	4.32 (m)
Maximum depth (Dmax)	7.10 (m)
Centroid depth (Dc)	5.90 (m)
Cross-sectional area (A=w*Dm)	518.01 (m2)
Area left of centroid (Al)	242.30 (m2)
Area right of centroid (Ar)	275.71 (m2)
Depth difference (Ddif=Dmax-Dc)	1.20 (m)
Length between Dmax & Dc (L)	21.74 (m)
Mean velocity (Vm)	n/a (m/s)
Discharge (Q=A*Vm)	
CHANNEL SHAPE:	
Width-depth ratio (w/Dm)	32.64
Depth ratio (Dmax/Dm)*	1.64
Asymmetry**	
A*=Ar-Al/A	0.06
A2=2L(Dmax-Dc)/A	0.10

* after Fahnestock,1963
** after Knighton, 1984

FIGURE 3.9

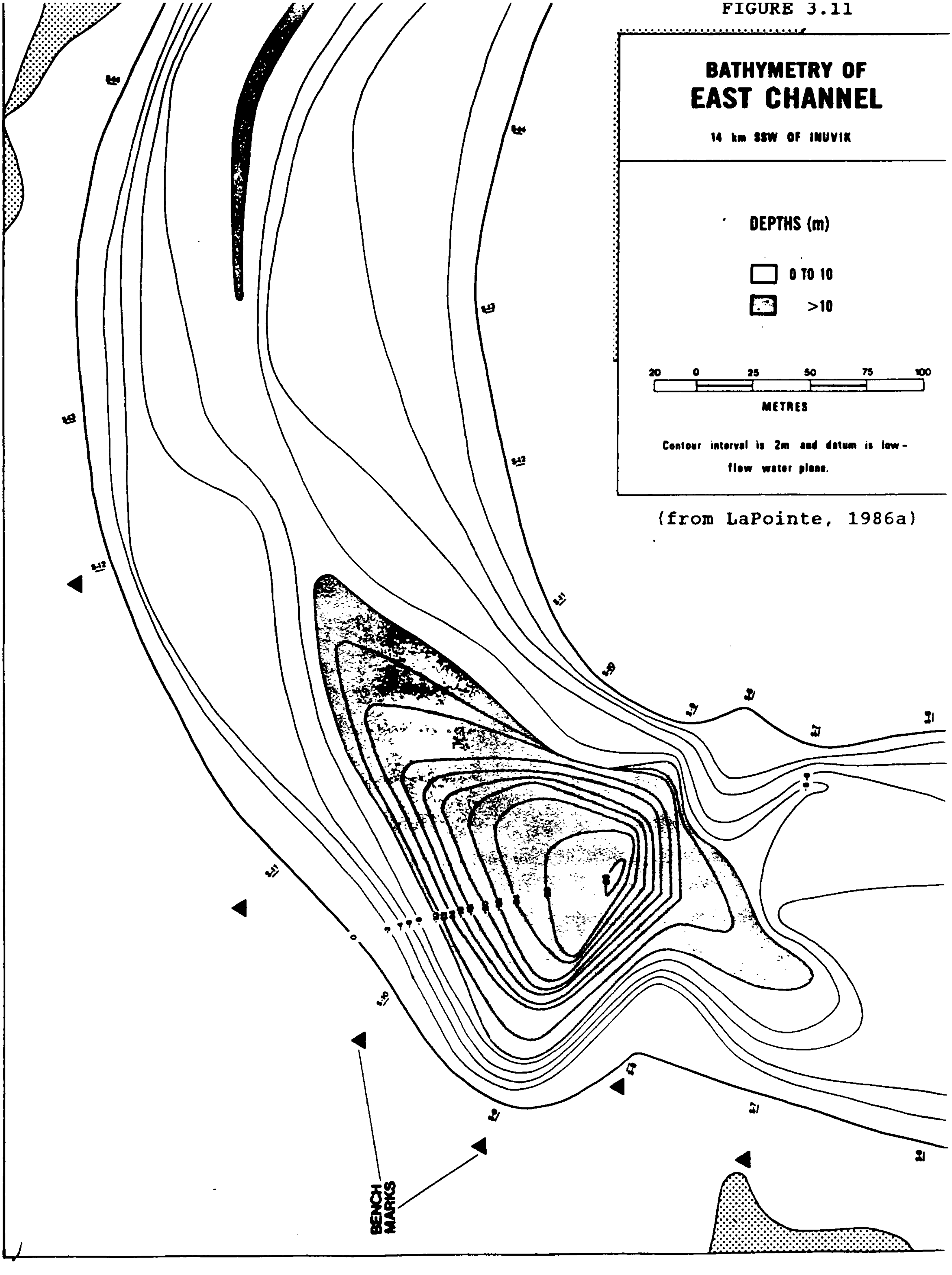
TYPICAL BATHYMETRIC DATA DERIVED
BY GSC FOR CHANNELS IN
NORTHWEST AREA OF MACKENZIE DELTA

(from Traynor and Dallimore, in prep.)

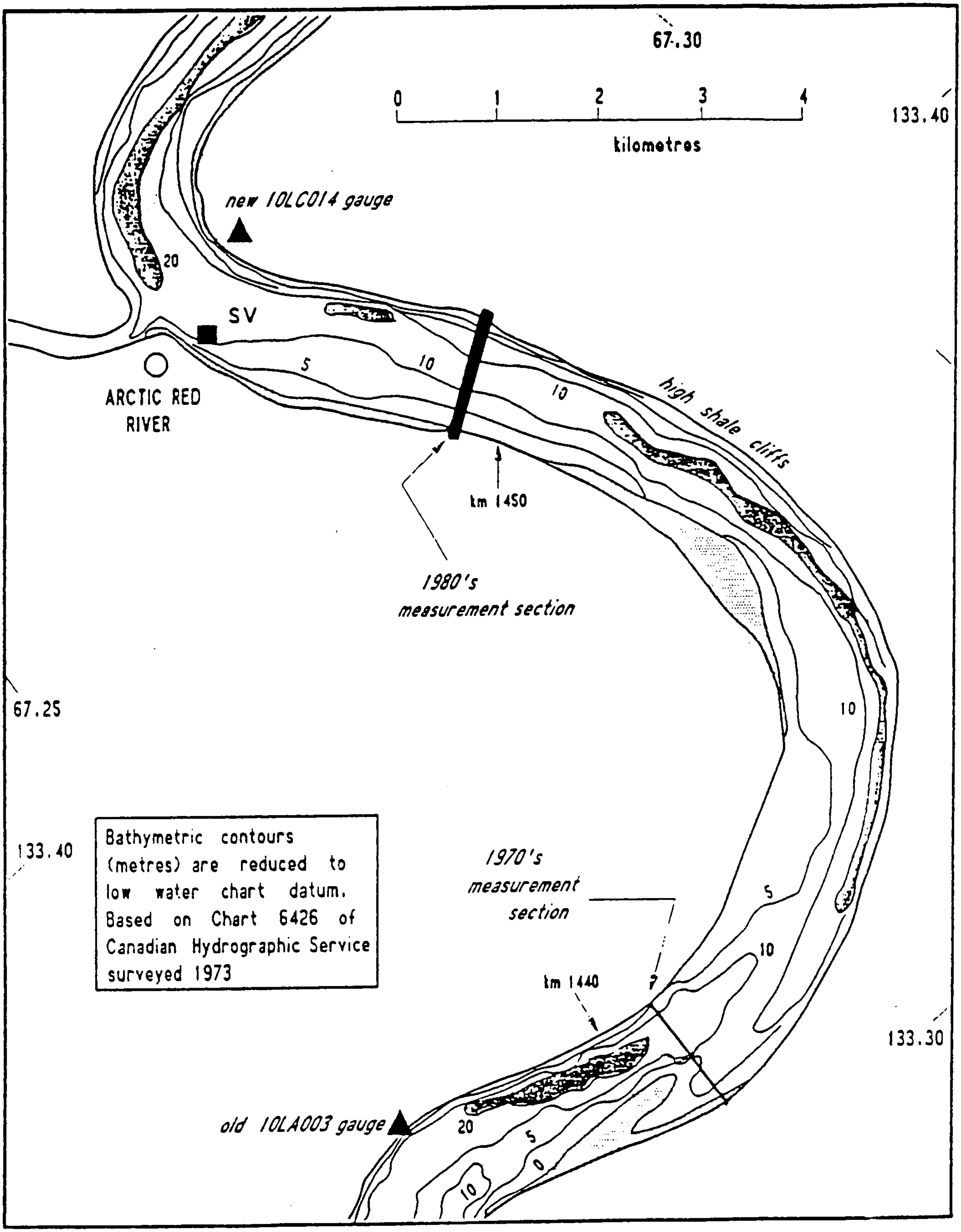
FIGURE 3.10

LOCATION OF SCOUR HOLE SITE ON EAST CHANNEL

FIGURE 3.11



(from LaPointe, 1986a)



Bathymetric contours (metres) are reduced to low water chart datum. Based on Chart 6426 of Canadian Hydrographic Service surveyed 1973

FIG. 3.13 BATHYMETRY OF MACKENZIE RIVER AT THE LOWER RAMPARTS, NWT. Flow is to top of page.

(from Carson, 1988)

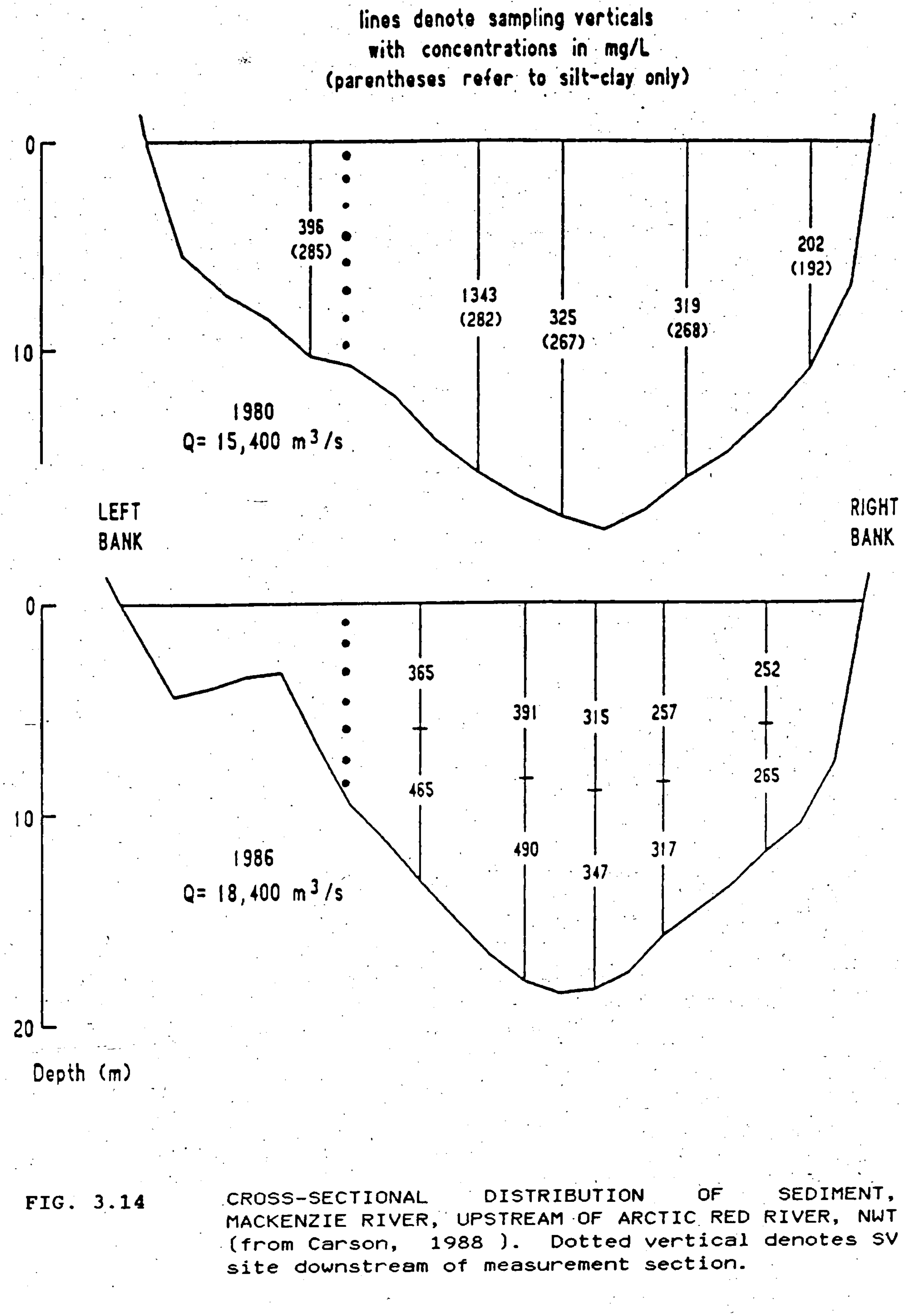


FIG. 3.14 CROSS-SECTIONAL DISTRIBUTION OF SEDIMENT, MACKENZIE RIVER, UPSTREAM OF ARCTIC RED RIVER, NWT (from Carson, 1988). Dotted vertical denotes SV site downstream of measurement section.

SEDIMENT STATION ANALYSIS IN THE MACKENZIE BASIN, NORTHWEST TERRITORIES

by

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for

Inland Waters Directorate
Environment Canada
Yellowknife, NWT

under contract
KE521-1-0085/01-XSG
Supply & Services Canada, Edmonton

March, 1992

Preface

This report was prepared as one part of Contract KE521-1-0085/01-XSG administered by Supply and Services Canada with F. M. Conly of Inland Waters Directorate, Yellowknife, NWT as Scientific Authority. The assistance provided by Malcolm Conly and Jesse Jasper is duly acknowledged.

Other IWD personnel have also contributed assistance in the acquisition of material upon which this report is based. They include: Terry Day, Moe Hansen, Scott McDonald, Joseph McIlhinney, Jack Wedel, Henry Westermann, Pat Wood, Richard Yungwirth and the late Herb Wood.

Executive Summary

1. This report summarizes suspended sediment data collected by Inland Waters Directorate in the Mackenzie Basin between Great Slave Lake and the Mackenzie Delta. The four main stations involved are: the Mackenzie River at Arctic Red River, Arctic Red River near the mouth, Peel River above Fort McPherson and Liard River near the mouth.

2. The sediment ratings derived in this analysis are, to varying degrees, different from those given in previous reports because they include sediment data collected since 1986. The sediment loads are also different, being based on discharge data that have been extensively revised, especially in the case of the Peel and Mackenzie rivers. The revised Peel data (based on an intensive discharge-monitoring program during breakup in 1988) indicate much smaller May and June flows than published previously.

3. Sediment concentrations for the Mackenzie are predicted from a sediment rating approach based on 502 data points. Summer rainstorms produce above-average concentrations compared to snowmelt. No fully satisfactory procedure was found for reducing the scatter produced by this effect, though, in part, it can be taken into account using a monthly correction factor: August concentrations, for example, average 1.36x those predicted by the sediment rating, those in May-July need no adjustment, while those in September-October average only 0.8x the values predicted. The sediment rating, in combination with these monthly adjustments, predicts mean monthly loads for the 1974-90 period with reasonable precision. A similar approach was used for the Liard River based on 396 data points. Monthly adjustment coefficients were again used: in this case, the peak coefficient was in May (1.7x), averaging about 0.9x in the summer, and decreasing to 0.64x in October. Precision in prediction of mean monthly loads is very good.

4. No distinctive monthly pattern in the residuals from the sediment rating was found for Arctic Red River and no monthly adjustment was made. A reasonably strong sediment rating equation exists. In contrast, the sediment rating data for the Peel for 1988-90 show considerable scatter, with above-average concentrations (compared to predictions) at the start of summer rainstorm-floods. The scatter is reduced by modelling concentration on other aspects of the hydrograph - elapsed time from start of flood, steepness of rising limb - as well as simply discharge. Insufficient data are currently available, however, to indicate how much precision exists with this method. The loads of the Peel must therefore remain uncertain.

5. Mean annual suspended load (based on 1974-90) was 47 (± 6) Mt for the Liard, 98 (± 8) Mt for the Mackenzie, 7 (± 1) Mt for Arctic Red River and about 20 (± 2) Mt for the Peel. The figures in parentheses refer to the standard error of the sample

mean. This is generally about 10%, but higher for the Arctic Red River and Liard rivers which experienced unusually high loads in 1974 and 1988 respectively. Longer term discharge data for the Mackenzie R. at Norman Wells and the Liard R. at Fort Liard indicate that these loads are above average for the 1944-90 period.

6. Almost all suspended sediment is moved in the months May through October at all four main sites. The peak month for sediment movement on all four rivers is June. On the Mackenzie and Liard this is followed by July and May; August loads are almost as high as May on the Mackenzie, but much less on the Liard River. On the Peel and Arctic Red River, May loads are only slightly less than those in June, while July loads are much smaller.

7. The Liard load is slightly less than 50% of the suspended load of the Mackenzie. In excess of 20% of the Liard suspended load is sand, much of which is probably deposited in the Mackenzie long before reaching Arctic Red River. The sand component of the lower Mackenzie (like the Arctic Red River and the Peel) is much smaller at about 5-10 percent.

8. Sediment production in the Liard basin is high (at about 170 t/km2/yr and a mean load-flow ratio of 610 mg/L). These figures are comparable with those for the Mackenzie at Arctic Red River provided that the basin area (and discharge) of the Mackenzie above the outlet of Great Slave Lake are eliminated. Sediment production in the Peel and Arctic Red rivers is much higher per unit area of basin (about 300 t/km2/yr and 1000-1400 mg/L). It is believed that similarly high yields are characteristic of west bank tributaries of the Mackenzie upstream of Arctic Red River, compensating for lower yields from the east-bank basins. Preliminary data have been collected for some of these west-bank tributaries but have not yet been analyzed. It seems likely that much sediment in the Mackenzie is acquired through erosion along the margins of the main stem itself, but no data are available to address this issue.

9. In general, the sediment program for this part of the Mackenzie Basin has met the objectives of the initial program in determining inputs to the delta area. Additional monitoring is required on the Peel River to improve accuracy in prediction of sediment concentrations, but continuation of regular sampling at the other three main stations appears unnecessary: concentrations and loads can be predicted from the hydrograph record. Available resources might now be moved to addressing other sediment issues in this part of the basin (such as outflows from Great Slave Lake, sediment quality investigations, etc.) and to sediment issues elsewhere in the region (such as the Delta).

1. SEDIMENT STATION ANALYSIS IN THE MACKENZIE BASIN, NORTHWEST TERRITORIES: INTRODUCTION

1.1 Purpose of report

The importance of documenting fluvial sediment data in the Mackenzie Basin was emphasized recently by Wedel (1990) in his project design summary for IWD's NOGAP program for the 1990s. It was also highlighted in two other recent reviews of sediment-related issues on the Mackenzie River (Carson, 1988a) and in the Mackenzie Delta (Lewis, 1988).

Among the various issues identified, the magnitude, timing and composition of the export of suspended sediment from the Mackenzie Basin to the Beaufort Sea were viewed as key factors. These affect the offshore sediment plume (and its relationship to marine productivity through turbidity, nutrients and contaminants) and offshore sedimentation (and its effect on rates of infill of pipeline trenches, seabed stability, etc.).

To date, few data are available on sediment outputs to the Beaufort Sea, and this is now an important area of sediment monitoring by Inland Waters (Carson, 1991a). In contrast, considerable sediment data have been collected by IWD at input stations to the Mackenzie Delta (the Mackenzie, Arctic Red and Peel rivers), as well as on the Liard River, the major tributary source of sediment in the Mackenzie system.

The purpose of this report is to synthesize the existing sediment data available for these four main sites in the Mackenzie network (as well as to summarize the fragmentary data for other stations) in an attempt to make it more useful to other agencies concerned with sediment issues in the area. These parties include the Department of Fisheries and Oceans and the Geological Survey of Canada, both of whom are interested in throughput to the Beaufort Sea; Coast Guard Canada and Public Works Canada who are involved with maintenance of a navigable channel up the Mackenzie; agencies and environmental groups concerned with the possible impacts of hydrocarbon development in the delta; as well as agencies and environmental groups concerned with development in the interior (hydrocarbon movement, hydro power, logging) and its possible impacts downstream.

Detailed reviews of the sediment programs (up to the end of 1986) have already been provided for each of the four main stations (Carson, 1988b, 1988c, 1989a). These technical reports - aimed at IWD staff - concentrated on the quality of the data, gaps in the data, and remedial work needed to rectify problems encountered. A short (and necessarily preliminary) synthesis of the data, as might be of interest to users of sediment data, was provided by Carson (1989b). In the light of supplementary work done since then, it is now possible to provide a more complete "user-oriented" report describing the sediment programs of the Mackenzie network.

1.2 Scope of the report

The report deals essentially with the four main stations identified above.

The report begins with a summary of the sediment program at the stations: objectives; history of the program; descriptions of the basin; and a summary of the basin hydrology.

The next chapter (3) provides a summary of data collected: discharge; bed material in relation to channel bathymetry; and suspended sediment. It includes a description of the methods used by IWD to determine daily mean sediment concentration at a station based on intermittent sampling of a single vertical in the cross-section.

The main body of the report (Chapter 4) summarizes analysis of the data and its interpretation. This includes presentation of the sediment rating relationships; predicted annual and mean monthly loads; breakdown of sediment load by grain size; and discussion of sediment sources.

Sediment data for other stations in the basin are briefly summarized in Chapter 5.

The last chapter provides an overall assessment of the findings and a consideration of the implications.

2. SEDIMENT PROGRAM BACKGROUND

2.1 Objectives

During the mid-1970s, prompted by plans for oil and gas exploration, production and movement in the valley and delta of the Mackenzie River, and offshore in the Beaufort Sea, an extensive program of background environmental data collection was initiated by Environment Canada.

As part of this program, the Water Survey of Canada (Inland Waters Directorate) established a sediment program to monitor the inputs of sediment to the delta, with stations on the Mackenzie River upstream of the Arctic Red River, the Arctic Red River itself (near the mouth), and the Peel River upstream of Fort McPherson (Fig. 2.1). A similar program was undertaken on the Liard River near its mouth, recognizing the Liard to be a major sediment source for the Mackenzie River.

In 1978, the sediment load of the Liard River became a specific item of interest in BC Hydro's consideration of possible power development on the Liard upstream of Beaver River. Some concern was expressed regarding the impact of sediment-trapping and flow regulation on the delivery of sediment (and bound nutrients) to the Mackenzie Delta, as a consequence of the development.

In recent years, attention has been focused increasingly on sediment quality, particularly the adsorption of hydrocarbons by the finer grains of the suspended load, and the source and fate of these contaminants as they move downstream.

2.2 History of the sediment program

The sediment programs at all four sites have been concerned primarily with the monitoring of suspended sediment. The purpose has been to document the changing concentrations of the suspended sediment, the monthly and yearly loads, and the grain size composition. Some samples of bed sediment have been collected at all sites, and subjected to particle size determination; these data have been useful in assessing the relationship between bed material and suspended sediment. There has been no measurement of bed load.

Users of IWD data should recognize that for any given station reach, the water-level gauge, the measurement section (for discharge and multiple vertical (MV) sampling of sediment) and the single-vertical (SV) site for suspended sediment, are usually located on different cross-sections. It should be noted that, in all cases, more than 95% of the suspended sediment database is derived from the SV site. Changes in station number indicate changes in location of the gauge, not necessarily of the measurement section or SV site. The locations are summarized below.

Mackenzie River

The hydrometric and sediment sampling programs on the Mackenzie upstream of Arctic Red River were begun in 1972. The hydrometric program has operated without interruption. The sediment program was discontinued during the period 1976-79 inclusive because of limited funding. The program was resumed in 1980, with support initially from BC Hydro, and later from Indian and Northern Affairs Canada; only a limited sampling program is maintained today.

The hydrometric program on the Mackenzie River at Arctic Red River is one of three active programs on the main stem: the others are at Fort Simpson (below the Liard confluence) and at Norman Wells. Sediment data have been gathered at the two other sites, but are fragmentary (Chapter 5).

The sampling reach for this station coincides with the bedrock gorge known as the Lower Ramparts (Fig. 2.2). Proximity to the settlement of Arctic Red River has been an advantage, and much of the suspended sediment sampling was undertaken by local personnel trained by WSC staff.

The station number has changed three times. The original gauge for water level (10LA003: "above" Arctic Red River) was located on the left bank upstream of the main bend. Prior to the 1985 open water season, the gauge site was moved closer to the settlement on the right bank (because of better year-round access). The new site ("at" Arctic Red River) was originally designated 10LA005 (1985 only) and subsequently changed to 10LC014.

The measurement section for the reach was originally upstream of the bend. In 1980 it was shifted downstream of the main bend into the straight reach before the entry of Arctic Red River tributary. Velocity metering and sampling of suspended sediment at multiple verticals in the cross-section have been undertaken at both sections. Bed material has been collected at the upstream measurement section only.

The SV suspended sediment site, during most of the 1980s at least, has generally been about 200 m offshore from the left bank, near the village, and marked by a buoy. There is some uncertainty where SV sampling was actually done in the 1970s, and when the changeover to the present site took place.

Arctic Red River

Streamflow gauging on this river was begun in 1968, and supplemented with a sediment program in 1972. The sediment program was discontinued after the 1975 field season, but the hydrometric program remains in operation. There are short gaps in the discharge record during the open water season in several of the years between 1969 and 1980.

The gauge (10LA002) and measurement section for this river are located at the abandoned site of Martin House (Fig. 2.3), about 75 km upstream of the confluence with the Mackenzie River. All velocity-metering, bed material collection and MV suspended sediment sampling have been done on this measurement section. The SV suspended sediment site of the 1970s was located about 3 km upstream from the mouth (Fig. 2.4), at mid-stream in a relatively straight and narrow reach, easily accessible from the village.

Peel River

The hydrometric program on the lower Peel was initiated in 1969 and continued (except for gaps in 1970-73 and the full year 1987) to the present. The sediment program was established in 1972 and continued through to 1976. Examination of the data (largely collected by local observers rather than WSC staff) during a program review in the mid-1980s led to several concerns, and the program was resumed in 1988. It still continues on a miscellaneous basis.

The gauge site 10MC002 is located on the right bank of the Peel River about 20 km upstream of Fort McPherson (Fig. 2.5). In the 1970s, the measurement section was located just upstream of the gauge, while the SV sediment site was in the reach opposite Fort McPherson (Fig. 2.7). In view of doubts regarding the reliability of the SV sediment samples taken in the 1970s (Carson, 1989a), these data have been ignored in this report. The measurement section was shifted in the late 1980s to about mid-distance between the gauge and Fort McPherson; the section is just upstream of the ferry crossing (Fig. 2.6). From 1988 on, MV sediment sampling has been done at this section, and SV sampling has been done from the in-channel end of the ferry, moored at its right bank station.

The Peel River gauge is much closer to the Mackenzie than is the Arctic Red River gauge; it is quite markedly affected by backwater conditions from the main stem.

Liard River

The hydrometric and sediment programs on the Liard River near the mouth were also begun in 1972, continuing to the present. There have been no interruptions in the discharge record, but the sediment program was discontinued during 1977-1978. As on the Mackenzie River (at Arctic Red River), the sediment program was resumed in 1980, with support initially from B.C. Hydro, and later from Indian and Northern Affairs Canada; only a limited sampling program is maintained today.

The gauge site 10ED002 is shown in Fig. 2.8, adjacent to the Fort Simpson airport, just upstream of the ferry crossing to the Mackenzie and Liard Highways to

Hay River and Fort Nelson; the gauge was established just prior to the 1974 open water season. In 1972 and 1973, the gauge site was further upstream, approximately 50 km south of Fort Simpson.

Two measurement sections have been used in the sampling reach as shown in Fig. 2.8. Various locations have been used for the SV sediment site: in 1974-76 on a section about 200 m upstream of the gauge; in 1979-80 at the ferry crossing; from 1981 on, about 300 m above the gauge. In all cases, the SV site was located at midchannel. Unlike the other three stations, proximity of the site to the WSC office has allowed IWD staff to undertake all sampling.

2.3 Basin description

The catchment of the Mackenzie River, about 1.7 million sq. km. in area at the LC14 gauge, occupies one-fifth of the total area of Canada. From its headwaters in the Finlay River, the watercourse extends over 4,000 km to the Arctic Ocean.

The major water sources are the Peace and Athabasca rivers, draining from the Rocky Mountains, through the Prairies, before converging at the western end of Lake Athabasca. The flow of these two river systems then merges as the Slave River through to Great Slave Lake. The Mackenzie River itself begins as the outflow from Great Slave Lake. Because of deposition of sediment in these large lakes, very little sediment from the upper basin reaches the Mackenzie River. Indeed, even by the time the Mackenzie reaches Fort Simpson, the river is usually pale in comparison with the inflow of the Liard River.

The Liard River is the largest tributary to the Mackenzie; its basin area at Fort Simpson is 277,000 sq. km. The first half of its 1200 km course is southeastwards (Fig. 2.9), the river being incised in generally subdued terrain, though the basin is bounded by mountain ranges. In the downstream half of its course, leaving the Cordillera, it flows northeastwards, towards the Mackenzie, incised in the soft shale strata of the interior plateau. In this reach it acquires the tributary flows of the Fort Nelson River (from plains to the southeast) and the South Nahanni River (from mountains to the northwest). Most of the Liard basin is underlain by easily eroded sedimentary rock, mantled by glacial drift, and covered by typical Boreal Forest vegetation. Mining is found in several parts of the basin; logging is predominantly in the southern part.

Other west-bank tributaries, draining mountainous watersheds, are known to supply large sediment loads to the Mackenzie. These include (Fig. 2.1) the North Nahanni, the Root, the Redstone, the Keele and the Mountain rivers. The east-bank tributaries drain subdued terrain developed on generally flat-lying sedimentary rocks. The low slope and abundant lakes limit the supply of sediment from these east-bank catchments. Unconsolidated glaciolacustrine deposits of silty clay occur along the banks of much of the mainstem, and supply sediment to the river through landslides and gullying.

The Arctic Red River has a basin area of 18,800 sq. km only; the Peel River drains a basin of 70,700 sq. km (Fig. 2.10). The headwaters of the rivers rise in the steep terrain of the Ogilvie, Wernecke and Selwyn mountains in the southern half of the catchments. In the main, the northerly parts of both basins correspond to broad lowlands, the low-lying area forming a much greater percentage of the Arctic Red River basin than in the case of the Peel River. About 50% of both basins is forested, mostly in the lowland areas. In late glacial times, the front of the large Laurentide icesheet abutted the east side (and north end) of the Mackenzie Mountains, blocking the drainage to form proglacial lakes. Accumulation of fine-grained sediments in these lakes took place; the deposits became exposed and permafrosted after retreat of the ice. It seems probable that thawing of these deposits is an important source of fluvial sediment in these (and possibly other west-bank) basins.

2.4 Hydrology

The historical streamflow summaries for the Northwest Territories note that, since 1968, the flow in the Mackenzie River has been "regulated" by construction of the large Williston Reservoir behind the W.C. Bennett Dam on the upper Peace River in British Columbia. This artificial dampening of the flow regime (5% reduction in summer mean flows: Wiens, 1991) is added to the natural regulation by the large lakes in the catchment.

The catchment of the Mackenzie, upstream of the Liard confluence, is about 993,000 sq. km. No direct measurement of discharge on the Mackenzie, just above the Liard confluence, was undertaken before 1991, though summary statistics for Fort Providence (1962-1978), below the outlet of Great Slave Lake, are available. Mean monthly flow is at a minimum in March (about 1800 m3/s), with little change in April, but a substantial increase as a result of snowmelt and spring rains in May and June, peaking in July at about 7200 m3/s. There is a gradual decline in mean flow until October and then an abrupt decrease with freezeup in November. Mean annual flow was about 4300 m3/s.

The mean annual flow of the Liard is only about a half of the upper Mackenzie, but -lacking the dampening effects of Great Slave Lake - mean monthly flow peaks in June at a slightly higher level than at Fort Providence (about 7500 m3/s 1972-84). The mean March flow (400 m3/s) is substantially less than on the upper Mackenzie.

Breakup in the Liard-Mackenzie system is usually initiated by early snowmelt (and rising discharges) in the Fort Nelson River basin (Grey and Sherstone, 1980; Prowse, 1984). This triggers a downstream progression of river ice breakup along the

Liard, which then initiates breakup down the Mackenzie below its confluence, typically leaving the ice cover on the upper Mackenzie intact for another two weeks. Mean breakup date for Fort Simpson was given by Mackay and Mackay (1973) as May 16, and for Fort Good Hope only two days later. (Wood (WRB, Fort Simpson, 1992, pers. comm.) suggests that a mean date of May 6 is more appropriate for Fort Simpson.) Observations reported by the same authors during the period 1961-68, however, give breakup at Fort Good Hope occurring on about May 24. During the same period, breakup at Arctic Red River was given about another week later, averaging June 1. The breakup of the lower Peel River is usually indicated as about ten days earlier than that of the Mackenzie at the latitude of Fort McPherson. Thus, in the delta itself, Peel Channel at Aklavik generally breaks up before East Channel at Inuvik.

Discharge in the Liard-Mackenzie system generally peaks well after breakup. Peak flow on the Liard near the mouth has ranged from May 21 to July 21; and on the Mackenzie at Arctic Red River from May 24 to June 26 (IWD, 1989). Flow from the Arctic Red tributary is relatively minor, peak daily flow being about 1000 m3/s, and occurring at any time between mid-May and late August. Peak daily flow on Peel River is much more variable in magnitude, and was reported (IWD, 1989) as ranging 3,000 to 10,500 m3/s, but generally occurring in the last week of May or the first week of June.

Mean monthly flows for the Peel above Fort McPherson are given as 2040 m3/s (May) and 2700 m3/s (June), compared with flows on the Mackenzie at Arctic Red River of 12,700 m3/s (May) and 21,400 m3/s (June) (IWD, 1989). These data indicate a larger relative inflow from the Peel in May (16% of Mackenzie) and June (13%), than expected on the basis of mean annual flow (8%). In part, this reflects the much weaker winter flow of the Peel River which, lacking outflows from a large lake such as Great Slave Lake, has only 3% of the December flow of the Mackenzie River.

The high flows of both the Mackenzie at Arctic Red River and, especially, the Peel above Fort McPherson are, however, affected to varying degrees by backwater conditions from the Mackenzie Delta, during and after breakup. The discharge data for these two sites have been revised as a result of springtime hydrometric work in the late 1980s, but the revised data have not yet been published; the descriptions above are based on the unrevised published data. Examination of the revised flow data (Section 3.1) indicates that the relative importance of the Peel (compared to Mackenzie) in May is slightly reduced (to 14.4%) and that in June is unchanged with the revised data.

There are nonetheless significant revisions in mean May and June flows. The new mean May flow (1974-86) for the Peel is 1729 m3/s, down from 2040 m3/s and that for June is 2590 m3/s, down from 2700 m3/s. The new mean May flow (1974-

86) for the Mackenzie is 12,000 m3/s, down from 12,700 m3/s, and that for June is 20,640 m3/s, down from 21,400 m3/s. Marked flow reductions occur in some individual months, as documented in the next chapter.

The computations of sediment load in this report are based on the revised discharges.

3. DATA AVAILABILITY

Data collected by Inland Waters Directorate at the four sites include: daily mean water level and discharge; water temperature at the time of sampling; instantaneous suspended sediment concentrations during the open-water season (these are converted to daily mean sediment concentrations); particle size distribution for some samples of suspended sediment, generally when concentrations were greater than 300 mg/L; and grain size distribution of bed material.

3.1 Flow data

Water level (stage) is recorded virtually continuously, and, during ice-free conditions, is converted to discharge by use of stage-discharge curves. The latter are derived through periodic visits to the sites (at a range of flows) during which the cross-section is surveyed and the velocity measured on 15-20 verticals spanning the section. Adjustments are made for flow when an ice cover is present, and for the backwater conditions that occur during and immediately after breakup. Daily mean discharge is determined through digitizing the water level record of each day.
Some uncertainty existed about the accuracy of the discharge data during and immediately after breakup at all four sites, especially on the Mackenzie and Peel rivers, which were known to be subject to backwater effects from the delta, and where few actual gauging under these conditions had been done. A special program of springtime gauging was therefore undertaken on these two rivers in 1986-88; these data provided the basis for a review of the published flow record by Ozga and Associates. All previous reports dealing with sediment loads (determined from the product of daily mean discharge and concentration) at these stations have used unrevised flow data.

Mackenzie River

The published discharge data for the reach upstream of Arctic Red River show a continuous record from September 1972 to the present. In actual fact, however, breakdown in operation of the gauge, often associated with shifts, and even loss of the orifice under ice breakup, means that gaps did exist. Daily discharges during such periods were estimated and flagged as such ("E") in the published data.

Substantial revisions to the flow record (up to 1986) have been recommended by Ozga and Associates primarily for winter months, but also for May and June in many years (mostly decreases) and July-September in 1983 (increases). The changes for May-September are summarized in Table 3.1. These revisions have not yet been approved or implemented by WSC. The flow file used in the computation of sediment loads in this report nonetheless incorporates all revised flows recommended by Ozga for the period May-September.

Some uncertainty still persists, however, in the case of high flows computed for the normal open-water season at the new gauge site (10LA005; 10LC014), i.e. for 1985 on. Prior to July, 1988, the highest flow actually gauged in conjunction with levels at the new gauge was about 22,000 m3/s. Thus, extrapolation of the stage-discharge curve beyond that level was uncertain. A series of gauging during the high flows of July 1988 indicated that discharges were greater, for a given stage, than indicated by the rating curve extension that had previously been used (by about 12% at flows of 30,000 m3/s) (Fassnacht, 1991a). All previous flows since 1985, greater than 23,000 m3/s, therefore, are likely to be revised in the near future (Brumwell, 1991).

Arctic Red River

Though discharge has been monitored in this reach since 1968, there are significant gaps in 1969-71, 1973-75, and 1980. Previous analyses of sediment loads for the three delta head stations (Lewis, 1988; Carson, 1989b) have restricted attention to the post-1973 period. This still requires some strategy for dealing with the flow data gaps in June-July of 1974 and August of 1980; this is dealt with in Chapter 4.

The station is far upstream of the confluence with the Mackenzie main stem and therefore is unlikely to be affected by backwater effects from the delta. The published data have been examined by Ozga and Associates, and revised accordingly. Actual changes were minimal: some data for daily flows in May 1976 have been eliminated and left blank; and some flows in May 1977 have been increased.

Peel River

The original daily discharge record was continuous for 1974 and later years. The 1981 flow record was revised in the late 1980s: no flow data were available for computing the load in this year in previous studies. As part of the revision noted below, however, discharge values are no longer available for two periods in 1974: May 1 - June 9 and July 28 - August 25. No published data were available for 1987 at the time of preparation of this report.
As in the case of the Mackenzie, flows during and immediately after breakup were suspect because of the absence of velocity measurements during these conditions. The published springtime data have undergone substantial revision by Ozga and Associates, following the 1988 spring hydrometric program.

The numeric changes to the flow data, as a result of this revision, are summarized on a monthly basis in Table 3.2. These indicate the large reductions made to daily flows (compared to the published data: IWD, 1989) during May and June of most years. This is especially pronounced in the May flows of 1975, 1980 and 1984.

Some doubt still exists, however, regarding the accuracy of the stage-discharge curve used for high flows during normal open-water conditions (Fassnacht, 1991b). It appears that flows above 2,000 m3/s may have been underestimated, with discrepancies approaching 14% at 3,500 m3/s. No plans have been made to revise these high flows, but extra high-flow measurements are planned to verify the nature of the rating curve (Brumwell, 1991).

Liard River

A complete record of daily discharge is available at this site from June 1972, though, as at other sites, estimates have been necessary on some days, usually arising from movement or loss of the orifice.

Determination of discharge is difficult under breakup conditions because of the severe ice jamming that occurs at the Mackenzie confluence. Prowse (1984) concluded that mechanical ice jams typically result in stage increases of 4m to 8m above the stage that would occur during open-water conditions.

The published data have been reviewed by Ozga and Associates. The revisions involve only two small periods of numeric changes (in 1975) during the 1974-86 period. They do, however, involve a substantial number of deletions of daily flow data, particularly during winter, but also during break-up (the first week or more in May) and freeze-up. These revisions have not yet been approved or implemented by WSC. The flow record used in the computation of sediment loads in this report is the old (complete) file but with the numeric alterations noted for 1975.

3.2 Channel bathymetry and bed material

Though channel bathymetry and bed material, and their changes over time, are important attributes of channels in their own right, they are described below primarily from the standpoint of their influence on the suspended sediment sampling program. In particular, the changing configuration of the channel bottom at and immediately upstream of the SV site can have an appreciable effect on how well the concentrations measured at that site represent the mean for the cross-section as a whole.

Mackenzie River

The valley walls in the Lower Ramparts reach are made up of sedimentary strata, primarily shale. Weathering of the walls supplies rock fragments to the channel margins, and, for this reason, some gravel-size material is occasionally found in the bed sediment close to the channel sides. In general, however, the channel bed is underlain by sand, with some silt in backwater areas. Scour and fill during the intervals between hydrometric soundings at the measurement section imply that the bed is indeed alluvial, and not bedrock-controlled, although it is to be expected that some parts of the thalweg may occasionally scour down to bedrock.

Bed material has been sampled at the upstream measurement section, but not at the downstream section, nor in the vicinity of the SV site (Fig. 2.2). Sampling at the upstream section was undertaken between 1972 and 1975: four sets of data have been published, but only as a mean grading curve for the 5 (or 7) samples in the cross-section. These mean data mask considerable variation in grain size in the cross-section. Bed material data for individual verticals are available for three sampling sessions and are summarized in Appendix I.

The 1972-73 data show that the bed material is almost entirely sandy sediment, generally coarser than 0.125 mm. Material in the thalweg near the left bank was coarser (mostly > 0.25 mm) than in the right bank bar complex (mostly 0.125-0.25 mm). Appreciable differences are indicated in the 1974 sampling, following the high flows of August of that year, and the resultant changes in bathymetry (Fig. 3.1). Material in, and near, the deepened thalweg had become coarser, while sediment deposited in the right bank bar complex was somewhat finer, including 64% silt-clay in the near-bank sample.

These few data available indicate that a grain size of about 0.125 mm generally represented the lower limit of bed material in the 1970s: the wash load in this section therefore includes very fine sand, as well as silt and clay. The amount of total suspended load sampled at the SV site that was coarser than 0.125 mm was generally less than 5 percent. There was, however, a trend to increased bed material amounts during the 1980s. This trend appears to be due, primarily, to extension of the left bank bar towards the SV site. In other words, the trend does not appear to be applicable to the section as a whole. The higher suspended sand concentrations towards the left bank at the 1980s measurement section, and the change in bathymetry there between 1980 and 1986, are indicated in Fig. 3.2.

The adequacy of the SV site as it represents the suspended sediment concentrations in the full measurement section can only be assessed from comparative sampling. Such sampling were made on eleven occasions during 1974-86. The k-value (ratio between cross-section mean concentration and SV concentration) varied between 0.73 and 1.88, a rather large range. The extremes tend to coincide with low discharges and concentrations. In those cases where grain size data were obtained, the k-value for the wash load alone was much closer to unity than for the full sample. In Chapter 4, therefore, analysis of the suspended sediment at this site is initially restricted to the wash load. Estimates of the mean annual bed material load through the Lower Ramparts have been made using indirect methods (movement of alternate bars); mean annual bed material load in 1973-77 appeared to be about 6% of wash load in the same period.

Arctic Red River

The WSC gauge on the Arctic Red River at Martin House (Fig. 2.3) occurs in a weakly sinuous reach (with a pattern of alternating bars). The valley floor is narrow and incised about 50 m into the plain. Downstream of the gauge, and for about half the distance to the mouth, the valley floor widens irregularly, up to about 1500 m in places, and the slightly overwidened channel splits around many island bars.

The measurement section, opposite the gauge, is just downstream of a mild bend. Samples of bank material collected in 1973-75 show both banks to have very fine sediment (up to 60% silt and 20% clay) in contrast to the sandy bed material.

The published bed material data (collected in 1972-75) refer to a mean grading curve for the section. Inspection of data for individual verticals showed that medium sand (0.25-0.5 mm) dominated the cross-section in 1972, but was replaced by fine sand (0.125-0.25 mm) in the left half of the channel during 1973. The bed texture changed appreciably after the large August 1974 flood, becoming dominantly fine sand. The detailed changes in the percentage of bed sediment finer than 0.125 mm are shown in Appendix I. Prior to August 1974 (highest monthly flow on record: IWD, 1989), this grain size would appear to have represented the lower limit of bed material.

The bed material data for this section, though highly variable, are broadly comparable with those of the Mackenzie River in the Lower Ramparts reach.

No bed material sampling has been done in the reach near the mouth of the river which is where (at midstream) all SV suspended sediment sampling was undertaken. The valley in the downstream half of the reach below Martin House becomes much narrower than in the upstream half. The channel becomes straight to weakly sinuous, with islands generally absent; the hydrographic chart of the reach (6440) shows no shoals in this reach. It is uncertain how much of the channel sand (which is assumed to produce the channel splitting downstream of the gauge) reaches the lower reach. The cross-section surveyed through the SV site in 1988 (Fig. 3.3) is relatively simple, with only mild asymmetry. In terms of obtaining a SV site that adequately represents the full river width, this section would appear to be more suitable than the one at the gauge site. However, no comparative sampling has been done at the station which would allow verification of this conclusion. No steps have been taken to adjust the SV data in an attempt to make them better estimates of the mean for the full river section.

The long distance separating the SV site and the WSC gauge is not regarded as a problem. There is little input of water in the reach, though there may be systematic deposition of suspended sediment during backwater conditions. Thus, sediment loads computed for this station should be regarded as referring to the mouth rather than to Martin House.

Peel River

The general bathymetry of the lower Peel River is indicated on Chart 6438 of the Canadian Hydrographic Service, surveyed in the summer of 1973.

Upstream of the 10MC002 gauge (Fig. 2.5), the Peel has an irregular winding (not meandering) course, the valley floor being incised more than 50 m into the plain, as in the case of the Arctic Red River. In the lower reach, apart from the island and bend downstream of the gauge (Fig. 2.6), the channel is essentially straight until it bifurcates at the entrance to the Mackenzie Delta.

Sampling of bed material was done on the 1970s measurement section upstream of the gauge (Fig. 2.5) in each of the three years 1972-74. The published data refer to the mean grading curve for the composite sample. They show the sediment to be very poorly sorted with grains ranging from less than 0.016 mm to greater than 32 mm. These composite curves are misleading, however, because they include bank material.

The bed material data for individual verticals at the measurement section are summarized in Appendix I. Sediment finer than 0.125 mm which is only rarely present at the Mackenzie and Arctic Red River measurement sections (usually in pools or sloughs) is more widespread in the Peel section. This fine sediment dominated the main body of the section in 1972, and, though more variable in 1973-74, still averaged about 30% away from the immediate channel margins. The thalweg was, in all cases, dominated by medium (0.25-0.5 mm) and coarse (0.5-1.0 mm) sand. It is probable that the finer bed sediment at this site - compared to the Arctic Red River - is due to the difference in location. The Peel site is much closer to the Mackenzie: the normal channel gradient is probably less, and the river is liable to backwater effects during floods.

The fineness of this bed material (most of which is easily moved in suspension) implies that temporal fluctuations in bed material transport, as well as lateral changes across the river, could have a marked influence on suspended sediment concentrations at any SV site. The 1980s measurement section and SV site are about 10 km downstream of the 1970s measurement section, but there is little reason to expect much change in bed sediment composition.

The 1980s MV section and SV site are, however, immediately downstream of a mild left-hand bend in the river, and (as indicated in Fig. 2.6) the left bank inner-bend bar extends downstream through the MV section. The SV site is about 25 m from the right bank, close to the thalweg, and about 500 m downstream of the MV section.

In most bend situations of this type, bed-material is deflected away from the thalweg towards the inner bank bar. This applies to suspended bed material as well as bed load. The lateral distribution of suspended sediment in the 1980s measurement section shows the expected increase in concentration from the right bank to the left (Fig. 3.4). The k-value which would be needed to adjust SV concentrations to the mean for the section was 1.33 on this sampling occasion. Breakdown of concentrations by grain size indicated the k-value to be 1.98 for sand, 1.36 for silt, and 0.96 for clay. Thus, though the SV site is representative of the section for the clay fraction, it underestimates concentrations for silt and, especially, sand. Other comparison sampling were undertaken on Sept. 9, 1988 (k = 1.08), and in 1989 on May 25 (k = 1.31), June 3 (k = 1.33) and October 3 (k = 1.13). The higher k-values correspond to higher stages and sediment concentrations.

The instability in the k-value at this site is reminiscent of (but even more marked than) that of the SV site on the Mackenzie. In that case, however, the bed material load represented only a small percentage of the total suspended load, and in the present study it has been eliminated, the sediment-rating analysis referring to the wash load only. This strategy cannot be adopted on the Peel given the large overlap in grain size of the bed material and the suspended load. The only option in the present case is frequent comparison sampling to ensure that SV data are adjusted to make them representative of the full river width. This is being undertaken by WSC staff. The 1988-90 SV data used in the present analysis have been "adjusted" by a k-values estimated for each day by WSC in the case of 1988, and from provisional k-value curves for 1989 and 1990 (Fig. 3.5).

The lower reach of the Peel (Fig. 2.7) is dominated by a classic channel morphology of pools and riffles alternating from bank to bank. It was in this reach (opposite Fort McPherson) that SV sediment sampling was done in the early 1970s. The erratic results from this site may have been partly the result of instability of the lateral bar at that section, but also seem to reflect inconsistent location of sampling by the observer (Carson, 1989a, Section 4.1.4). As noted previously, these early SV data, though published, are not used in this report. Sediment data collected by WSC staff on multiple verticals at the 1970s measurement section, together with 1988-90 SV data, form the data base for the present analysis.

Liard River

The location of the MV section on the Liard (Fig. 2.8) is similar, in some respects, to that on the Peel River (Fig. 2.6). The section is downstream of a large mid-channel island, where the main flow takes the left fork and enters the sampling reach after travelling around a mild left-hand bend. Thus, in this case also, bed material is deflected to the left side of the river as it approaches the measurement section. This is manifest in the left-bank bar in the Liard section (Fig. 3.6: bottom), and the lateral change in bed material in the section.

Bed material was sampled at the section once in both 1973 and 1974, the former providing sufficient material to analyze on two bed verticals only. The composite data are given in Appendix I. They show (Fig. 3.6: bottom) the thalweg, near the right bank, to be largely (83%) gravel, the sand fraction increasing towards both banks, but especially over the left-side bar. The gravel component is less than 16 mm b-axis, except in the thalweg where the coarsest 20% of the full sample is in the 16-32 mm range. The sand fraction is almost exclusively medium and coarse on the right side of the channel, but contains increasing amounts of fine sand on the main left-side shoal. Very fine sand (< 0.125 mm) was found in small amounts only, and restricted to the left bank area.

As in the case of the Mackenzie and Arctic Red rivers, therefore, the 0.125 mm grain size can be taken as the lower limit of bed material, though sand forms only about half of the bed material at the Liard site. Bed material accounts for slightly more of the suspended load than at the other three sites, but still less than 10 percent.

The increase in sandy bed material towards the left bank (and its decreasing grain size) on the MV section would be expected to lead to higher suspended sediment concentrations towards that bank also. This is usually the case: silt-clay concentrations are generally constant across the channel, but sand amounts in suspension increase towards the left bank (Fig. 3.6: top). The SV site on the Liard has always been at mid-channel, however, and this appears to have ensured sediment concentrations that were representative of the mean for the section. Nine comparison sampling have been done at the site, producing k-values that show very limited range from 0.97 to 1.06, taken during flows with discharges ranging from 2,000 to 14,000 m3/s.

3.3 Suspended sediment data

3.3.1 Sampling instrumentation

Almost all suspended sediment samples collected by WSC at these sites have been depth-integrated through the full depth of the single vertical: depending upon flow depth, the sampler used may have been a DH-48 (hand-held), a cable-mounted D-49 (theoretically restricted to depths less than 5 m), or a cable-mounted P-61, the latter allowing split sampling of different parts of deep verticals. Some deviation from standard practice has occasionally taken place as noted below.

At the Mackenzie River SV site, all samples prior to 1984 June 13 were taken with the D-49 sampler through the full depth of water, ranging from 7 m up to 19 m, i.e. always in excess of the theoretical maximum depth. No comparison was made between concentrations from deep-water D-49 sampling and P-61 split-sampling: it was previously recommended (Carson, 1988b) that some full-depth comparative sampling be undertaken to provide more assurance for the pre-1984 data. Since June 13, 1984, all D-49 sampling has been restricted to the top 5 m only. In 1984-86 the concentrations were adjusted (increased by amounts of 10-20%) on the basis of comparative sampling with the P-61 split sampling method. No adjustment was made to samples in the years 1987-89 because of lack of comparative sampling.

No deviations from standard practice have been noted for the Arctic Red River SV program.

Many of the observer-collected SV samples on the Peel River in 1988-90 were obtained with a DH-48 sampler, but integrating through the top two or three metres of the vertical only, not the full depth. A program of comparative sampling through the full-depth in 1988 indicated that, on average, concentrations based on full-depth integration were only 1.03 times those of the two-metre samples. A comparison sampling on June 3 1989, however, indicated a concentration of 650 mg/L in the top 2.5 m, only 85% of the D-49 integration in the full 4 m of flow. Additional assessment of the practice of shallow-depth sampling at this site seems warranted.

On the Liard River, though virtually all SV sampling has been done with the DH-48 and D-49 samplers, flow depth at the site has generally been less than 5 metres. The only real reservation about the sampling instrumentation is the fact that the depth-integrating samplers are operated to miss the bottom 20 cm of flow (to avoid nozzle entry into bed load). Thus sand concentrations may be slightly underestimated. This applies to all sites, but is less serious on the Mackenzie River (where only the wash load is being considered) and on the Peel River (which has much finer sediment).

3.3.2 Daily mean values

Monthly suspended sediment loads have been published for all four stations by Inland Waters Directorate, for most of those periods when sampling was actually done. These loads were computed from the sum of daily sediment loads; in turn, these daily loads were derived from the product of daily mean discharge and daily mean sediment concentration.

Sampling on large rivers, such as those discussed here, is usually not undertaken more than once a day during the open water season. Indeed, in many cases, sampling is done no more than once a week during periods of average flow. The number of sampling days is given, by year and month, for each of the four stations in Tables 3.3 to 3.6.

On the Mackenzie River, sampling ranged 30 to 80 days per year during 1980-88, substantially higher than in the 1970s. The 1970s programs on the Arctic Red and Peel rivers were comparable in sampling intensity to that on the Mackenzie River during the same time. The virtual absence of data during breakup (May and early June) is evident. The 1988-89 programs on the Peel are unique in their coverage of breakup conditions. The Liard program has been more consistent, ranging 20 to 40 days during most years. Using these intermittent data, WSC determines daily mean concentrations by plotting instantaneous concentrations on the water level recorder chart, plotting a "sedigraph" through the points guided by changes in water level, and then digitizing the area under the sedigraph for each day. The procedure works well when sampling is done relatively frequently (once a day during high flow conditions), but such sampling has not always been possible. The published monthly load for the Mackenzie River during August 1974 (the largest on record at 118 million tonnes) involved sampling on only three days during the month. The above approach is also unable to provide estimates of load during unsampled months, and unsampled years.

The procedure adopted in this report, therefore, is to predict concentration from discharge (and other variables if necessary) and use these predicted concentrations in the computation of daily suspended sediment load. This is the "sediment rating" approach described in Chapter 4. The approach does not always work well: sometimes other variables produce too much scatter in the sediment rating. As will be seen later, the method works well for the Mackenzie, Liard and Arctic Red rivers, but improvement is needed for Peel River. On the other hand, given the gaps in the data program on these rivers, and given the expense of maintaining an ongoing monitoring program with frequent sampling, the sediment rating approach is the only viable method.

4. SUSPENDED SEDIMENT: ANALYSIS AND INTERPRETATION

The present chapter provides an analysis of the suspended sediment data at all four stations, with special attention to the following points:

- a summary of the data used in the development of the sediment rating relationships;
- development of the best predictive equation;
- application of the equation to predict annual loads and mean monthly loads;
- breakdown of these loads by grain size class;
- discussion of the temporal representativeness of the data;
- comments on sediment sources.

4.1. Sediment data used

Sediment sampling in the Mackenzie Basin has been largely an open-water program: very few samples have been taken during winter through an ice cover. From the standpoint of computing sediment loads, this is not a problem. Discharges are relatively low at this time of year. In addition, sampling undertaken on distributary channels of the Mackenzie Delta during winter confirms that concentrations (and hence loads) are very low (Erickson and Fowler, 1987): suspended sediment varied little, being typically about 5 mg/L. The open water program of each of the four sites is summarized below.

Mackenzie River

The suspended sediment data collected from 1972 to 1989 and used in this report comprise 502 sample days, of which only 16 were based on MV mean values. The extreme concentration of August 12, 1974 (9640 mg/L) was ignored because of uncertainty in the laboratory record. All sediment concentrations (except the 1989 MV value) were derived as daily mean values.

The 1980 data constitute the only year in which a k-adjustment was applied to the SV values before publication. To maintain consistency, these data have been restored to their original values. As noted previously, from June 13 1984 on, all SV sampling has been confined to the top 5 m of flow. The 1984 SV values were then increased by 1.20x, the 1985 SV values by 1.12x, and the 1986 SV values by 1.14x, on the basis of comparison with full depth-integration with the P61 sampler. The 1984 data prior to June 13 were also (inappropriately) adjusted with the 5 m k-value (Carson, 1988b, Section 4.2.1.i): the original values have been restored. No adjustment was made by WSC to the SV data in 1987-89 because of lack of comparative sampling.

The final adjustment to the published data was elimination of the fraction coarser than 0.125 mm (for which the SV data are believed to be unrepresentative of the section), so that the values used refer to wash load. This was done by multiplying all the sampled concentrations in a given year by the mean figure for percentage-finer-than 0.125 mm in that year. This adjustment was small (94-99%), except for 1972 in which a figure of 86% was used.

Arctic Red River

The suspended sediment data collected from 1972 to 1975, and used in this report, comprise 56 sample days, of which only 8 were based on MV mean values.

There is some inconsistency in the sediment file. The sediment data for 1973 and 1974 are daily mean values, computed using the procedure described in Section 3.3.2. In 1972 and 1975, however, the station was operated on a miscellaneous basis only: no sediment loads were computed by WSC and the published sediment data refer to actual (instantaneous) concentrations. The sediment rating analysis uses both types of data in a regression on daily mean discharge, because no instantaneous discharge data were found corresponding to the 1972 and 1975 samples. This strategy may have contributed to the minimal scatter in the relationship but should not have produced any bias.

Peel River

The suspended sediment data used in the sediment rating analysis derive from two periods: 11 MV samples taken during 1972-75 and 1988-89 and 187 SV samples taken in 1988-90. All discharge data are daily mean values, using the revised values in the case of May-June data. All 1988 SV sediment concentrations are also daily mean values. Sediment data for 1989 and 1990 sampling have not yet been interpolated by WSC to provide daily mean values.

All 1988 SV data were previously adjusted by WSC to make them representative of the full cross-section. All 1989-90 SV data were adjusted, as part of the present analysis, by similar curves as noted in Section 3.2.

Liard River

The suspended sediment data set used for this site involves 396 days of concentration values between 1972 and 1988. All data refer to depth-integrated SV samples at mid-stream, except for 11 MV samples. All data are daily mean values.

None of these SV data has been adjusted with a k-value. Several samples were taken at the left bank in the second half of the 1980s, but these have been ignored in the sediment rating analysis (because they would have been unrepresentative of the full cross-section mean). Details of the sampling program for 1989-90 are unavailable, and the sediment data for these two years have therefore also been ignored.

4.2 Sediment rating relationships

The sediment rating determined here is the ordinary least squares (OLS) solution of log(c) against log(Q):

$$\log(c)^* = a + b \log(Q) \quad (4.1)$$

where concentration (c) is in mg/L, discharge (Q) is in m3/s, and the asterisk denotes predicted value. This is not, however, the best predicting equation in the computation of sediment loads for the following reason.

The OLS line minimizes the sum of squares of the residuals (actual value minus predicted value) for the points in the plot. It thus minimizes the "average" error in the predicted logarithms of concentration: the positive residuals (actual values above the line) are balanced by the negative residuals below the line.

It is the actual value of concentration that matters, however, not the logarithm. The former can be obtained by taking antilogs to yield:

$$c^* = 10^a \,.\, Q^b \quad (4.2)$$

There is a problem here, however, because in changing from a logarithmic to an arithmetic scale, the residuals of actual concentration will be much greater for positive residual log values than for negative residual log(c) values. Thus positive residuals tend to plot much further above the curve given by Eqn 4.2 than negative residuals do beneath it. In other words, on detransformation, the OLS solution gives a biased curve which tends to underpredict actual concentrations. A correction factor is usually applied to the OLS curve therefore to increase the detransformed values. The usual correction factor (Ferguson, 1986) is:

$$cf = \exp\,(2.65\ SEE^2) \quad (4.3)$$

where SEE is the standard error of estimate of the log(c) values, a measure of the average log residual from the regression. In the calculation of sediment loads, this correction factor is always applied in the analysis.

An additional correction factor frequently used was a monthly adjustment. In this case, the ratio of actual and predicted concentrations was determined for each sample day and the mean ratio for each month was calculated. In the case of Mackenzie River at Arctic Red River, for example, the mean ratio for August was 1.36. This implies that, on average, actual concentrations were 36% greater than predicted concentrations in August on the sampled days. Thus all predicted values in August at this station were increased by this amount.

The details of the sediment ratings for the four stations are summarized below.

Mackenzie River

The sediment rating diagram is shown in Fig. 4.1 (top), and the residuals from the regression are plotted, by year, in Fig. 4.1 (bottom). The OLS sediment rating is:

$$\log(c)^* = -7.169 + 2.288 \log(Q) \quad (4.4)$$

with a percentage prediction (coefficient of determination (r^2) x 100) of 68% and a SEE of 0.222 log units. The standard error of the b-value is 0.08.

The bias-adjusted (Eqn 4.2) detransformed rating is:

$$c^* = 7.730 \times 10^{-8} \times Q^{2.288} \quad (4.5)$$

The monthly mean residuals (c/c*) were 1.02 (May), 0.99 (June), 0.95 (July), 1.36 (August), 0.82 (September) and 0.77 (October). All predictions were multiplied by these monthly correction factors.

It had been hoped to improve on the overall precision of the sediment rating by using water temperature as a second predictor variable, but the decrease in SEE was insignificant. Inspection of the data indicated that large positive residuals in August were associated with the onset of new floods produced by rainstorms. Accordingly, a new multiple regression was developed using days since the start of each flood and flood intensity (steepness of the rising limb). The latter was determined as the largest one-day increase in discharge as a percentage of discharge at start of the flood. Again, however, the decrease in SEE was minimal. The reason for the continued scatter is not difficult to determine. The residuals from Eqn 4.4 for the month of August are plotted in Fig. 4.2 (top) as a function of time since start of flood. There is, as expected, a tendency to high positive residuals in the early part of the flood, followed by a decrease to negative residuals. Similar patterns occur in the other months. There is, however, considerable scatter in the first 12 days or so of the flood. This scatter is not random. The same data are shown in Fig. 4.2 (bottom) but with the points identified by the steepness of the rising limb. It can be seen (e.g. the flood with relative steepness of 32%) that individual floods build up to a peak residual concentration in the first week of the flood and then decrease. There is, however, considerable variation in the timing of the peak residual. Moreover, the magnitude of the peak residual is not solely determined by flood intensity (maximum peak residual in Fig. 4.2 occurs with relative steepness of only 6%). It thus seems that summer rainstorms produce varying sediment responses depending on where they occur within the basin as well as the intensity of the storm.

Attempts to model the changes in sediment concentration beyond the level of Eqn 4.5 were therefore abandoned, and the only modification used was that of the monthly correction factors.

Arctic Red River

The sediment rating diagram is given in Fig. 4.3 (top labelled by month; and bottom labelled by hydrograph position). The OLS regression is:

$$\log(c)^* = -2.267 + 1.881 \log(Q) \quad (4.6)$$

with a prediction of 76% and a SEE of 0.267 log units. The standard error of the b-value is 0.14.

The bias-adjusted detransformed sediment rating becomes:

$$c^* = 6.546 \times 10^{-3} \times Q^{1.881} \quad (4.7)$$

There is some indication that concentrations on the rising limb tend to be less than those on the falling limb, but no adjustment has been made for this possible effect, in view of the small data set. Unlike the Mackenzie, there was no obvious monthly pattern to the residuals, and therefore no monthly correction factor was applied. Though there remains some uncertainty regarding the representativeness of the SV site, the limited data show no significant difference between SV data and MV data in relation to the sediment rating.

Peel River

Previous predictions of sediment concentration at this site had used a sediment rating based on MV data only or on the 1988 SV data set. The OLS sediment ratings for these two data sets were:

$$\log(c)^* = -0.339 + 0.942 \log(Q) \quad (MV) \quad (4.8)$$

$$\log(c)^* = -3.768 + 1.887 \log(Q) \qquad (1988) \quad (4.9)$$

with SEE values of 0.232 and 0.213 respectively.

The OLS sediment rating for the combined 1988-90 (and 1970s MV) data set is:

$$\log(c)^* = -2.781 + 1.655 \log(Q) \qquad (4.10)$$

with a percentage prediction of only 61% and a SEE of 0.34 log units. The scatter about Eqn 4.10 is substantially greater than in the data for 1988 alone. The slope is only slightly less than the 1988 rating, but the line is higher by a full log unit: that is, apart from the lower slope, predicted concentrations would be ten times higher than for the 1988 sediment rating. The significance of the difference between the ratings is considered in Section 4.3.

The bias-adjusted detransformed equation based on the same data set is:

$$c^* = 2.252 \times 10^{-3} \times Q^{1.655} \qquad (4.11)$$

Inspection of the data reveals no obvious trend in residuals from Eqn 4.11 during the course of the open-water season (Fig. 4.4 top), but it was noted that each hydrograph rise in 1989-90 produced a short period of (usually high) positive residuals at the start of the flood, and this was the main cause of the increased scatter. This increased scatter is not entirely unexpected. In the earlier review of the Peel data (Carson, 1989a: Section 4.2) the following comments were made:

> "There was, however, no major rainstorm during the 1988 summer, in contrast to the sediment sampling period of the 1970s. The increase in residuals (up to +0.6 log units) is not as marked as in the 1970s data, but confirms, nonetheless, that sediment production during summer storms yields higher concentrations (for given discharge) than snowmelt."

The residuals (expressed as actual divided by predicted) from Eqn 4.11 were examined in terms of timing of sampling (in relation to start of flood) and strength of the flood (as represented by steepness of the rising limb), as previously done for the Mackenzie. The pattern is summarized in Fig. 4.4 (bottom). Steepness of rising limb is expressed as maximum increment in daily flow in that flood hydrograph as a percentage of initial flow. Because the measure is being used primarily as an index of rainfall intensity, the initial snowmelt-induced flood at breakup is given a steepness of zero. The pattern in Fig. 4.4 indicates a definite tendency for above-average concentrations to be restricted to the early days of a flood. (The two extreme actual/predicted ratios shown in the top figure have been ignored in the bottom diagram to provide greater clarity.)

The general decline in the magnitude of positive residuals during the first ten days of a flood is illustrated more clearly in Fig. 4.5 (top) where, again, the point-labelling refers to steepness of each flood's rising limb. The plot indicates not only the general decline in residuals during the first ten days, but also the tendency of more intense storms to produce higher residuals, though there are clearly exceptions to the trend.

The mean value of (actual/predicted) concentrations were determined for each day of elapsed time from the start of floods: these ranged from a peak of 2.51 on day 2 to a minimum of 0.43 on day 8. However, the plot of actual versus predicted (using this adjustment) concentrations showed considerable scatter depending on whether samples were taken in the early open-water flow (before June 14) or after (Fig. 4.5 bottom). Accordingly, separate daily correction factors were determined for the two periods:

day from start	1	2	3	4	5	6-10	>10
before June 14	0.56	0.91	0.79	0.79	0.79	0.63	0.82
after June 13	1.51	3.17	1.56	0.97	0.76	0.64	0.61

The reduction in scatter with this adjustment is still small (Fig. 4.6 top), but, importantly, it is reduced at high concentrations compared to Eqn 4.10 and unadjusted values (Fig. 4.6 bottom).

It should be noted that, of the two extreme (actual/predicted ratios) shown in Fig. 4.4 (top) - both almost 20x - the one for day 2 was retained in the determination of the coefficients above, while the one for day 14 was omitted. Additional SV data will allow a better estimate of the appropriate daily correction factors, but the present data set is sufficient to assess the overall methodology (Section 4.3).

Liard River

The OLS sediment rating is:

$$\log(c)^* = -4.086 + 1.798 \log(Q) \qquad (4.12)$$

with a prediction of 84%, a SEE of 0.21 log units and a standard error of the b-value of 0.04. The bias-adjusted detransformed rating is:

$$c^* = 9.216 \times 10^{-5} \times Q^{1.798} \qquad (4.13)$$

The detransformed curve is shown, relative to the scatter diagram, in Fig. 4.7 (top). Residuals from the logarithmic regression are shown by year and month in Fig.

4.7 (bottom). There is clearly a significant change during the open water season: May concentrations are generally above-average relative to discharge, while October concentrations are below-average. Mean monthly residuals (c/c*) were: April (1.31), May (1.71), June (0.92), July (0.94), August (0.90), September (0.85) and October (0.64). These were applied to sediment load computations.

The expected decrease in residuals during autumn baseflows matches the pattern on the Mackenzie River. On the other hand, the high spring residuals are absent on the Mackenzie, while the high August residual at 10LC014 is not found on the Liard. These differences appear to be related to sediment sources and are discussed further in Section 4.6.

4.3 Prediction of monthly and annual loads

The sediment rating approach here is based on daily mean values. The daily suspended sediment load is computed from the product of daily mean discharge and the concentration (predicted by the sediment rating) as follows:

$$L = c^* \times Q \times 0.0864 \qquad (4.14)$$

where the constant 0.0864 is used to convert from mg/L and m3/s units to tonnes per day. In all cases, c* is adjusted - relative to the OLS equation - with the detransformation correction (Eqn 4.3). In the case of the Mackenzie and Liard rivers, a monthly correction factor, determined in the manner outlined in Section 4.2, was also applied. In the case of the Peel, a daily correction factor was used instead, as described in Section 4.2. No additional corrections were made to the Arctic Red River data.

The sediment rating is applied to each day of the hydrometric record in the 17 year period from 1974 to 1990 and summed to yield total suspended sediment loads for each month. These data are summarized here in terms of annual loads for each year, mean monthly loads in the period, and the mean annual load.

The accuracy of these estimates is affected by many factors, some of which have already been addressed: reliability of depth-integration at the SV site; representativeness of the SV site for the cross-section; as well as accuracy of the discharge data.

The precision of these load estimates, as defined here, ignores possible errors in these three components and relates solely to the reliability of the estimates in being derived from the sediment rating approach. Theoretically, this imprecision might be examined by statistical inference from the sediment rating regression. In practice, this is a difficult task, and one based on assumptions that are frequently dubious (Thompson et al., 1988). The approach used here is to compare monthly loads predicted by the sediment rating approach with those (for months of frequent sampling) computed by the WSC method based on actual concentrations. Though the approach may seem to lack the statistical rigour of conventional inferential statistics, it serves the useful purpose of providing practical results in a simple and meaningful way.

The differences between the two loads for a given month are taken to be errors in the sediment rating prediction. The mean error is generally close to zero, but actual errors may range up to ± 100% of the prediction. The imprecision in the estimate for the load of a single month is taken as one standard deviation (s) of these error values.

In the simplest case, in which all the sediment load is carried in five months, and provided that certain assumptions are met, the imprecision for the annual load (based on 5 months of sediment transport) can be taken as $\sqrt{5}.s$ (but improves as a percentage of the load); the imprecision for the mean monthly load based on 17 years can be taken as $s/\sqrt{17}$; and the imprecision of the mean annual load can be taken as $\sqrt{5}.s/\sqrt{17}$. These expressions assume that there is no dependence among monthly errors and that the mean error remains constant irrespective of load. Neither assumption is strictly valid, and the actual imprecision is likely to be greater than given above. A different approach is therefore taken in this report.

The approach used is to assume that the absolute imprecision in a monthly load is proportional to the magnitude of that load, i.e. that the relative imprecision is fixed. This percentage imprecision is then applied to all predicted monthly loads (in each year of the 17-year period) to determine the absolute monthly imprecision (ami) for each month. The imprecision of any annual load is then taken as the square root of the sum of squares of these (ami) values in the year. The imprecision in any mean monthly load of the 17-year period is taken as the square root of the sum of squares of the 17 (ami) values for that month, divided by seventeen. The imprecision in the mean annual load is taken as the square root of the sum of squares of the 17 annual absolute imprecisions, divided by seventeen.

It should be clearly recognized that, even with good sediment ratings, appreciable errors can occur in the calculation of sediment load for a single day. When this involves one or more days of heavy loads, this can produce significant errors in the prediction of the monthly load. It is only as more data are added - as in the computation of mean monthly loads and annual loads - that the imprecision becomes acceptable.

Mackenzie River

The annual and mean monthly suspended loads are presented in Table 4.1. These were derived from Eqn 4.5 as wash load estimates and then increased by 3.5%

to convert to total suspended load. Comparison of predicted loads and actual loads for 15 months with reasonably frequent sampling (more than 10 days and covering the high flows) is made in Table 4.2.

The sediment rating prediction is shown to be badly in error, on a percentage basis, in three of these months: June 1984 (-16.1 Mt), August 1987 (-7.2 Mt) and August 1988 (13.4 Mt). These are months in which the residuals from the sediment rating were consistently positive (first two) and consistently negative (1988). Such discrepancies must be expected occasionally: the lower-than-predicted concentrations in August 1988, for example, are almost certainly a result of the high floods in the previous month which would have removed much of the available sediment.

The overall precision for an individual monthly load is about 33% of the prediction. Thus great caution is needed in dealing with individual months. The precision for annual loads is somewhat better, at about 20% of the prediction, that for mean monthly loads about 10%, and that for the mean annual load for the period is 5 percent. These are all acceptable levels of precision, notwithstanding the scatter in the sediment rating diagram previously noted.

The loads of 1974 (major floods in northern Mackenzie tributaries), 1975 and 1988 (major floods in Liard and nearby basins) - at close to 150 Mt - were appreciably higher than those of other years. The minimum load of 34 Mt occurred in 1980. Mean monthly load peaks in June at about 35 Mt, followed by July (23 Mt), with May and August both at about 16 Mt. These loads are not directly comparable with those reported previously (Lewis, 1988; Carson, 1989b) which were based on the period 1974-83 only. The latter are inflated because of the shorter period (with two major flood years) and overestimates of discharge during breakup. These trends were countered by the use of a 1972-89 regression which was somewhat steeper than the 1972-83 sediment rating.

The mean annual suspended load for 1974-90 is determined at 98 Mt, compared to previous estimates of 88 Mt (Lewis, 1988) and 101 Mt (Carson, 1989b). The period May through October accounts for 99% of the annual load. The 1974-90 mean is, of course, only an estimate of the longterm mean. The standard error of that estimate is, however, only 8.2 Mt, or about 9% of the mean.

Arctic Red River

The annual totals for 1974-90 and the mean monthly loads are given in Table 4.3. The annual loads for 1974, 1975, 1976 and 1980 are all underestimates because of gaps in the discharge data, preventing predictions for some months. The mean monthly loads are thus based on 16 years for May, June and July and 15 years for August.

The precision in these loads is unknown because no months exist with sufficiently frequent sampling to allow accurate determinations by the WSC method for comparison. It is assumed that the precision is comparable with that of the Mackenzie River, given the similarity in the SEE value.

The 1974-90 mean annual load is 7 Mt, approximately 7% of the load of the Mackenzie River in the same period. The two main months are May and June, with a secondary peak in August. The high August mean is, however, essentially the result of the major flood of 1974 in which month an estimated 13.8 Mt of sediment was moved (virtually the full load for the year). This is substantially higher than any other month in the period, all others being less than 1.5 Mt. There is no question that considerable sediment was moved in this month. Jasper (1976) indicated this in his 1972-74 study of Twisty Creek basin, located in the upper Arctic Red River watershed (Fig. 2.10). The accuracy of the August 1974 load is, however, uncertain. The one concentration at high flow was well below the sediment rating prediction. And the load computed by WSC (4 sample days only) was only 7.6 Mt.

The extreme character of the 1974 flood highlights the point that, irrespective of the precision of the 17-year load, a reliable estimate of the longterm mean is likely to require a longer discharge period than currently available. The standard error of the 1974-90 mean is, based on the data of Table 4.3, about 1 Mt, or 15% of the mean.

Peel River

The computed sediment loads for this site vary significantly according to which sediment rating formula is used and which flow data are applied. A comparison of mean annual loads using the different approaches is given in Table 4.4. The mean load in this table refers to the 8-year period 1975-80 and 1982-83. Flow data for much of the year 1974 are no longer given following revision. Unrevised flow data for the years after 1983 were not available. Previous sediment load computations (Carson, 1989a) were not made for 1981 because of unavailable data: the present comparison therefore ignores this year.

Estimates of mean annual load are given for six sediment rating predictions. These include two approaches previously employed: one using pre-1989 MV data only and one using 1988 SV data. The two approaches developed in this report comprise Eqn 4.11 on its own, and then adjusted by daily correction values. Both of the two approaches developed here used the sediment rating after it had been adjusted for bias (Eqn 4.3). The two approaches developed earlier are given with and without bias correction for comparison.

The pre-1989 MV and 1988 SV sediment rating output indicate the major reduction in load estimates resulting from the revision of the discharge data. However, the effect of adding new sediment data from 1989 and 1990 (which include significant summer rainstorm floods) has been to restore the estimate of the mean annual load to the level given in the previous report which was based on unrevised discharge data.

It is clear, therefore, that considerable attention has to be given as to what is the most appropriate sediment rating approach at this station. Some comments can be made now, but ultimately additional years of sediment data are needed to provide more confidence in the approach.

The estimates based on the pre-1989 MV sampling should, theoretically, provide most confidence, because there is much greater reliability in the sediment data (compared to SV samples) as they represent the full cross-section. There are two main problems with the MV data set (Fig. 4.6 bottom) : the limited number of samples and the fact that only one of them was taken from a flood produced by a heavy summer rainstorm. The latter means that predictions at high flows will tend to underestimate concentrations in rainstorms. The former means that the one anomalously high concentration at low flow (72 July 18) has a marked influence on the MV sediment rating. The effect of both of these influences is that the MV sediment rating has a slope that is too gentle: thus sediment loads at high flow tend to be underestimated by it.

The substantial difference in predicted loads between those using the 1988 SV sediment rating and the equations developed in the present report seem to result from the point noted previously: the 1988 year contained no significant floods from summer rainstorms. Thus no large positive residuals occurred which would have acted to raise the overall level of the best-fit line in the 1988 data set.

In testing the precision of the sediment rating approach for this station, the only reliable monthly data available for comparison are those computed by WSC for 1988. The 1989-90 computations were not ready at the time of this report. The comparisons between actual and predicted are given in Table 4.5. Neither prediction is especially good. The prediction based on the 1988 sediment rating is better, but over the long term, in which 1988 conditions (and hence rating) are not typical, this is perhaps somewhat irrelevant. Additional months of frequent sampling at the Peel SV site are clearly needed in order to assess the sediment rating approach more fully.

The predicted mean monthly loads for the period 1975-90, based on the two sediment ratings, are given in Table 4.6. The mean annual load is given at about 20 Mt by both approaches: this is 20% of the amount computed for the Mackenzie's load, compared to 10% for the May-September runoff. Monthly loads peak in June, followed closely by May. Mean monthly runoff on the Peel is much higher in June than in May but peak daily flows usually occur in May.

Liard River

The annual loads and mean monthly loads for the period are listed in Table 4.7. Mean annual load is 47 Mt with 99% of this occurring in the period May through September. This is almost 50% of the Mackenzie load during the same period. The loads are slightly higher than estimates for earlier periods (Lewis, 1988; Carson, 1989b) primarily because of the extreme nature of 1988 flows. The predicted load for that year was 118 Mt, with more than 30 Mt in both May and June, and almost 50 Mt in July.

Some indication of the precision of these sediment rating estimates may be obtained by comparing them with actual WSC loads in 8 months for which the WSC load is based on more than 10 sampling spaced suitably through the month. These data are given in Table 4.8. They indicate a standard deviation in the individual monthly errors of 15 percent. This is substantially less than for the Mackenzie, but is based on a smaller sample of months and may not be as reliable. These values indicate a precision for annual loads of about 10%, mean monthly loads (based on 17 years) at about 5%, and for the mean annual load at about 3 percent.

The standard error of the 1974-90 mean is 6 Mt, about 13%, somewhat higher than for the Mackenzie. The 1988 load, at more than twice the period mean, was far more extreme in the case of the Liard than the Mackenzie.

4.4 Suspended load broken down by grain size

Mackenzie River

Interpretation of the grain size data at this site is complicated by the fact that since 1984 all SV sampling has been restricted to the top 5 m only. Attempts have been made to adjust total suspended sediment concentrations to make them representative of the full vertical, as noted in Section 4.1. These data are inadequate, however, to accurately adjust the grain size breakdown. The grain size data below are therefore based only on samples taken prior to 1984 through the full depth of the single vertical site.

The mean values (and standard errors) for these data (for 62 SV sampling) are broken down as follows:

clay	34 % ±	1 %
silt	57 % ±	1 %
vf sand	5.5 % ±	0.5%
bed sand	3.5 % ±	0.5%

These means change little on a monthly basis. At very high sediment concentrations (> 1000 mg/L), the sand fraction becomes less, and the clay fraction is greater, but such levels are rare. Apart from this, there is no obvious systematic trend in the grain size breakdown with either discharge or overall sediment concentrations.

Arctic Red River

Particle size analyses were reported by WSC for 15 sampling of suspended load during 1972-75. Ten of these were for the SV site near the mouth; these samples showed less sand than those at the measurement section above Fort McPherson, but the limited sample size restricts any statistical inference. Overall, the mean particle size breakdown (and associated standard error) was as follows:

clay	35 % ±	4%
silt	57.5% ±	3%
sand	7.5% ±	2%

Though slight changes in these percentages were determined according to discharge, month of sampling etc., the small number of samples rendered these comparisons of limited statistical significance. Overall, the grain size breakdown is comparable with that on the Mackenzie River.

Peel River

Particle size data for the suspended sediment on the Peel were previously analyzed by Carson (1989a: Section 4.5). The mean breakdown for 11 sampling taken in the 1970s (including 4 MV sampling) was given (with standard errors) as:

clay	32.5 % ±	2%
silt	59 % ±	2%
sand	8.5 % ±	2%

and the mean breakdown for 42 SV sampling in 1988 was:

clay	24.5 % ±	1%
silt	69 % ±	1%
sand	6.5 % ±	0.5%.

The difference was attributable to the timing of sampling. Almost all the 1970s samples were from July-September rather than during breakup. The difference between the two data sets probably underestimates this difference, bearing in mind that the 1988 SV site tends to overestimate the clay fraction because of its location over the thalweg.

The 1989 SV data tend to confirm this pattern with the twenty-four May-June sampling having means of 28% clay and 69% silt in contrast with the means of the four August-September sampling of 37% clay and 59% silt. The standard errors are 1.5% for the May-June means and 3.5% for the August-September means. This seasonality in the grain size breakdown exacerbates the difficulty of adjusting SV particle size data to make them more representative of the full cross-section. A satisfactory analysis will require more MV grain size data.

Liard River

Previous analysis of the grain size data for this site (Carson, 1988c) indicated the following means and standard errors:

clay	27 % ±	1%
silt	52 % ±	1%
vf sand	11 % ±	0.5%
bed sand	10 % ±	0.5%

with no significant difference between the 65 SV samples and 7 MV-series samples. It was noted, however, that at overall concentrations greater than 1800 mg/L, there was a marked increase in clay (to 34%) and decrease in the sand fraction.

Data derived from depth-integrated midstream samples in 1987 and 1988 represent a puzzling departure from this summary. The means and standard errors are as follows:

	1987	1988
clay	20.5 ± 2.4	16.7 ± 0.9
silt	53.3 ± 1.3	53.0 ± 2.6
sand	26.2 ± 2.2	30.2 ± 2.1

The sand fraction has increased at the expense of the clay fraction.

All samples had overall sediment concentrations less than 1800 mg/L, notwithstanding the record sediment loads in 1988. The data for the two years appear to reflect a trend noted in the 1972-1986 data set: the sand fraction of the suspended load increased during the 1980s. Though the cause of this increase is unknown, it was previously speculated that it relates to the downstream extension of the left bank bar located above the measurement section. It must be anticipated that, where bed material constitutes a significant amount of the suspended load, there will be cyclic changes in the grain size breakdown of suspended sediment in response to local changes in bed geometry and texture. On the other hand, the late 1980s SV data do not show a marked increase in the magnitude of positive residuals, as would be expected from such channel changes.

4.5 Temporal representativeness of data

It has been noted above that, in most cases, the duration of the discharge record (from which the sediment loads have been predicted) is sufficient to provide a mean annual load with a relatively limited standard error, i.e. the sediment load period is generally long enough to represent the present.

The question remains as to whether "present" conditions are themselves representative of the long term state. Church et al. (1987) for example noted that at Norman Wells, for which a much longer discharge record exists, the annual maximum daily flow shows a substantial increase after 1962: during 1943-62 it averaged only 19,580 m3/s; between 1963 and 1984, the mean was 24,080 m3/s.

The comparison is admittedly complicated by the fact that annual peaks are missing from some of the earlier years at Norman Wells (1946, 1948, 1954 and 1956-62), and some of these may correspond to loss of the orifice at the gauge site under heavy flow conditions. Yet examination of the data for the Mackenzie R. at Fort Simpson does not support the view that these missing data correspond to years with high peaks. The conclusion that post-1962 years correspond to higher peak flows on the Mackenzie therefore seems to be valid.

There are insufficient years of discharge data on the Arctic Red River and the Peel River to assess the temporal representativeness of the 1974-90 period there.

On the Liard River, discharge data extend back to 1944 at the Fort Liard settlement. Aitken (1986) previously concluded that there was very little difference in flows between the 1972-85 period and the 1944-85 period at Fort Liard. Yet historical discharge data for Fort Liard show the mean annual maximum flow to be 7687 m3/s for 1944-71 and 10,122 m3/s for 1972-84, indicating (as on the Mackenzie) higher peak flows during the period for which sediment loads have been computed.

Again, interpretation is complicated by missing discharge data, in the case of Fort Liard these being for 1956 and 1962-65. Yet examination of these years at Norman Wells indicates that they do not correspond to particularly high flows. The impression is sustained that post-1960 flows are higher than 1944-1960, and that the sediment load computations refer to a period of apparently above-average flows.

4.6 Regional patterns of sediment production

The 1974-90 monthly pattern of mean sediment concentrations (expressed as load divided by runoff) is given in Table 4.9. The summary is slightly different from that given previously (Carson, 1989a, Table 3), partly because of the additional years of data, and partly because of revisions to the flow data.

4.6.1 The Liard's share of the Mackenzie's load

Sediment concentrations decrease sharply on the Liard from May-June through the summer, whereas in contrast, the July-August levels on the Mackenzie are comparable with those in May. It is inferred that sediment inputs from other west-bank tributaries (and from the Mackenzie mainstem) increase in importance (relative to the Liard) during the summer. It should be remembered that May concentrations on the Mackenzie are largely conjecture, being based on a sediment rating curve that included only 7 May sampling out of 502. The same comment applies to Arctic Red River on which no sampling at all have been made in May.

The mean annual concentration on the Liard is 610 mg/L. The figure for the Mackenzie is about half of this. On the other hand, the mean annual flow of the Mackenzie (8950 m3/s) includes a substantial amount of largely clean runoff from Great Slave Lake. Data for Fort Providence (1964-73) and for Fort Simpson (minus the Liard) for 1973-86 indicate that this clean runoff averages about 4300 m3/s. Assuming that the mean annual runoff for the Mackenzie downstream of Great Slave Lake is given by the difference between these figures (4650 m3/s), the mean concentration for the Mackenzie is then 635 mg/L, essentially the same as the Liard's.

A similar conclusion emerges when examining regional sediment production in terms of sediment yields. The Liard basin (277,000 km2) produced sediment at an average rate of 170 t/km2 per year in 1974-90; the Mackenzie basin downstream of Great Slave Lake (689,000 km2) yielded about 140 t/km2 per year.

The Liard is the major contributing basin to the load of the Mackenzie, with 48% of the load in 1974-90, compared to only 40% of the land area. Its share of the Mackenzie load is higher than reported earlier (Carson, 1989b) because of the extreme sediment production in 1988.

4.6.2 Sediment sources within the Liard basin

Earlier investigations (Grey and Sherstone, 1980; BC Hydro, 1985) have shown that much of the sediment load of the Liard originates in the tributaries draining the Interior Plains (the Muskwa and Fort Nelson rivers) rather than the upland basin of the upper Liard. In the period 1977-79, it was estimated that the Muskwa and Fort Nelson rivers (at their confluence) accounted for 36% of the Liard's load (at its mouth), while the upper Liard (above Beaver River) produced only 20 percent.

The sediment produced in the plains rivers appears to derive largely from bank erosion of fine-grained glaciolacustrine sediments and weak shaly bedrock. The overall importance of the plains rivers is likely to be greater than indicated in the above sediment budget because of additional sediment production along the Fort Nelson River below the Muskwa confluence.

The significance of sediment yield from the Fort Nelson basin is reflected in the above-average (residual) sediment concentrations for the 10ED002 station in May noted in Section 4.2. During this month, the Liard runoff is largely from the plains, whereas upland runoff peaks in June.

4.6.3 Arctic Red, Peel and other tributaries

The Arctic Red River load was 7% of the Mackenzie's suspended load in 1974-90. Though this is relatively insignificant, the basin area of the Arctic Red River, at its mouth (21,400 km2), is only 3.1% of the Mackenzie. The sediment yield of the Arctic Red River is estimated at 305 t/km2/yr, almost twice that of the Liard basin. The mean concentration of the river is 1390 mg/L, more than twice that of the Liard. (As noted previously, the accuracy and statistical reliability of the August data are uncertain.)

Similar high yields and concentrations are indicated for the Peel River. The predicted mean annual load of about 20 Mt (1975-90) corresponds to a specific yield for the 70,600 km2 basin of about 285 t/km2/yr, and a mean load-flow ratio of 920 mg/L.

The reasons for this high rate of sediment production in these basins has not been determined. It seems probable, however, that much of the sediment originates from slope instability and channel bank erosion in glaciolacustrine sediments as they thaw in the summer. Both basins were occupied by proglacial lakes in the last glaciation when the Laurentide ice sheet abutted the east side and north end of the Mackenzie Mountains.

It also seems probable that similarly high sediment production occurs in most of the other west-bank basins of the Mackenzie (Fig. 2.1), bearing in mind the similarity in terrain and late-glacial history. Isolated rainstorms in any of these basins would probably be capable of generating substantial increase in turbidity in the Mackenzie with a relatively small increase in the mainstem flow. This may account for the difficulty of predicting mainstem concentrations in the Mackenzie during summer floods (Section 4.2), though there are no long-term precipitation data for any of these basins.

A summary of 1974-90 sediment loads, as a percentage of the delta-head inputs, is given in Table 4.10.

5. SEDIMENT DATA FOR OTHER STATIONS IN THE MACKENZIE BASIN

5.1 Background

The 1988 Sediment Data Reference Index (Canada) includes the following stations in the Mackenzie Basin, upstream of the Delta, and downstream of Great Slave Lake. Each station is described by the duration of the sediment program and, in parentheses, by the number of samples of suspended sediment taken (to 1988).

Liard Basin:

10AA001 Liard R. at Upper Crossing	72 74-75 82-83 (9)
10AD001 Hyland R. near Lower Post	72 (2)
10BB001 Kechika R. at the mouth	72 82-84 (12)
10BE001 Liard R. at Lower Crossing	72 83-84 (22)
10BE005 Liard R. above Beaver R.	82-84 (12)
10BE008 Liard R. above Kechika R.	82-84 (13)
10CC002 Fort Nelson R. above Muskwa R.	79-80 82-84 (225)
10CD001 Muskwa R. near Fort Nelson	79-80 82-84 88 (223)
10EA003 Flat R. near the mouth	78-88 (46)

Mackenzie Basin above Liard R.

10FA002 Trout R. at Highway No. 1	73-75 (32)
10GC004 Mackenzie R. above Liard R.	72-75 (62)

Mackenzie Basin below Fort Simpson

10GA001 Root R. near the mouth	87-88 (12)
10GC002 Harris R. near the mouth	72-76 (124)
10GC003 Martin R. at Highway No. 1	73-76 (107)
10GB001 Willowlake R. near the mouth	73-74 (15)
10HB001 Redstone R. near the mouth	73 (3)
10HB005 Redstone R. 63 km above mouth	87-88 (7)
10KA001 Mackenzie R. at Norman Wells	73 (7)
10KB001 Carcajou R. below Imperial R.	87-88 (6)
10KC001 Mountain R. below Cambrian R.	87-88 (3)
10KD004 Ramparts R. nr Fort Good Hope	87-88 (6)

Peel River Basin

10MA002 Ogilvie R at km 197.9 Dempster	74 (2)

All of the miscellaneous data are summarized in the 1963-83 Miscellaneous Sediment Data (Canada) report by IWD (1988). Some of the sampling years at some of the above stations were "full program" operation, however, and the resultant data are located only in the relevant sediment yearbooks.

Additional sediment stations are operated in the Mackenzie Delta. These programs, and their data, have been reviewed separately (Carson, 1991a).

5.2 Liard River Basin

The only station listed in the Liard basin that is located within the Northwest Territories is the Flat River, a tributary of the South Nahanni R. (Fig. 2.9), with a basin area of 8560 km2, comparable in size with the Root River basin. No sediment loads have been computed by WSC for the station. The data for Flat River are sufficient, however, to generate a sediment rating curve. The gauge for 10EA003 has continuous data for the 1974-90 period: this would allow computation of sediment loads. The data would be useful in providing information on sediment yields in part of the upland Liard Basin.

With the exception of 10AA001 (in the Yukon), all the others are all located in British Columbia. The data have been discussed previously by Grey and Sherstone (1980) and BC Hydro (1985), and their conclusions summarized in Section 4.6.

5.3 Mackenzie Basin above Liard basin

The data for the Mackenzie above Liard R. were analyzed previously by Carson (1988c). The small natural range in discharge at this site renders the sediment rating approach of limited reliability. It is thus difficult to extend the data to years without sediment sampling. Sediment concentration also exhibited only minor variation during the 1972-75 open water period (13-52 mg/L). Mean values of concentration and load for May-October in this period are given in Table 5.1. The mean seasonal load for 1972-75 is 2.3 Mt. This compares, for example, with 9.5 Mt for the Arctic Red River in the same period.

The load of the upper Mackenzie is insignificant on an annual basis. Its October load, however, was comparable with that of the Liard and the Peel. The slow decrease in concentration during the open-water season suggests that the upper Mackenzie may form a relatively significant part of the lower Mackenzie's load during autumn and winter. This needs to be borne in mind, therefore, during any interpretation of sediment quality data in the Mackenzie Delta during the low-flow season.

The question arises as to the source of this sediment. How much is from the outflow of Great Slave Lake, relative to inputs from local tributaries and from erosion of channel banks and valley walls along the main stem? The data for the Trout River basin (Fig. 5.1) might assist in assessing the importance of tributaries, though sediment loads have been computed for the summer months of 1973-1974 only. These data are shown in Table 5.2. The loads have been extrapolated to the entire basin of the Mackenzie between Great Slave Lake and the Liard. The computations indicate that, at least during these two years, the tributaries supply an insignificant portion of the load of the Mackenzie River upstream of the Liard.

5.4 Mackenzie Basin below Fort Simpson

The two basins near Fort Simpson - the Harris R. (10GC002) and the Martin R. (10GC003) - are both small, at 700 km2 and 2050 km2 respectively. The data may, nonetheless, provide some guide as to sediment yields from west bank tributaries of the Mackenzie, downstream of Fort Simpson, including the Ram R., North Nahanni R. and Root River.

Only miscellaneous data were collected for the Harris R. in 1972, 1975-76 and for the Martin R. in 1975. The loads and mean concentrations (load divided by runoff) computed by WSC for summer months in the other years are indicated in Table 5.3. The sediment yields for both years on the Harris were about 1 t/km2/yr, and for the corresponding open water periods on the Martin were about an order of magnitude higher. The Martin yields were, in turn, more than an order of magnitude less than those of the Liard River near the mouth (200 t/km2/yr) in the same period. This pattern of increasing sediment yields with increasing basin size is typical of western Canadian drainage areas in which most fluvial sediment appears to originate from erosion of channel margins.

Sufficient data exist to produce a sediment rating for both stations, and though sediment sampling was restricted to the early 1970s, it would be worthwhile to generate the curve and apply it to the 1974-90 discharge data.

Sediment loads were computed by WSC for the Willowlake River in May-September 1973. These provided a sediment yield for the period of 5 t/km2 for the 20,500 km2 basin. This yield is comparable with that of the Martin basin, though the catchment is ten times its size. The data are consistent with the general view that sediment production in basins on the east side of the Mackenzie main stem is much less than on the west side.

None of the other data are yet adequate for computation of sediment loads. Assuming that the late 1980s program on the Root, Redstone, Carcajou, Mountain and Ramparts rivers is continuing, they should, in the near future, be ready to generate a sediment rating curve at each of these stations. The availability of data from the high-flow 1988 year is particularly useful. Use of the curves to predict sediment loads for the 1974-90 period will be difficult, however, because of the limited duration of some of the hydrometric programs. The Root R. station has data from 1975 on. The Carcajou R. and Mountain R. stations started in 1976 and 1978, respectively, but contain significant gaps. Both the Ramparts and Redstone (10HB005) hydrometric programs were not implemented until the mid-1980s.

Analysis of the Root R. data could usefully be made in the near future to allow comparison with the 1974-90 data presented in this report. Additional years of discharge data will be needed for the other stations in order to provide representative estimates of mean values. Care will be needed in the interpretation of the sediment data for the Redstone, Carcajou and Mountain rivers. The hydrometric (and sediment sampling) stations are located well above the mouths of these rivers. It must be expected that much of the sediment load entering the Mackenzie originates from the lower basin (where extensive glaciolacustrine deposits occur), so that sediment conditions at the stations will not represent those at the mouth.

5.5 Conclusions

The supplementary data provided by the various stations listed above are useful in addressing issues related to sediment sources in the Mackenzie Basin. There are, however, some questions that remain unanswered.

Though the load of the upper Mackenzie (above the Liard) is relatively minor, the chemical quality of the sediment may be more significant in view of the contaminants in Great Slave Lake and its collecting waters. It would be desirable to have some estimate of the sediment flux from Great Slave Lake in order to put future investigations of sediment quality into some perspective. Specific recommendations in this regard were made in an earlier report (Carson, 1988c, Chap.8).

The sediment inputs from the Liard basin are well-documented by the data from 10ED002 (Liard near the mouth), but the regional breakdown of sediment sources remains unresolved. It was previously noted that in 1973-79 about 36% of the 10ED002 load originated from the Muskwa and Fort Nelson above their confluence, and only 20% from the upper Liard (above Beaver River). The breakdown of the remainder is unknown. The establishment of a miscellaneous sampling program at Fort Liard (10ED001) and the development of a sediment rating curve for that site would allow some estimate of the relative contribution of the plains rivers (Fort Nelson and Petitot rivers) and the South Nahanni catchment. Again, this breakdown of sediment source would seem to be important in the context of sediment quality, given the marked contrast in actual and proposed development for the plains and the uplands.

The estimation of sediment loadings from the westbank tributaries of the Mackenzie downstream of the Liard is a challenging task in view of the difficulty of establishing good hydrometric stations near the mouth. The sediment programs on the Redstone and Mountain rivers are important given the probable heavy loads supplied to the Mackenzie. However, extrapolation of sediment loads from the inland hydrometric stations to the mouths of these rivers is likely to be subject to more uncertainty than in the case of extrapolation of runoff measurements. The feasibility of establishing a sediment sampling program near the mouth (in conjunction with discharge data routed down from the inland stations) should be investigated. Such an approach seems likely to provide a more reliable estimate of sediment inputs to the Mackenzie than the present program.

6. CONCLUSIONS

The following conclusions emerge from this review of the suspended fluvial sediment data at WSC stations in the Mackenzie Basin between Great Slave Lake and the Mackenzie Delta. They provide an update to the preliminary evaluation by Carson (1989b).

- Monthly sediment loads have been computed by WSC for four main stations, but, because of gaps in the sampling program, the data are fragmentary. The approach taken in this report is to use the existing data to develop equations to predict sediment concentration from the hydrograph records. This, then, provides estimates of monthly loads for all months with discharge data. The imprecision of this approach (compared to WSC determinations) has been estimated at about 35% for loads of individual months, at about 20% for loads of individual years, at about 10% for mean monthly loads and 5% for the mean annual load of the 1974-90 period.

- The combined mean annual load for suspended sediment inputs to the Mackenzie Delta is about 126 Mt of which the Mackenzie accounts for about 99 Mt, the Peel about 20 Mt and the Arctic Red River about 7 Mt. The estimate for the Peel will need to be reevaluated as additional data (which will affect the predictive equation) are collected.

- The peak month of sediment delivery on all three rivers is June. This is followed by July on the Mackenzie, May on the Peel and Arctic Red River.

- The mean annual load for the Liard River during the same time period was about 47 Mt, slightly less than 50% of the Mackenzie's load. The Liard load peaks in June, followed by July and May.

- Sand forms only a very small part of the suspended load on the three delta-head rivers, averaging 5-10%, whereas it forms more than 20% of the Liard load. The grain size breakdown of the suspended load shows significant fluctuation, however, especially in the extent to which it includes sandy bed material. The sand fraction on the Liard was 25-30% in the late 1980s, apparently a response to downstream extension of a sand bar.

- The major source of sediment within the Liard basin is bank scour and valley wall slumping of soft shale and fine-grained glacial-drift in the plains area of the catchment. Downstream of the Liard, the major sediment inputs are presumed to be from west-bank tributaries. Arctic Red River basin produced sediment in 1974-90 at a rate of more than 300 t/km2/yr with a mean load/flow ratio of 1400 mg/L (both about twice that of the Liard basin). Similar high levels of sediment production are indicated for the Peel basin.

The sediment program for this part of the Mackenzie Basin has generally met the objectives of the initial program in determining inputs to the delta area. In particular, the sediment regime of the Mackenzie R. at Arctic Red River, the Arctic Red River itself, and the Liard R. are now reasonably well established. No regular sediment monitoring program is now required at these stations, except for sampling in high-flows to check on the stability of the sediment rating. There is still some uncertainty regarding estimation of high flows from the open-water stage-discharge rating curve on the Mackenzie at Arctic Red River; any revisions here will affect estimates of sediment loads.

The Peel station requires additional sampling. There are two problems in this regard. One is the representativeness of the single-vertical: each season of SV sampling requires two or three multiple vertical checks. The second is the high sediment concentrations produced in major summer rainstorms. It is unlikely that routine visits by the WSC crew to the hydrometric station will catch such floods. For this reason, at least for a few years, it would seem advisable to maintain the SV sediment program. The sediment rating approach on the Peel is the least satisfactory of the four main stations because of the scatter produced by such storms, but extension of the method to include hydrograph pattern (as done here) may prove adequate. Additional data are needed to assess this. Estimates of high-flow discharge from the open-water stage-discharge rating on the Peel are also likely to be revised to some extent.

Additional programs may be required to address specific issues. These might include assessment of sediment outflows from Great Slave Lake, and sediment production in west-bank tributary basins. Some programs have been initiated on the Flat, Root, Redstone, Carcajou, Mountain and Ramparts rivers: it is suggested that these programs now be reviewed.

A major sediment issue in the future is likely to be that of sediment quality (e.g. hydrocarbon contamination). In this regard, careful attention needs to be directed to the representativeness of the SV sampling site used in such work, given the experience gained in the WSC sediment program.

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APPENDIX I

GRAIN SIZE DATA FOR BED MATERIAL

1.1 Mackenzie River upstream of Arctic Red River

1.2 Arctic Red River near Martin House

1.3 Peel River at 1970s measurement section

1.4 Liard River near the mouth

	Distance from right bank water's edge (m)			
72 JUL 13	1050	850	650	150
>2000	0	0	0	1
250 -2000	99	16	82	32
125 - 250	1	83	17	65
62 - 125	0	1	1	2
0- 62	0	0	0	0

	Distance from right bank water's edge (m)				
73 SEP 25	1006	823	579	396	213
>2000	0	14	0	0	0
250 -2000	100	73	25	42	10
125 - 250	0	13	70	56	59
62 - 125	0	0	4	2	12
0- 62	0	0	1	0	19

	Distance from right bank water's edge (m)				
74 SEP 24	1001	827	595	421	189
>2000	7	2	0	0	0
250 -2000	93	96	83	17	1
125 - 250	0	2	17	60	13
62 - 125	0	0	0	7	22
0- 62	0	0	0	16	64

All data given as percentage by weight in size class:
size given in micrometers, e.g 2000 um = 2.0 mm

TABLE APP. 1.1

MACKENZIE RIVER UPSTREAM OF ARCTIC RED RIVER:
GRAIN SIZE DISTRIBUTION OF BED MATERIAL AT MEASUREMENT SECTION

	Relative position of vertical				
	Near LB				Near RB
72JUL22**	5	*3	*3	25	3
72SEP21**	1	*3	4	1	5
73JUN20	30	5	3	*0	1
73AUG02	37	4	0	*7	13
73SEP19	36	31	11	*2	2
74SEP24	*51	32	32	34	22
75JUL29	13	14	12	*80	99

** denotes reference bank for first vertical is unknown and assumed

* denotes deepest vertical

TABLE APP. 1.2

ARCTIC RED RIVER NEAR MARTIN HOUSE MEASUREMENT SECTION:

PERCENT BED MATERIAL FINER THAN 0.125 mm

Relative location of vertical

	Near LB					Near RB
72JUL18						
0-250		58	87	99	84	37
0-125		9	58	93	49	16
0- 62		6	32	37	4	2
73SEP26						
0-250	94	39	94	66		25
0-125	69	17	35	17		2
0- 62	39	1	0	0		0
74SEP25						
0-250		63	97	91	48	8
0-125		27	56	47	10	1
0- 62		11	35	24	1	0

TABLE APP. 1.3

PEEL RIVER AT 1970S MEASUREMENT SECTION:
GRAIN SIZE DISTRIBUTION OF BED MATERIAL

Date	Distance from right bank (metres)					
73AUG02	590				101	
74AUG28		587	296	194		94
Size class						
>2000	0	25	52	83	12	69
500- 2000	40	35	36	14	76	23
250- 500	20	30	6	1	12	3
125- 250	33	8	4	1		4
62- 125	6	2	1			1
0- 62	1					

Data given as percentage by weight in size class:
size given in micrometers, e.g. 2000 = 2.00 mm

TABLE APP. 1.4

LIARD RIVER NEAR THE MOUTH AT MEASUREMENT SECTION:
GRAIN SIZE DISTRIBUTION OF BED MATERIAL

List of Tables

all data in m3/s

		monthly mean		annual daily peak	
		published	revised	published	revised
1976	May	18600	16600	32000	25000
1978	May	8820	9760		
	June	21700	20200	28300	23000
1979	May	10100	9310	28600	21000
	June	21600	21100		
1980	May	13900	10200	26400	15100
	June	16000	14200		
1981	May	14800	11800	28300	22200
	June	21600	19700		
1982	May	7210	7870		
	June	24600	23400	28800	25800
1983	July	13400	15200		
	August	9440	14200		
	Sept	8640	11300		
1984	May	12000	10100		
	June	17200	16700	22100	22100
1986	May	10300	11100		

TABLE 3.1

MACKENZIE RIVER AT ARCTIC RED RIVER:
DIFFERENCES BETWEEN PUBLISHED (1989) AND REVISED
MONTHLY AND ANNUAL PEAK FLOWS

all data in m3/s

		monthly mean published	revised	percent (revised/ published
1975	May	3230	2190	68
	June	4470	3650	82
1976	May	2660	2470	93
	June	2060	2010	98
1977	May	3340	2820	84
	June	2840	2710	95
1978	May	453	405	89
	June	3890	3470	89
1979	May	2370	2170	92
1980	May	3330	2420	73
1981	May	1380	1680	122
1982	May	1430	1150	80
	June	3800	3580	94
1983	May	1760	735	42
	June	3060	2730	89
1984	May	3090	2150	70
1985	May	2340	2170	93
	June	2440	2380	98
1986	May	558	372	67
	June	2700	2610	97

TABLE 3.2

PEEL RIVER ABOVE FORT MCPHERSON:
DIFFERENCES BETWEEN PUBLISHED (1989) AND REVISED
MONTHLY FLOWS

	May	June	July	August	Sept	October	Total	Percent
1972				1	1		2	0
1973		6	7	6	2		21	4
1974		1	6	3	3		13	3
1975		2	2	1	2	1	8	2
1976							0	0
1977							0	0
1978							0	0
1979							0	0
1980		9	9	7	8		33	7
1981	1	10	6	6	12	8	43	9
1982		12	14	14	4	2	46	9
1983		21	9	5		2	37	7
1984	2	29	24	6	3	3	67	13
1985		14	19	10	5	5	53	11
1986		12	15	13	7	2	49	10
1987		20	9	15	4	1	49	10
1988	4	30	28	11	4	3	80	16
1989				1			1	0
Total	7	166	148	99	55	27	502	

TABLE 3.3

MACKENZIE RIVER UPSTREAM OF ARCTIC RED RIVER:
NUMBER OF DAYS SAMPLED FOR SUSPENDED SEDIMENT

	May	June	July	August	Sept	October	Total	Percent
1972		1	2	2	2		7	13
1973		7	8	7	3		25	45
1974			6	4	4		14	25
1975		3	3		3	1	10	18
Total	0	11	19	13	12	1	56	
Percent	0	20	34	23	21	2		
PSA		6	4	4	1		15	

PSA denotes particle size analysis

TABLE 3.4

ARCTIC RED RIVER NEAR THE MOUTH:
NUMBER OF DAYS SAMPLED FOR SUSPENDED SEDIMENT AT SV SITE

	May	June	July	August	Sept	October	Total	Percent
1972			1		1		2	3
1973			13	5			18	23
1974		2	3	4	2		11	14
1975		12	11		1		24	31
1976		1	9	8	4		22	29
Total							77	
Percent	0	19	48	22	10	0		
1988	14	21	15	14	15	4	83	
1989	13	20	5	10	7	1	56	
1990	3	16	7	10	13		49	
Total							188	
Percent	16	30	14	18	19	3		

TABLE 3.5

PEEL RIVER UPSTREAM OF FORT MCPHERSON:
NUMBER OF DAYS SAMPLED FOR SUSPENDED SEDIMENT AT SV SITE

	May	June	July	August	Sept	October	Total	Percent
1972		1	3	1	1		6	2
1973	10	18	15	13	6	3	67	17
1974	6	15	9	8	4		42	11
1975			1	3	5		9	2
1976	2	13	7	6	4	1	33	8
1977							0	0
1978							0	0
1979		18	10	9	4	2	43	11
1980	5	7	5	5	5	3	30	8
1981	3	5	4	1	1	1	15	4
1982	2	6	5	3	3	1	20	5
1983	6	7	8	4	3	1	29	7
1984	8	8	6	5	4	1	36	9
1985	5	5	5	2	2	2	21	5
1986	5	4	3	1	2	4	20	5
1987	1	3	4	4			12	3
1988	2	4	1	3	1	2	13	3
Total							396	
Percent	14	29	22	17	11	5		

Annual totals include days in April and November

TABLE 3.6

LIARD RIVER NEAR THE MOUTH:
NUMBER OF DAYS SAMPLED FOR SUSPENDED SEDIMENT

1974	159
1975	149
1976	109
1977	111
1978	63
1979	107
1980	34
1981	59
1982	80
1983	85
1984	69
1985	117
1986	125
1987	61
1988	155
1989	89
1990	90
Mean	97.8
St.devn	34.9

Jan	0.1
Feb	0.1
Mar	0.1
Apr	0.1
May	17.1
Jun	35.2
Jul	23.2
Aug	15.6
Sep	4.0
Oct	1.9
Nov	0.3
Dec	0.1
Total	97.8

sediment loads in million tonnes (Mt)

TABLE 4.1

MACKENZIE RIVER AT ARCTIC RED RIVER:

ANNUAL AND MEAN MONTHLY SUSPENDED LOADS

	WSC (1)	predicted (2)	error (2)-(1)	% error
81 JUN	19.5	30.0	10.5	35
81 SEP	1.5	1.2	-0.3	-21
82 JUL	7.1	9.4	2.3	25
82 AUG	14.0	11.3	-2.7	-24
84 JUN	35.2	19.1	-16.1	-84
84 JUL	23.1	22.9	-0.2	-1
85 JUL	21.9	25.9	4.0	15
85 AUG	6.5	13.8	7.3	53
86 JUL	31.0	30.6	-0.4	-1
86 AUG	21.7	18.9	-2.8	-15
87 JUN	18.2	21.0	2.8	13
87 AUG	19.7	12.5	-7.2	-57
88 JUN	27.3	33.8	6.5	19
88 JUL	73.1	71.5	-1.6	-2
88 AUG	9.1	22.5	13.4	59
		Mean	1.0	1
		Stn devn	6.9	35

all loads in million tonnes (Mt)

TABLE 4.2

MACKENZIE RIVER AT ARCTIC RED RIVER:

ERROR IN PREDICTED MONTHLY SUSPENDED LOADS

1974	13880
1975	11320
1976	2670
1977	2070
1978	6010
1979	4340
1980	4830
1981	4470
1982	8600
1983	3470
1984	6420
1985	2220
1986	5600
1987	11220
1988	3350
1989	3180
1990	16300
Mean	6468
Std.devn	4171

Jan	0
Feb	0
Mar	0
Apr	0
May	2390
Jun	2550
Jul	490
Aug	1330
Sep	170
Oct	10
Nov	0
Dec	0
Total	6940

sediment loads in thousand tonnes (kt)

The following years are underestimates because of missing data:
1974 (June and July); 1975 (August), 1976 (May) and
1980 (August)

TABLE 4.3

ARCTIC RED RIVER NEAR MARTIN HOUSE

ANNUAL AND MEAN MONTHLY SUSPENDED LOADS

	unrevised flow	revised flow
1988 uncorrected rating	25.7	13.6
1988 bias-adjusted rating	29.0	15.3
MV uncorrected rating	21.3	15.7
MV bias-adjusted rating	24.6	18.1
Equation 4.11		26.3
Eqn 4.11 with daily correction factors		23.7

all loads in million tonnes (Mt)

TABLE 4.4

PEEL RIVER ABOVE FORT MCPHERSON:

COMPARISON OF MEAN ANNUAL SUSPENDED LOADS FOR 1975-80/1982-83 USING DIFFERENT SEDIMENT RATINGS AND DIFFERENT FLOW DATA

	1988 rating	WSC	Eqn 4.11	Eqn 4.11 with daily factor
May 16-31	4.98	3.88	8.58	5.85
June	2.57	2.91	4.87	4.23
July	0.42	0.48	0.93	0.98
August	0.26	0.26	0.60	0.56
Sept.	0.42	0.72	0.91	1.18
avg error	0.08		1.53	0.91
std dev	0.53		1.71	0.64

error refers to predicted load minus WSC load
avg and std dev refer to errors

all loads in million tonnes (Mt)

TABLE 4.5

PEEL RIVER UPSTREAM OF FORT MCPHERSON:

COMPARISON OF PREDICTED MONTHLY SUSPENDED LOADS WITH WSC COMPUTED LOADS IN 1988

	Equation 4.11	
	with daily	without adjustment
January	0.0	0.0
February	0.0	0.0
March	0.0	0.0
April	0.0	0.0
May	9.5	7.5
June	9.6	9.0
July	1.6	2.1
August	1.1	1.3
Sept	0.4	0.5
October	0.1	0.0
November	0.0	0.0
December	0.0	0.0
Total	22.3	20.4

Sediment loads in Mt

TABLE 4.6

PEEL RIVER UPSTREAM OF FORT MCPHERSON:

MEAN MONTHLY SUSPENDED LOADS, 1975-86/1988-90

1974	54
1975	43
1976	69
1977	82
1978	12
1979	58
1980	17
1981	42
1982	42
1983	16
1984	34
1985	37
1986	46
1987	44
1988	118
1989	39
1990	50
Mean	47.2
St.devn	24.8

Jan	0.0
Feb	0.0
Mar	0.0
Apr	0.0
May	11.6
Jun	17.7
Jul	13.3
Aug	3.2
Sep	1.0
Oct	0.3
Nov	0.0
Dec	0.0
Total	47.1

sediment loads in million tonnes (Mt)

TABLE 4.7

LIARD RIVER NEAR THE MOUTH:

ANNUAL AND MEAN MONTHLY SUSPENDED LOADS

	WSC (1)	predicted (2)	error (2)-(1)	% error
73 MAY	7.02	9.76	2.74	28
73 JUN	29.19	33.23	4.04	12
73 JUL	5.22	7.60	2.38	31
73 AUG	1.01	1.13	0.12	11
74 JUN	11.20	12.49	1.29	10
76 JUN	20.16	18.58	-1.58	-9
79 JUN	16.46	22.07	5.61	25
79 JUL	27.43	23.33	-4.10	-18
			Mean	11
			Standard deviation	16

all loads in million tonnes (Mt)

TABLE 4.8

LIARD RIVER NEAR THE MOUTH:

ERROR IN PREDICTED MONTHLY SUSPENDED LOADS

	Mackenzie	Arctic Red	Peel	Liard
May	510	2770	1620	980
June	650	1825	1375	940
July	485	580	640	820
August	415	1480	460	315
Sept	140	320	240	145
October	75	50	50	60
Annual	340	1390	920	610

all data in mg/L

TABLE 4.9

MEAN MONTHLY SUSPENDED SEDIMENT CONCENTRATIONS:
LOAD/FLOW RATIOS

	basin area thous.sq.km.	% of delta-head input area	suspended load Mt	% of delta-head input load	yield t/km2/yr	load/flow mg/L
Liard ED2	277	35.5	47.2	37.3	170	610
Mackenzie LC14*	689	88.2	97.8	77.3	142	635
Arctic Red at mouth	21	2.7	6.5	5.1	305	1390
Peel MC2	71	9.1	22.3	17.6	315	1026
Delta-head**	781		126.6		162	

* basin area taken as downstream of Great Slave Lake

** sum of Mackenzie, Arctic Red and Peel

TABLE 4.10

SUMMARY OF 1974-90 SUSPENDED SEDIMENT LOADS AS PERCENTAGE OF DELTA-HEAD SEDIMENT INPUT

	mg/L	Mt
May	27	0.6
June	20	0.4
July	20	0.4
August	17	0.3
Sept	19	0.3
October	18	0.3

TABLE 5.1

MACKENZIE RIVER ABOVE LIARD RIVER (10GC004):

1972-75 MEAN MONTHLY SUSPENDED SEDIMENT CONCENTRATIONS AND LOADS

	suspended load (thousand tonnes)			Lower basin as %10GC004
1973	Trout	Lower Basin	10GC004	
May	2.4	16.0	626	2.6
June	3.4	22.7	391	5.8
July	3.4	22.7	352	6.4
Aug	0.3	2.0	402	0.5
1974				
May	14.7	98.0		
June	5.5	36.7	398	9.2
July	1.9	12.7	471	2.7
Aug	1.9	12.7	273	4.7
Sept	1.2	8.0	238	3.4

"Lower basin" refers to basin of 10GC004
downstream of Great Slave Lake
and is taken as 62,000 km2

TABLE 5.2

ESTIMATES OF 10GC004 SUSPENDED LOAD FROM BASIN DOWNSTREAM OF GREAT SLAVE LAKE, 1973-1974

		load (tonnes)			concentration (mg/L)		
		Harris	Martin	Willow-lake	Harris	Martin	Willow-lake
1973	May	198	8750	84100	19	135	76
	June	26	5610	6250	10	120	25
	July	25	1140	3790	12	46	26
	August	2	195	4820	7	19	23
	Sept	0	61	2350	0	13	19
	October	0	4		0	3	
1974	May	896	16700		35	170	
	June	122	2250		12	45	
	July	45	298		16	20	
	August	5	1220		4	53	
	Sept	14	94		9	9	
	October	19			12		
1975	May						
	June		485			23	
	July		190			13	
	August		2220			57	
	Sept		282			10	
	October		50			6	

TABLE 5.3

MONTHLY SUSPENDED SEDIMENT DATA 1973-75 FOR

HARRIS (10GC002), MARTIN (10GC003) AND WILLOWLAKE (10GB001)

List of Figures

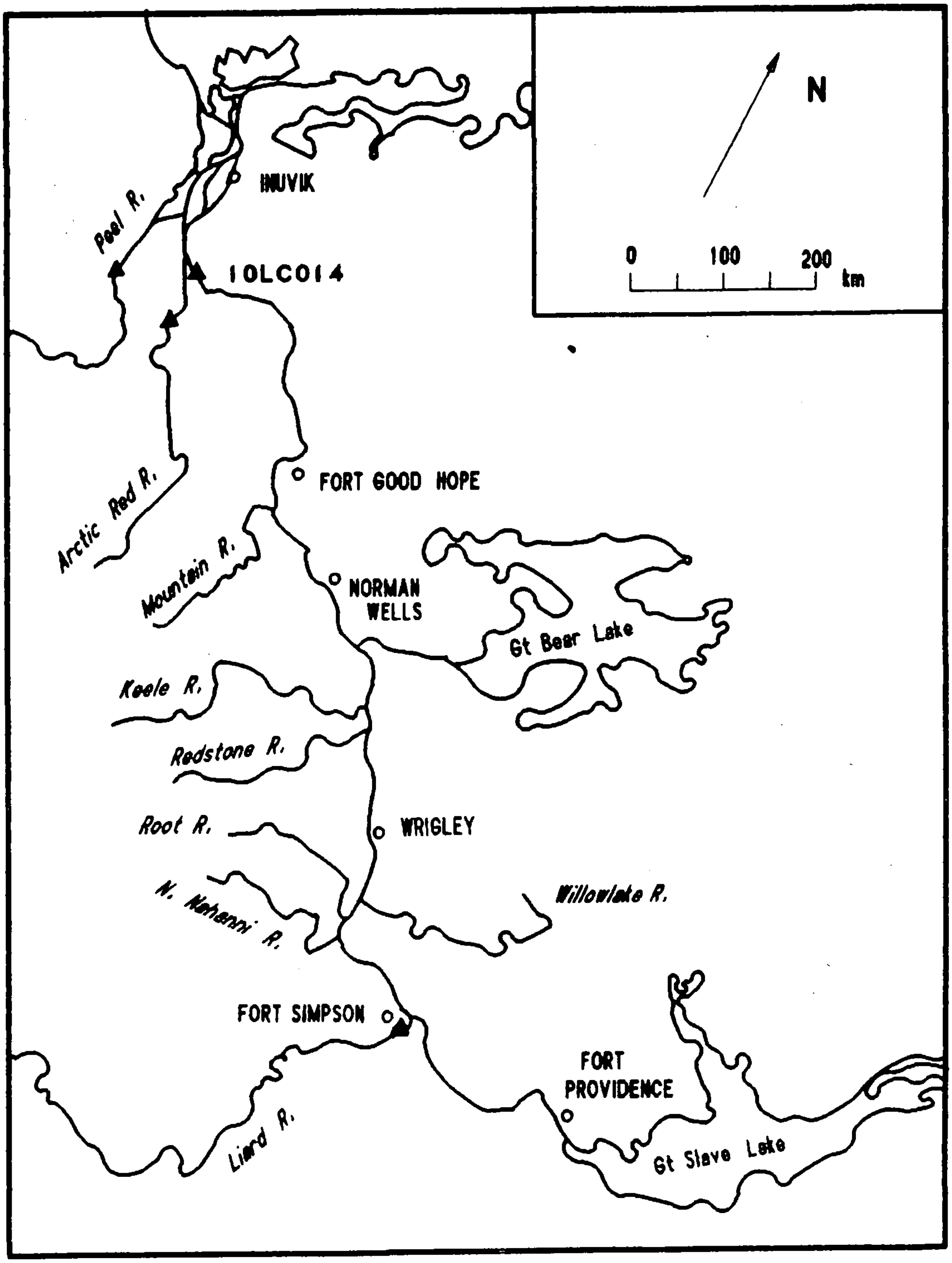
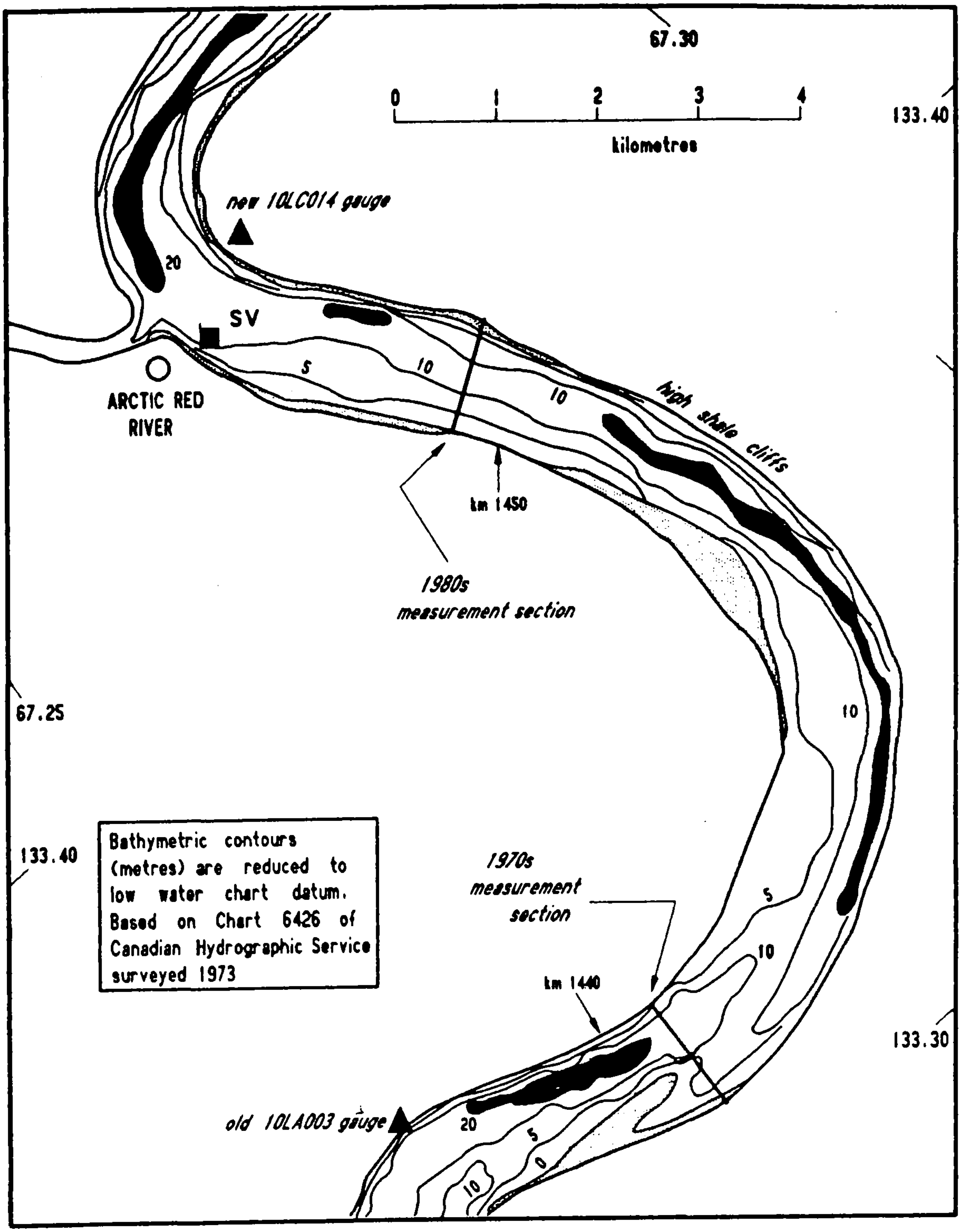


FIGURE 2.1

THE MACKENZIE RIVER DRAINAGE NETWORK



Bathymetric contours (metres) are reduced to low water chart datum. Based on Chart 6426 of Canadian Hydrographic Service surveyed 1973

FIGURE 2.2 MACKENZIE RIVER AT THE LOWER RAMPARTS

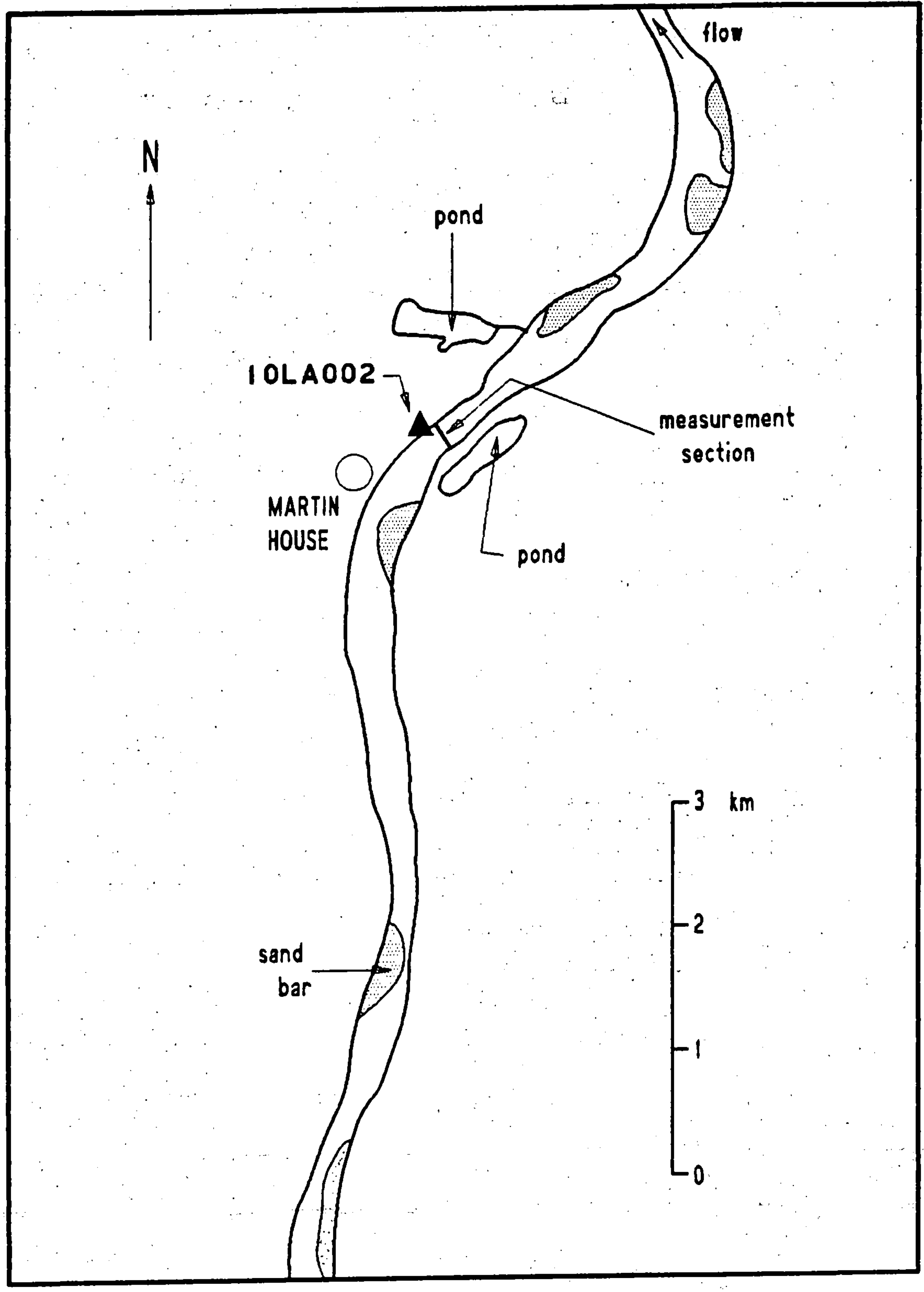


FIGURE 2.3

ARCTIC RED RIVER NEAR MARTIN HOUSE
LOCATION OF MEASUREMENT SECTION

(from Chart 6440, Canadian Hydrographic Service)

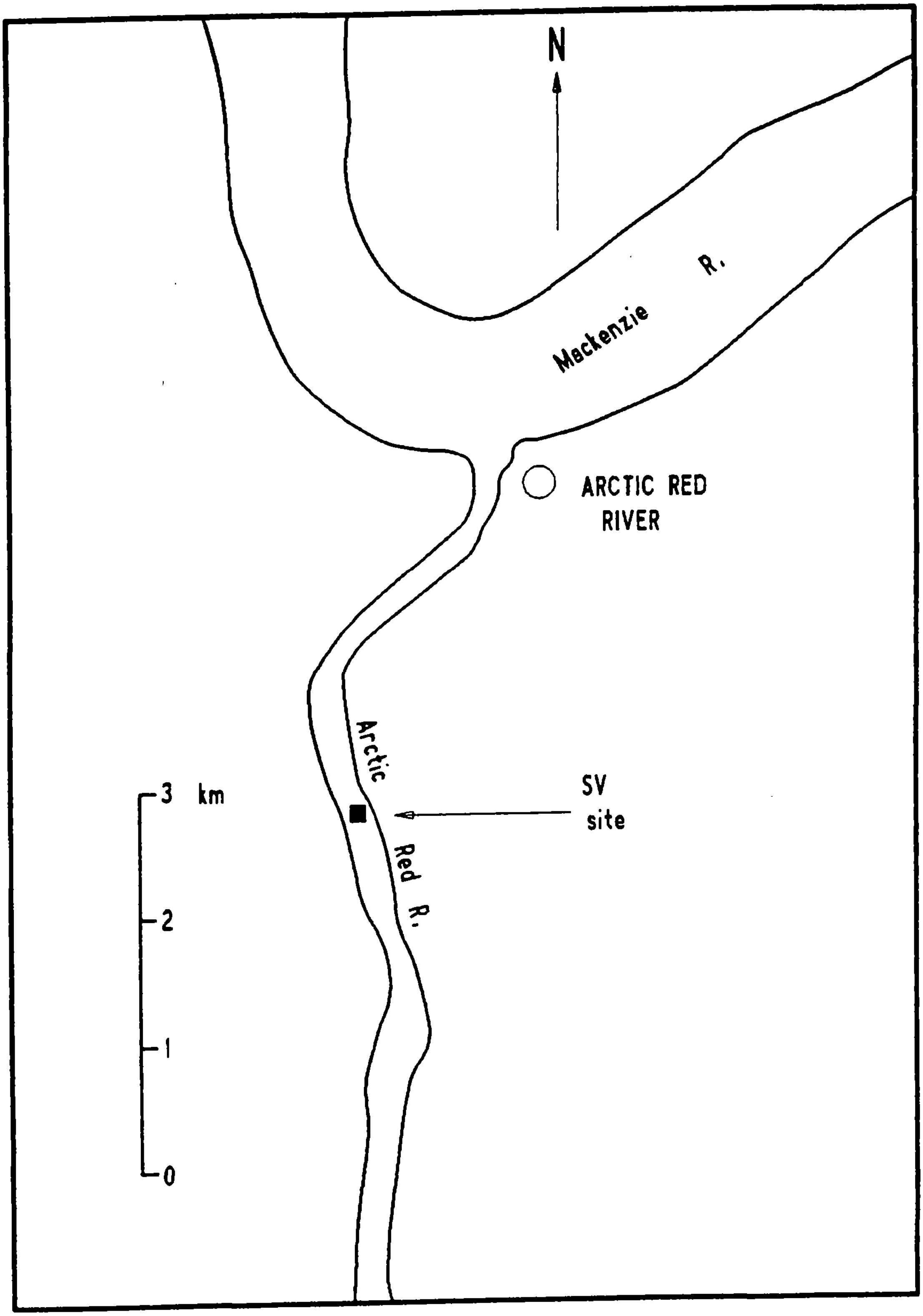


FIGURE 2.4

ARCTIC RED RIVER NEAR THE MOUTH
LOCATION OF SV SITE

(from Chart 6426, Canadian Hydrographic Service)

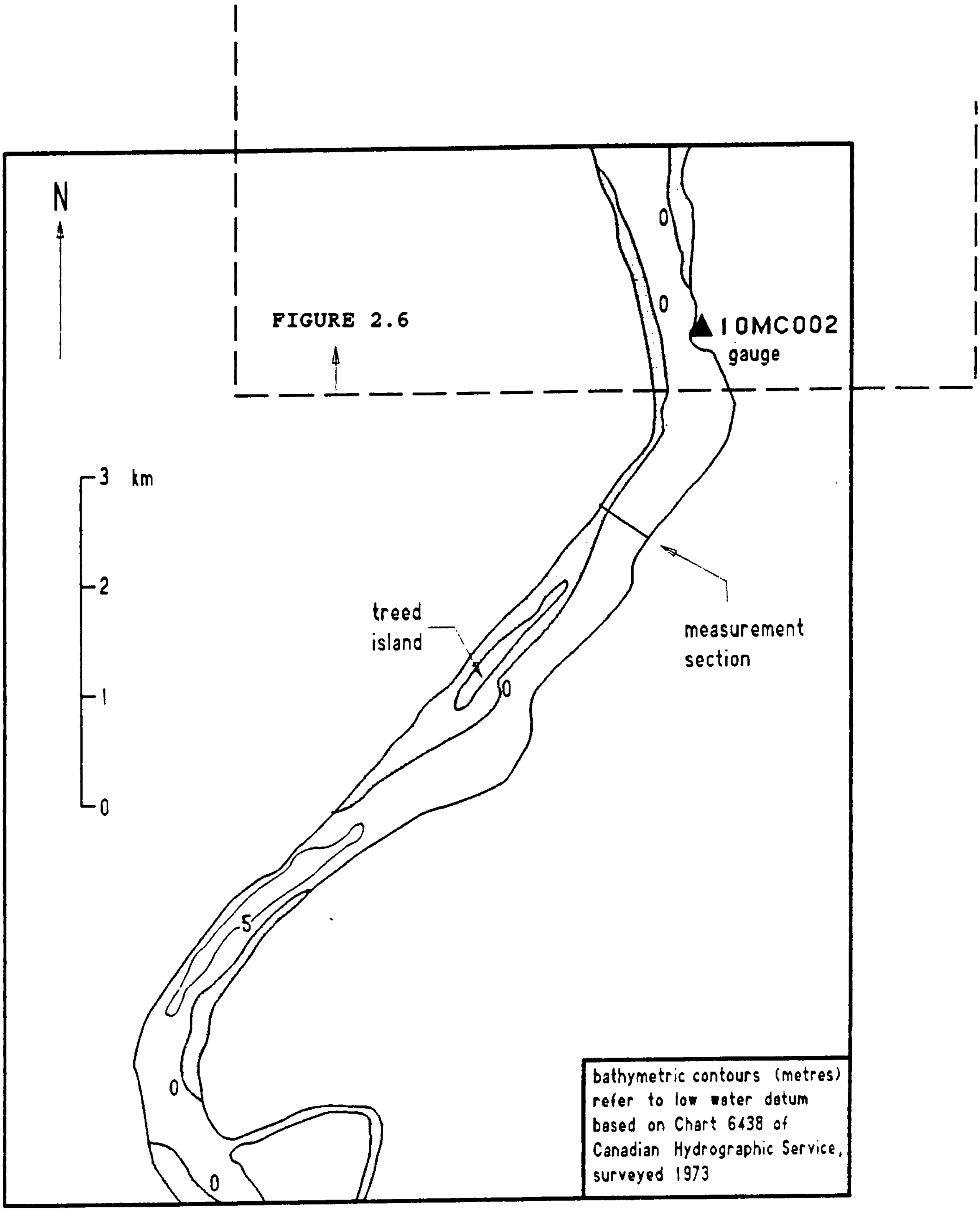
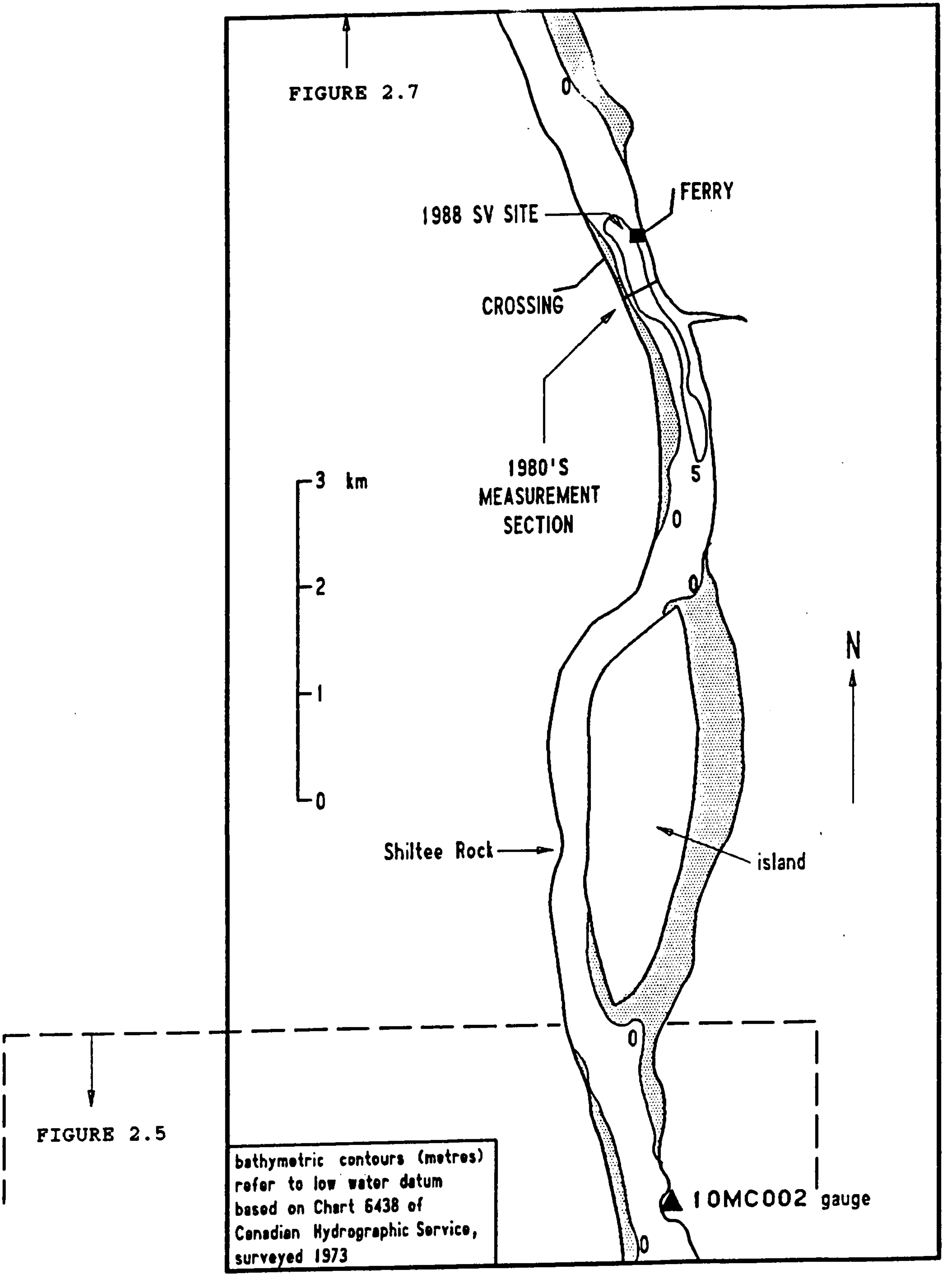


FIGURE 2.5

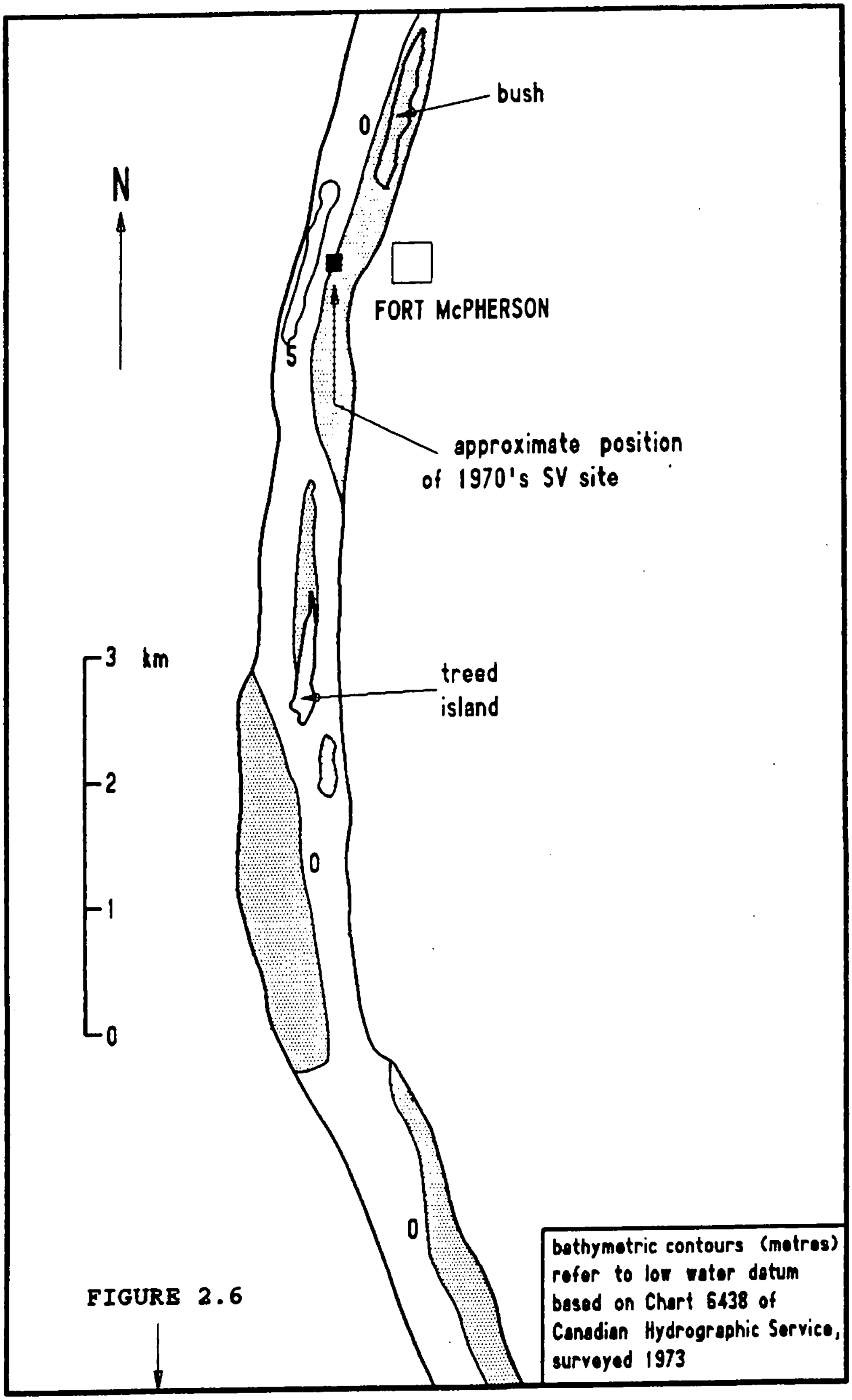
PEEL RIVER ABOVE FORT McPHERSON:
1970'S MEASUREMENT SECTION



bathymetric contours (metres) refer to low water datum based on Chart 6438 of Canadian Hydrographic Service, surveyed 1973

FIGURE 2.6

PEEL RIVER ABOVE FORT McPHERSON:
1988 SEDIMENT SAMPLING SITES



bathymetric contours (metres) refer to low water datum based on Chart 6438 of Canadian Hydrographic Service, surveyed 1973

FIGURE 2.7

PEEL RIVER AT FORT McPHERSON
1970's SV SAMPLING SITE

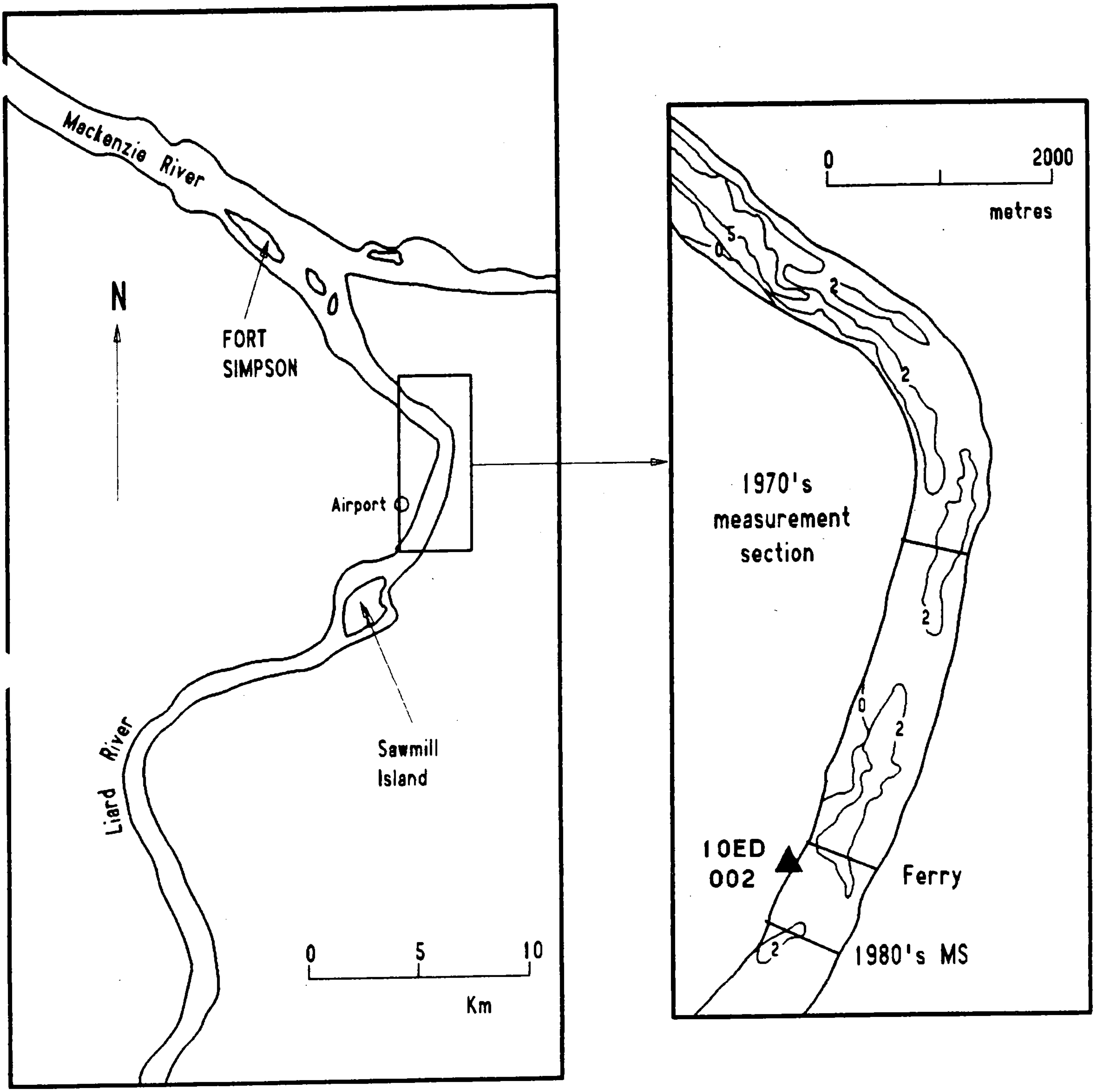


FIGURE 2.8

The Liard Sampling Reach : 10ED002

bathymetric contours are in metres, relative to low water datum, and based on a 1973 survey by the Canadian Hydrographic Service

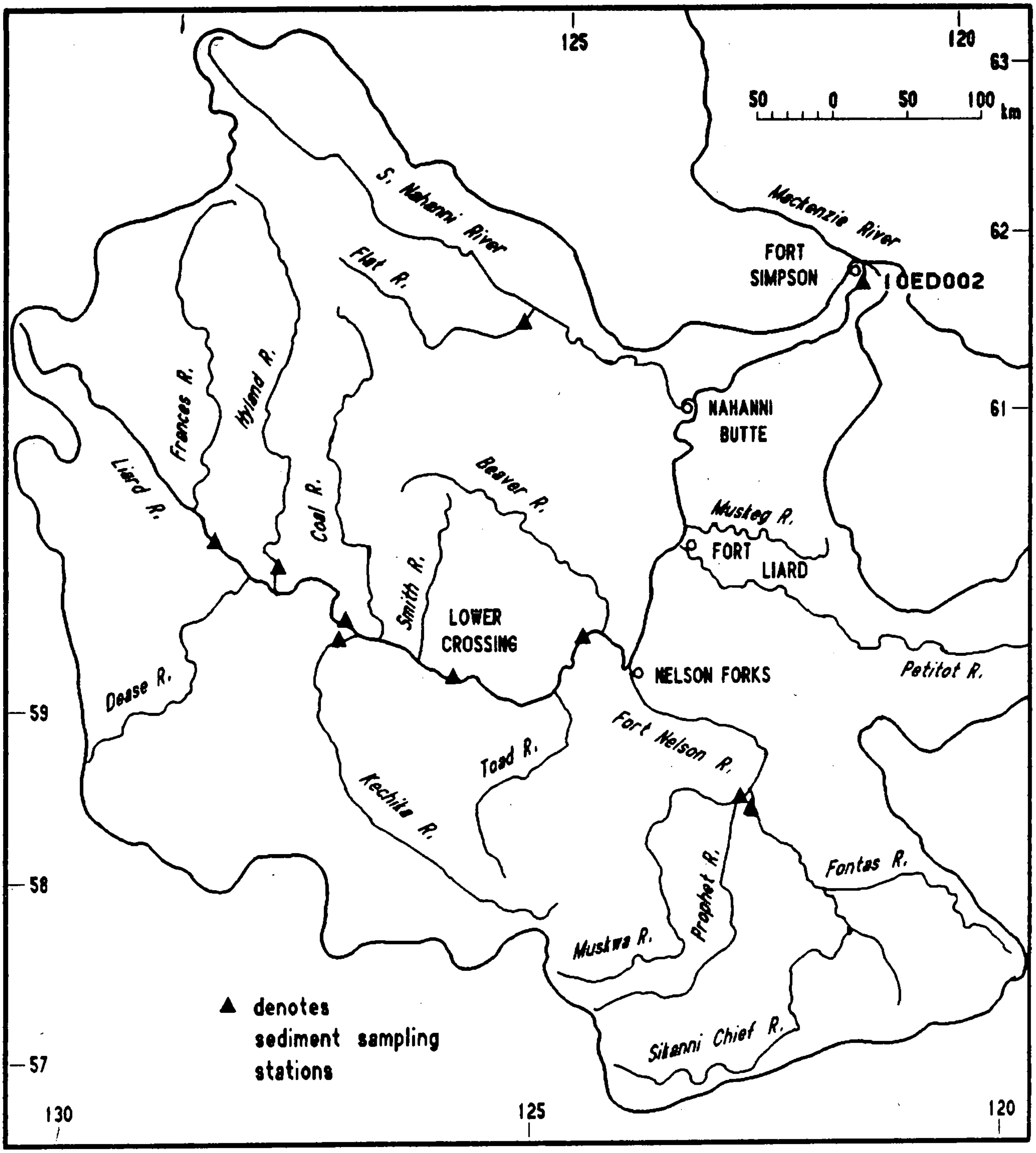


FIGURE 2.9

THE LIARD RIVER DRAINAGE NETWORK

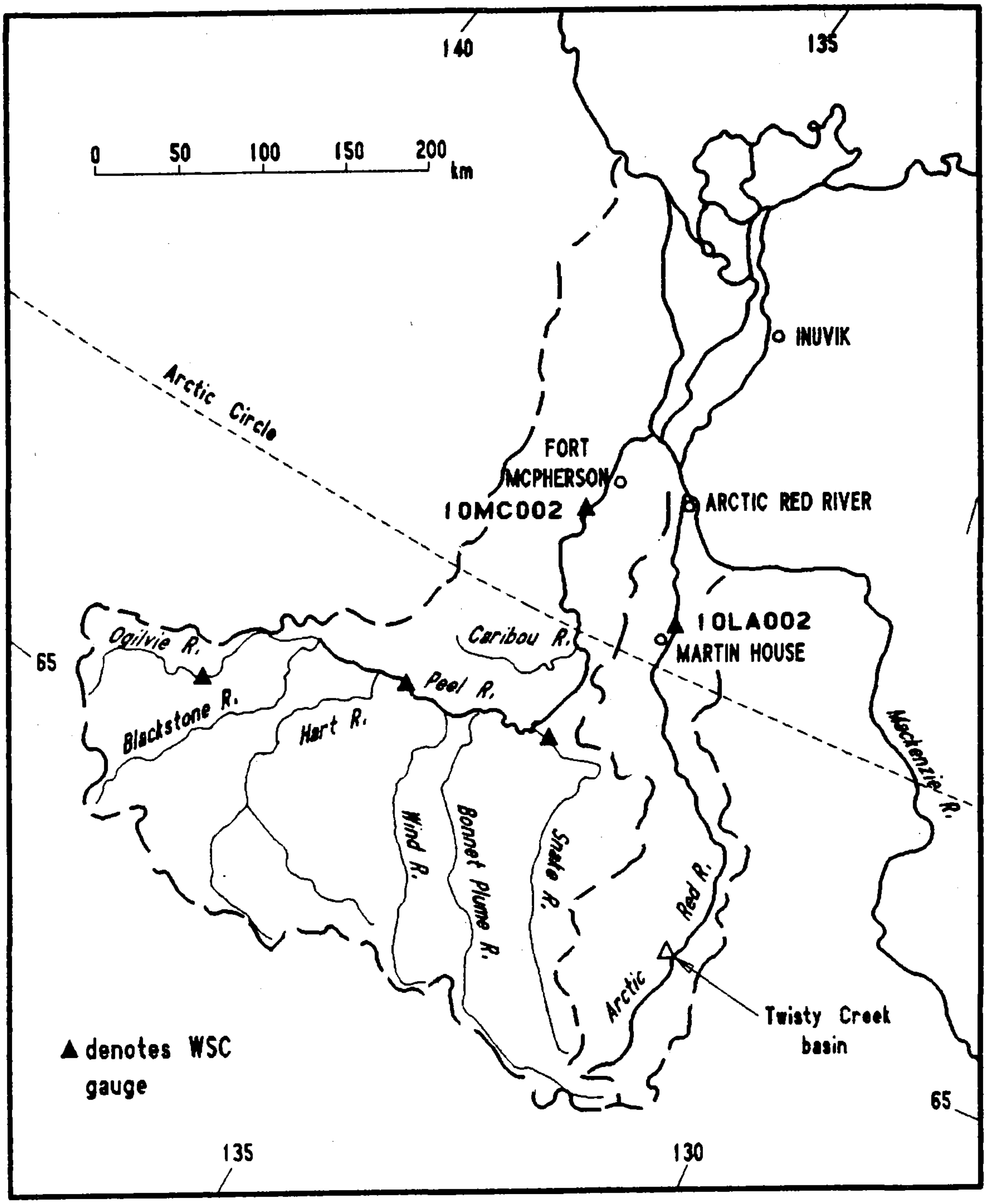


FIGURE 2.10
THE PEEL RIVER AND ARCTIC RED RIVER DRAINAGE BASINS

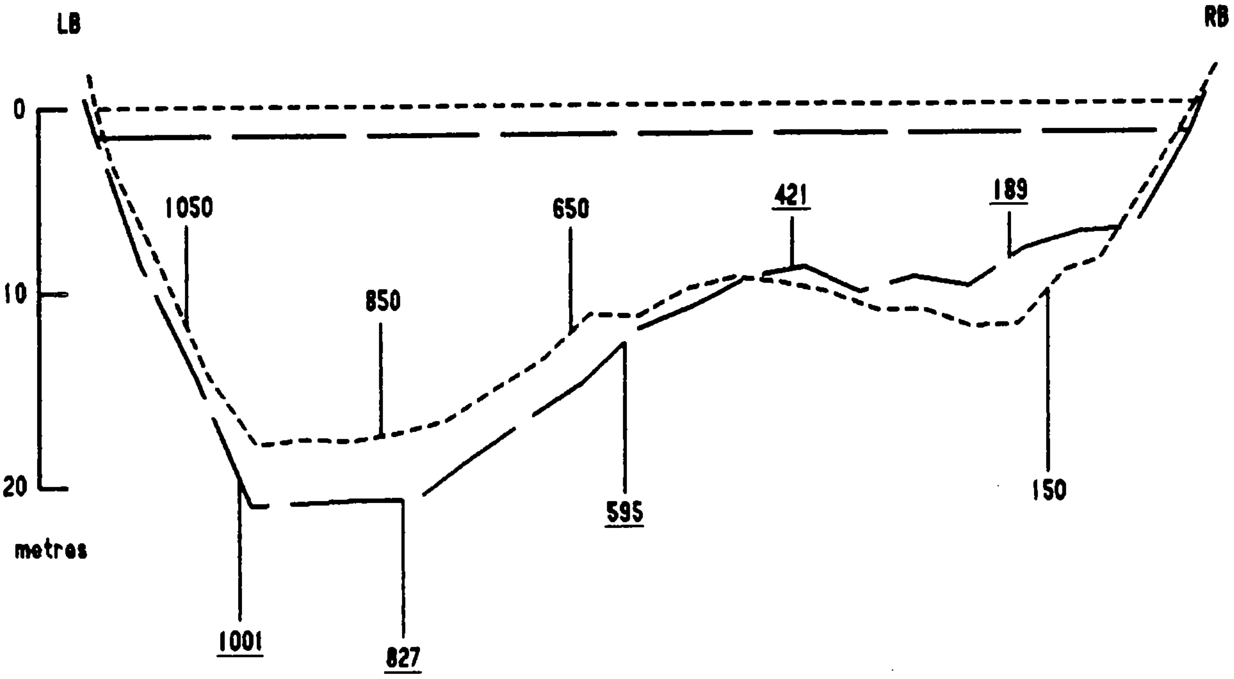


FIGURE 3.1

MACKENZIE RIVER UPSTREAM OF ARCTIC RED RIVER
CHANNEL GEOMETRY AT 1970's MEASUREMENT SECTION
short dash : 1972 July 13 Discharge = 17,260 m^3/s
long dash : 1974 Sept.24 Discharge = 11,600 m^3/s

Data taken from Hydrometric Survey Notes
Bed material taken on verticals shown (1974 underlined)

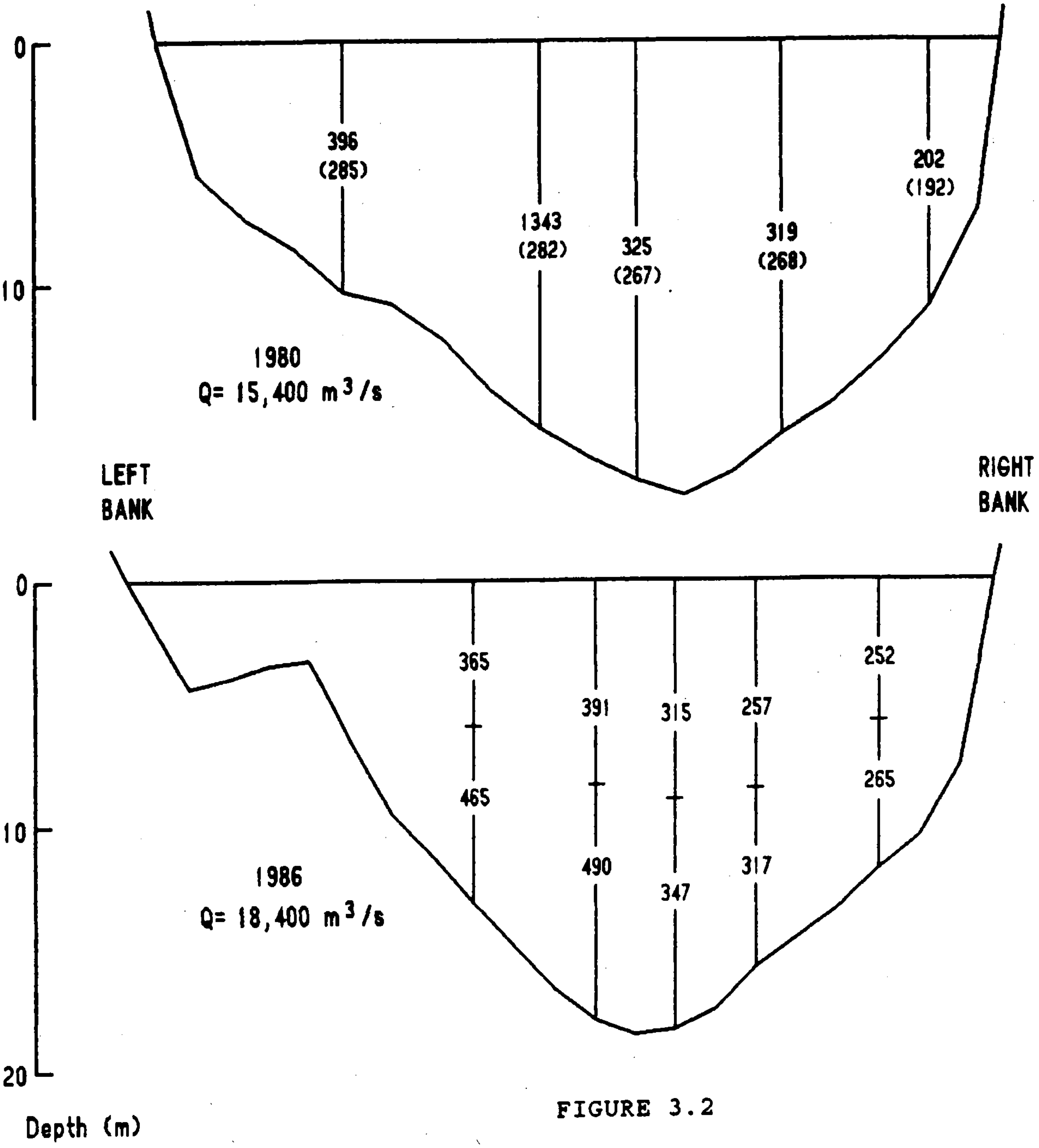


FIGURE 3.2

MACKENZIE RIVER UPSTREAM OF ARCTIC RED
1980'S MEASUREMENT SECTION
1980 June 12 and 1986 August 11

lines denote sampling verticals
with concentrations in mg/L
(parentheses refer to silt-clay only)

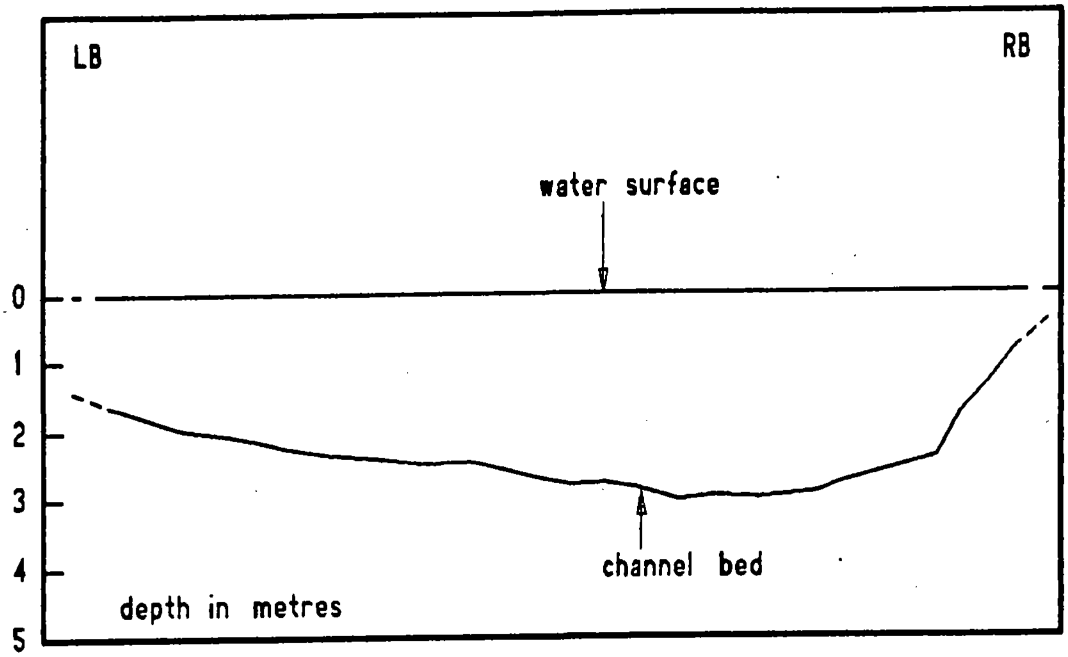
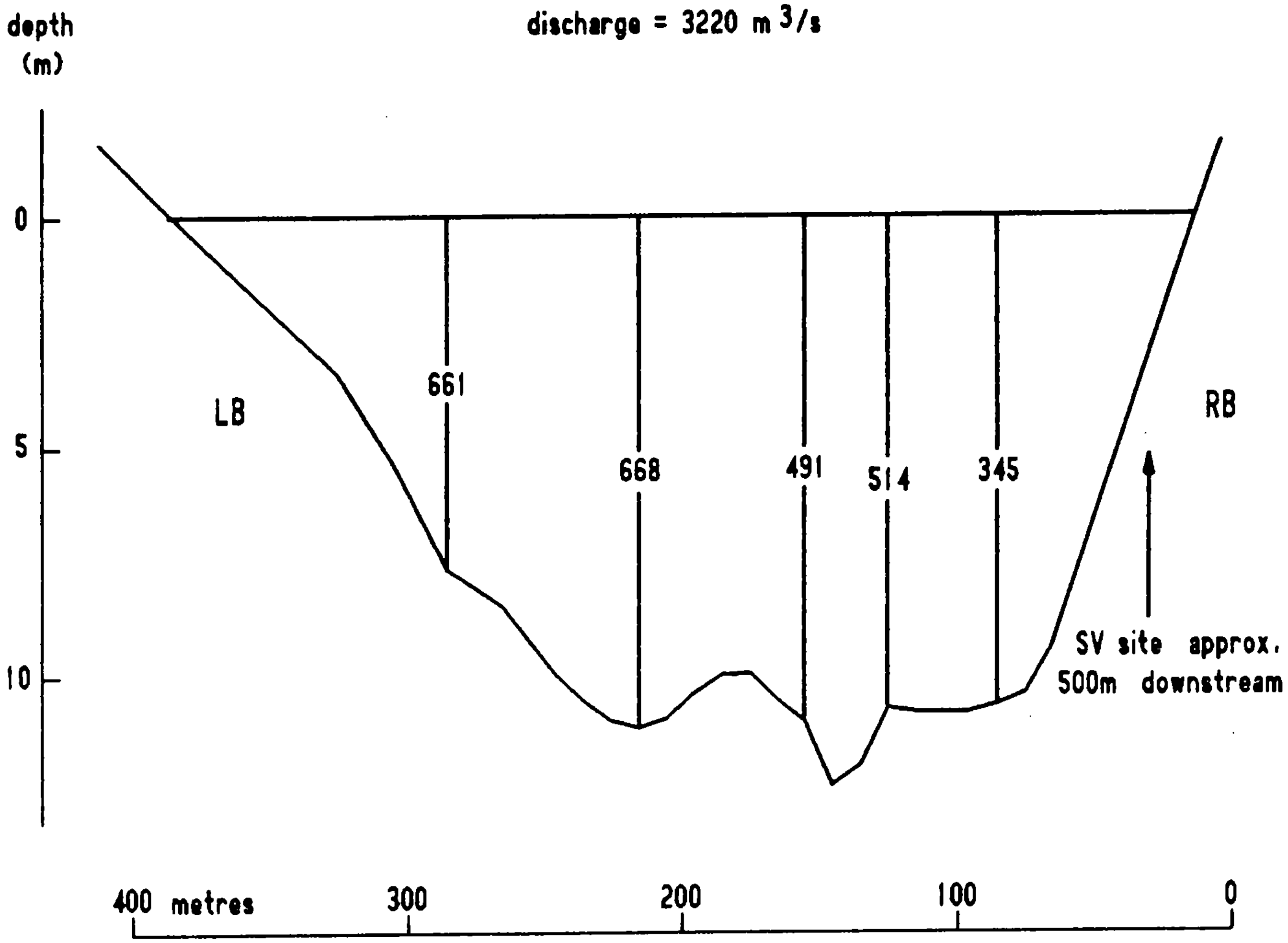


FIGURE 3.3

CROSS SECTION USED FOR SV SAMPLING
ARCTIC RED RIVER, NEAR THE MOUTH

surveyed by echo sounder, 1988 August 26
width approximately 200 metres



sediment concentrations in mg/l
SV concentration = 408 mg/l

FIGURE 3.4
PEEL RIVER AT 1980'S MEASUREMENT SECTION:
JUNE 2, 1988

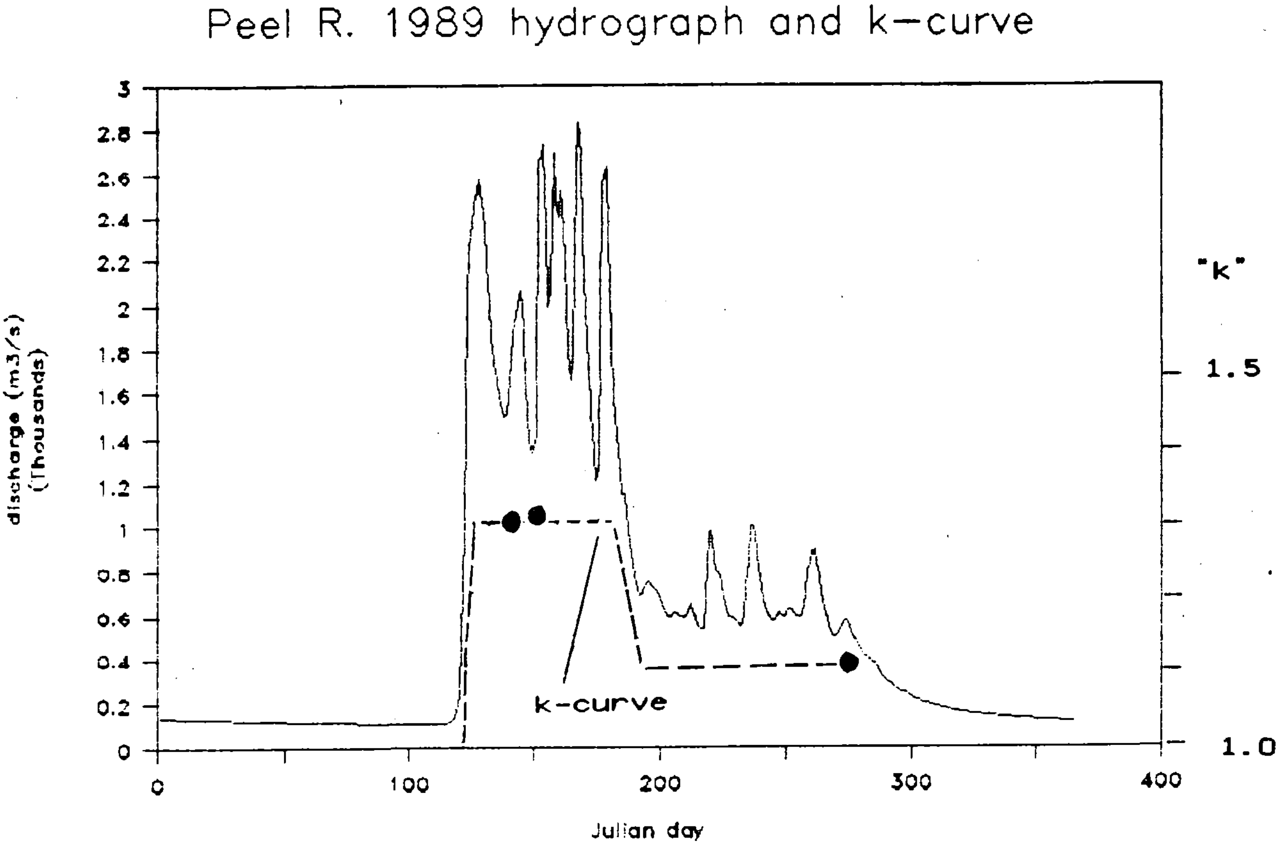
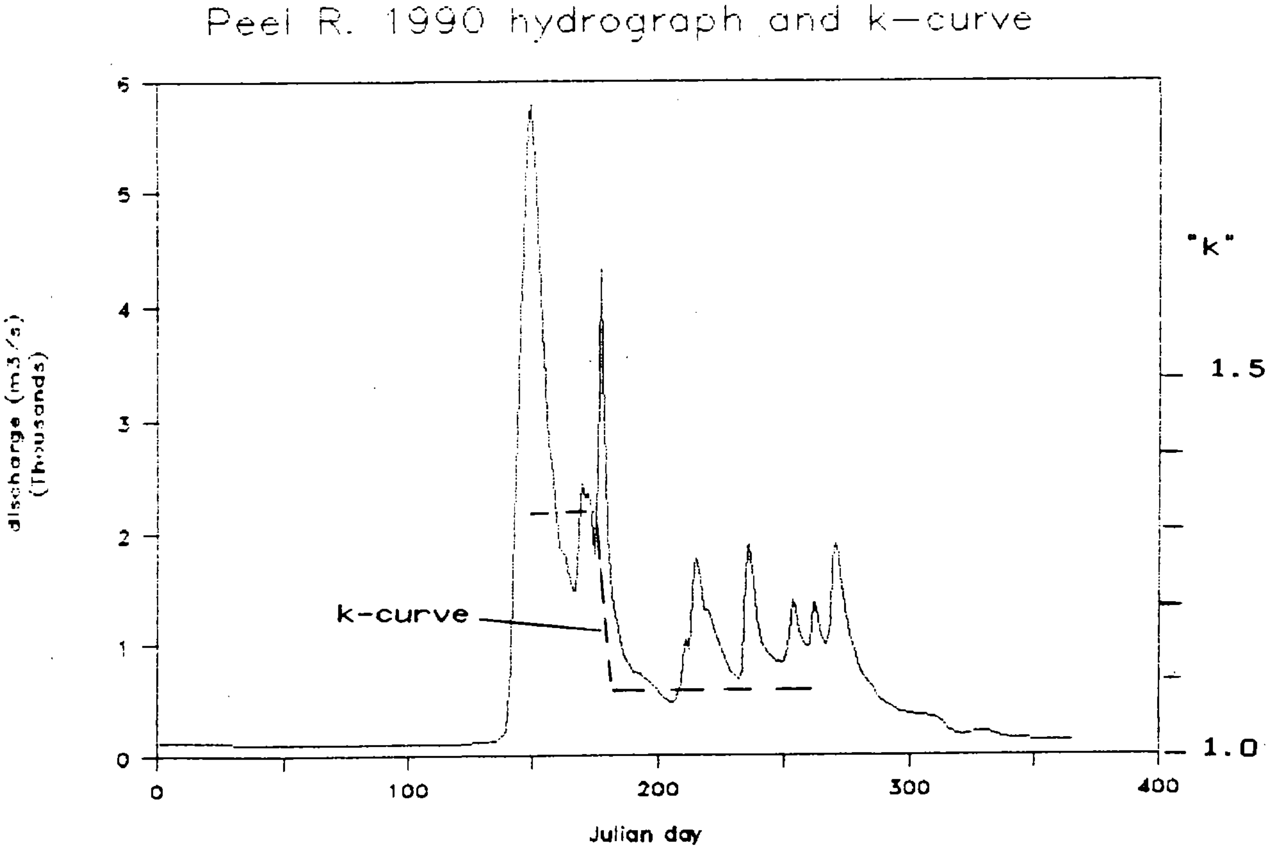
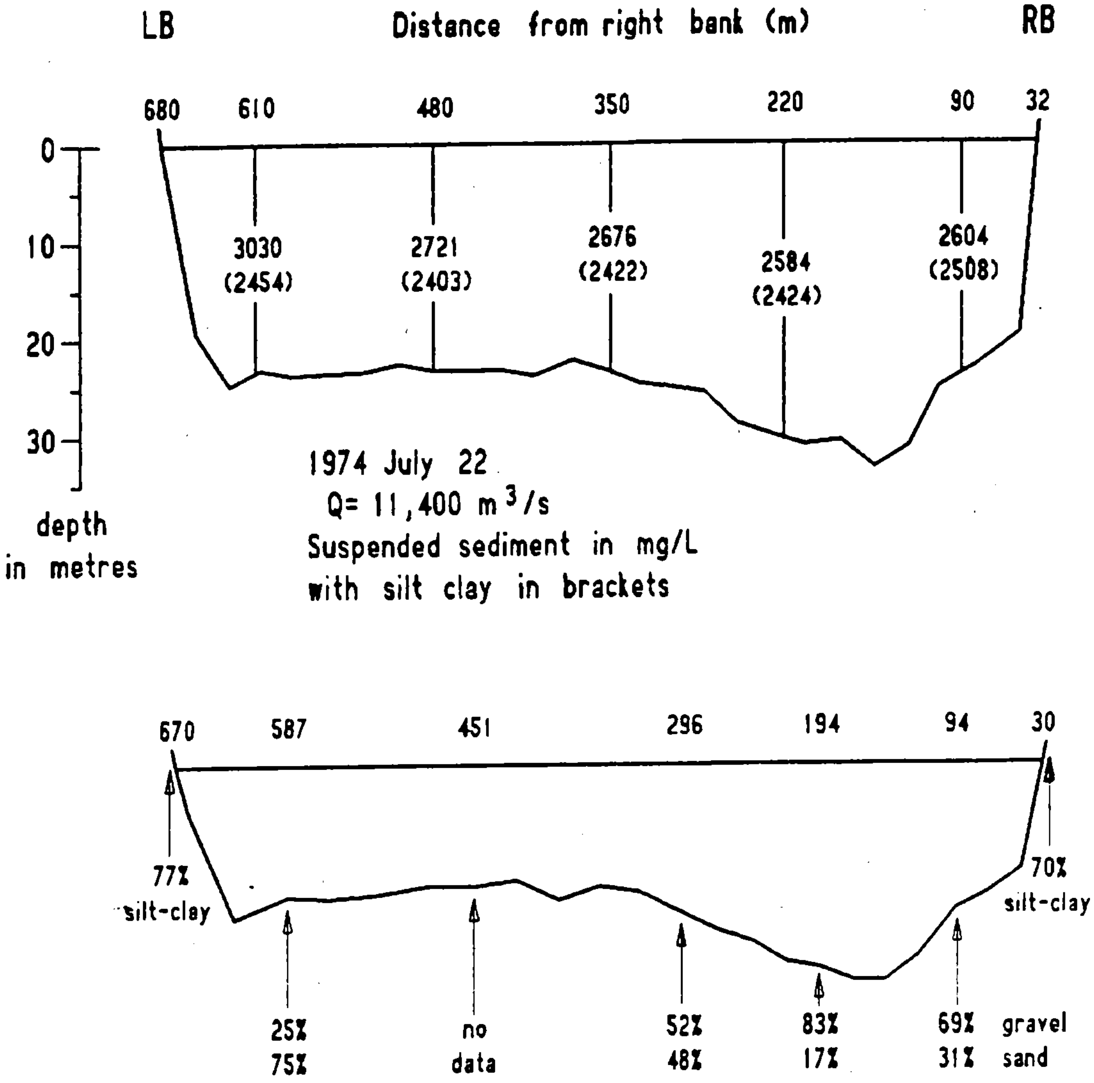

Peel R. 1989 hydrograph and k-curve
discharge (m3/s)
(Thousands)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
Julian day
k-curve
"k"
1.5
1.0

FIGURE 3.5


Peel R. 1990 hydrograph and k-curve
discharge (m3/s)
(Thousands)
6
5
4
3
2
1
0
0
100
200
300
400
Julian day
k-curve
"k"
1.5
1.0



Channel sediment : 1974 August 28

FIGURE 3.6

LIARD RIVER AT CN POWER LINE SHOWING SEDIMENT DISTRIBUTION

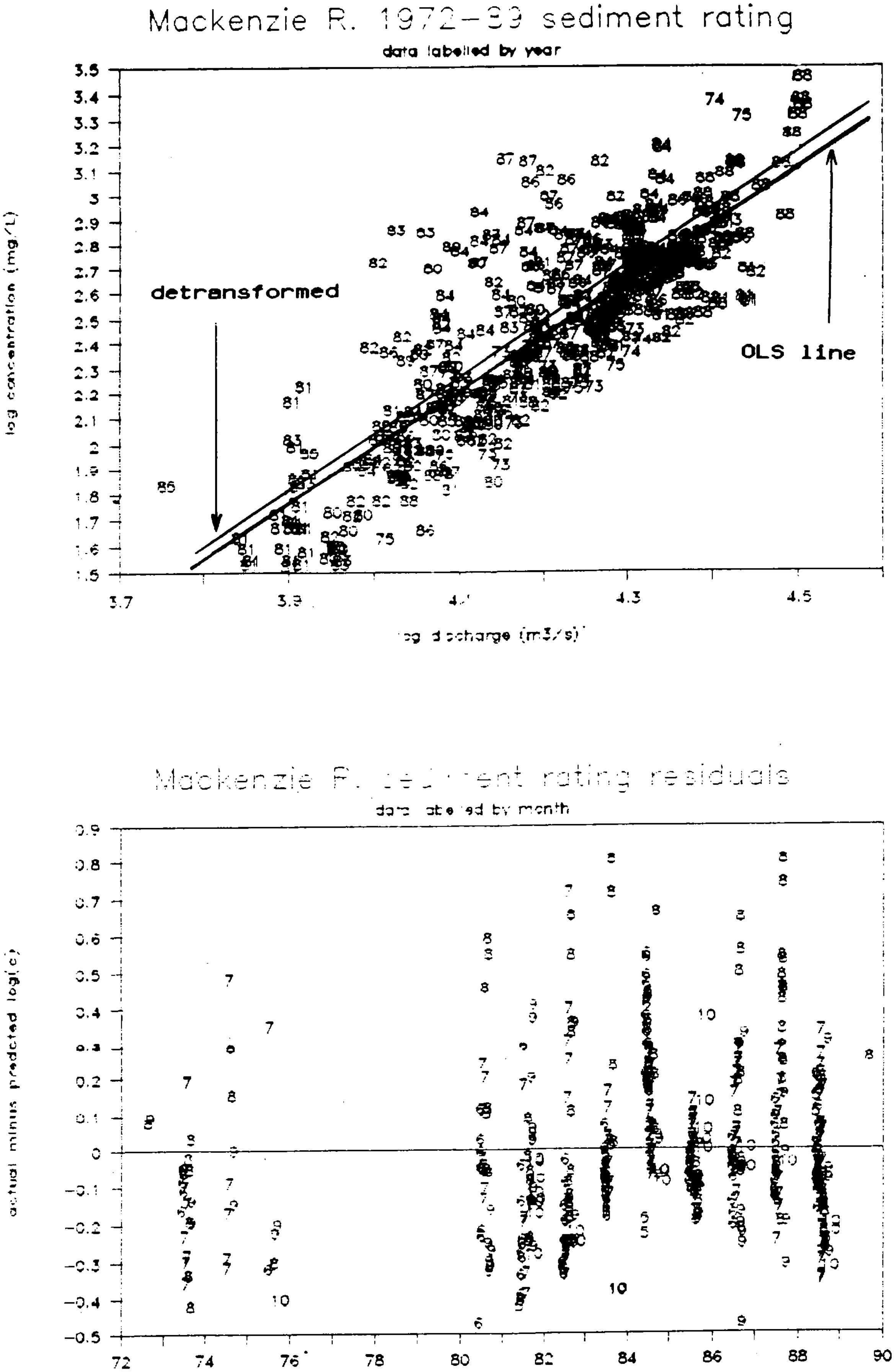

Mackenzie R. 1972-89 sediment rating
data labelled by year
log concentration (mg/L)
log discharge (m3/s)
detransformed
OLS line
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
3.7
3.9
4.1
4.3
4.5
Mackenzie R. sediment rating residuals
data labelled by month
actual minus predicted log(c)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
72
74
76
78
80
82
84
86
88
90

FIGURE 4.1

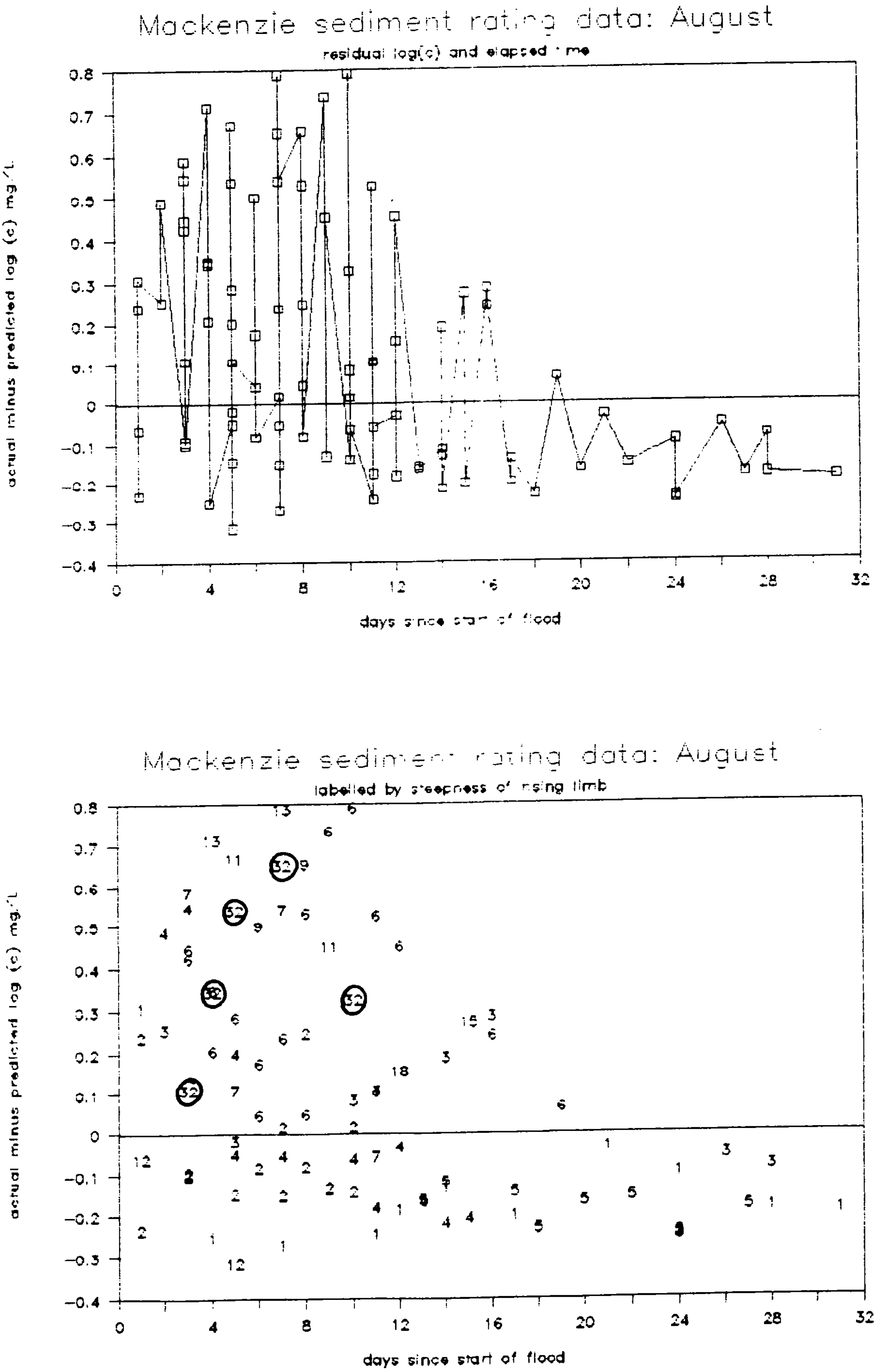

Mackenzie sediment rating data: August
residual log(c) and elapsed time
actual minus predicted log (c) mg/L
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
0
4
8
12
16
20
24
28
32
days since start of flood
Mackenzie sediment rating data: August
labelled by steepness of rising limb
actual minus predicted log (c) mg/L
days since start of flood

FIGURE 4.2

FIGURE 26
SEDIMENT RATING CURVE : 10LA002
Arctic Red River at Martin House , 1972–1975

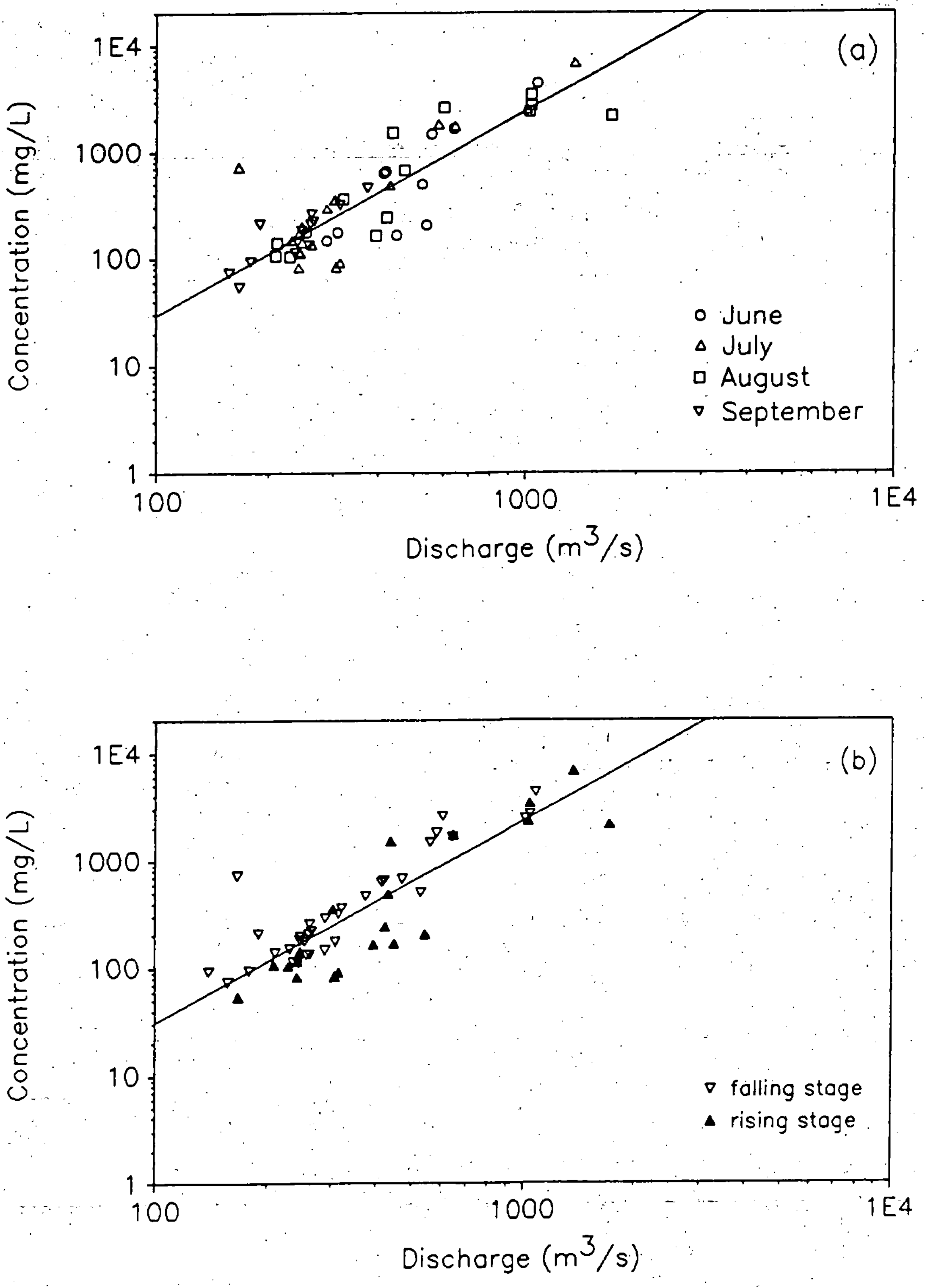


FIGURE 4.3

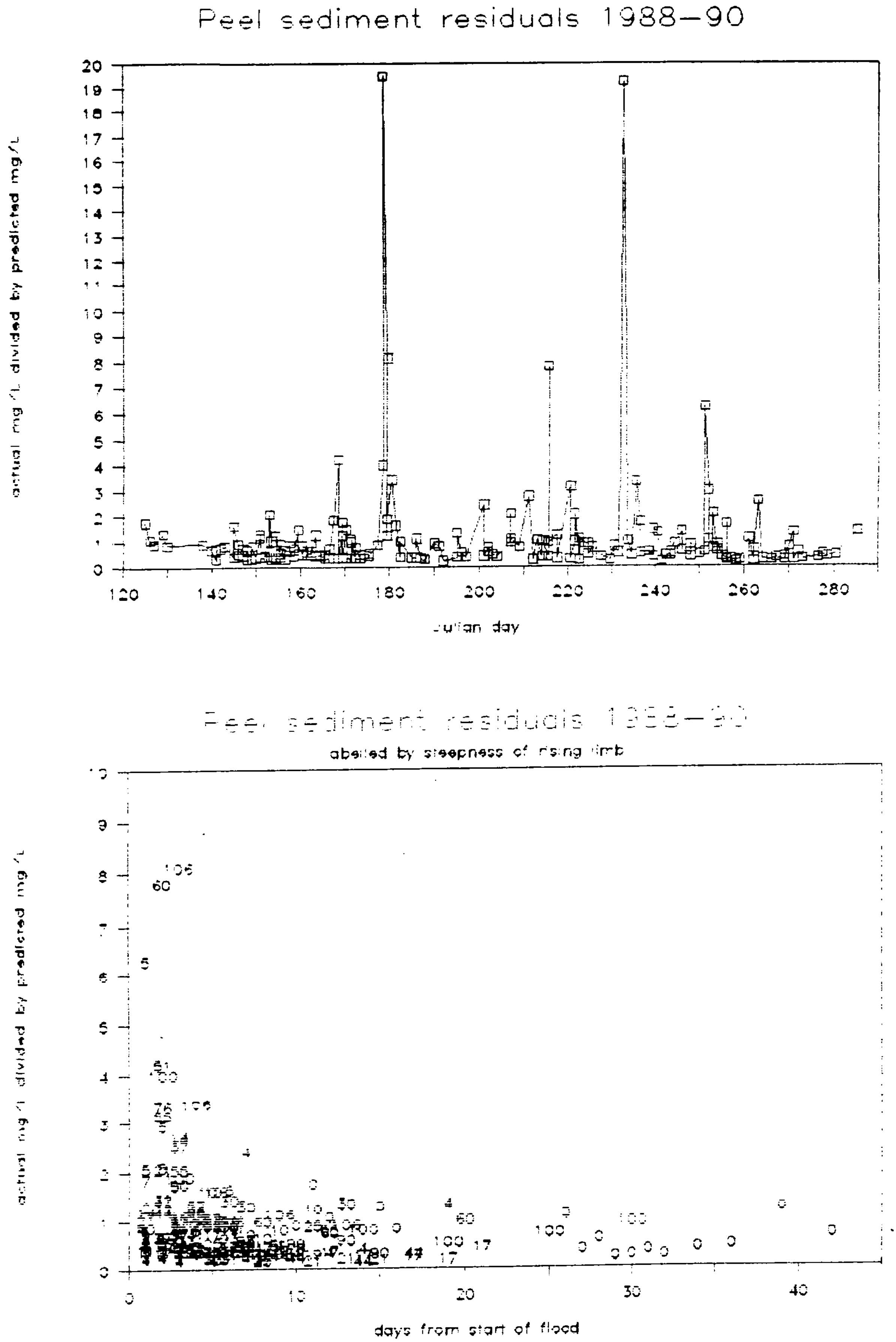

Peel sediment residuals 1988–90
actual mg/L divided by predicted mg/L
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
120
140
160
180
200
220
240
260
280
Julian day
Peel sediment residuals 1988–90
labelled by steepness of rising limb
actual mg/L divided by predicted mg/L
10
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
days from start of flood

FIGURE 4.4

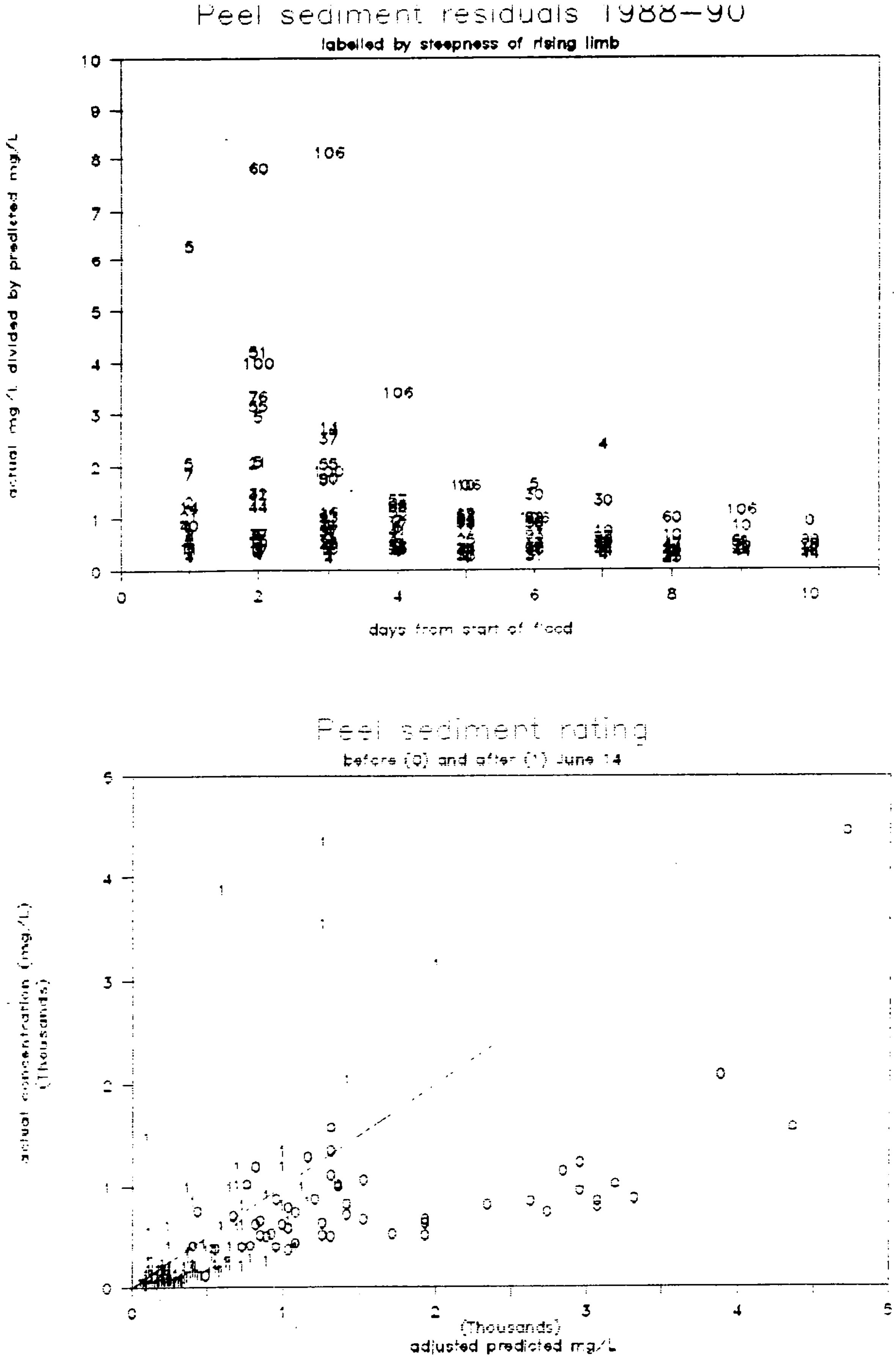
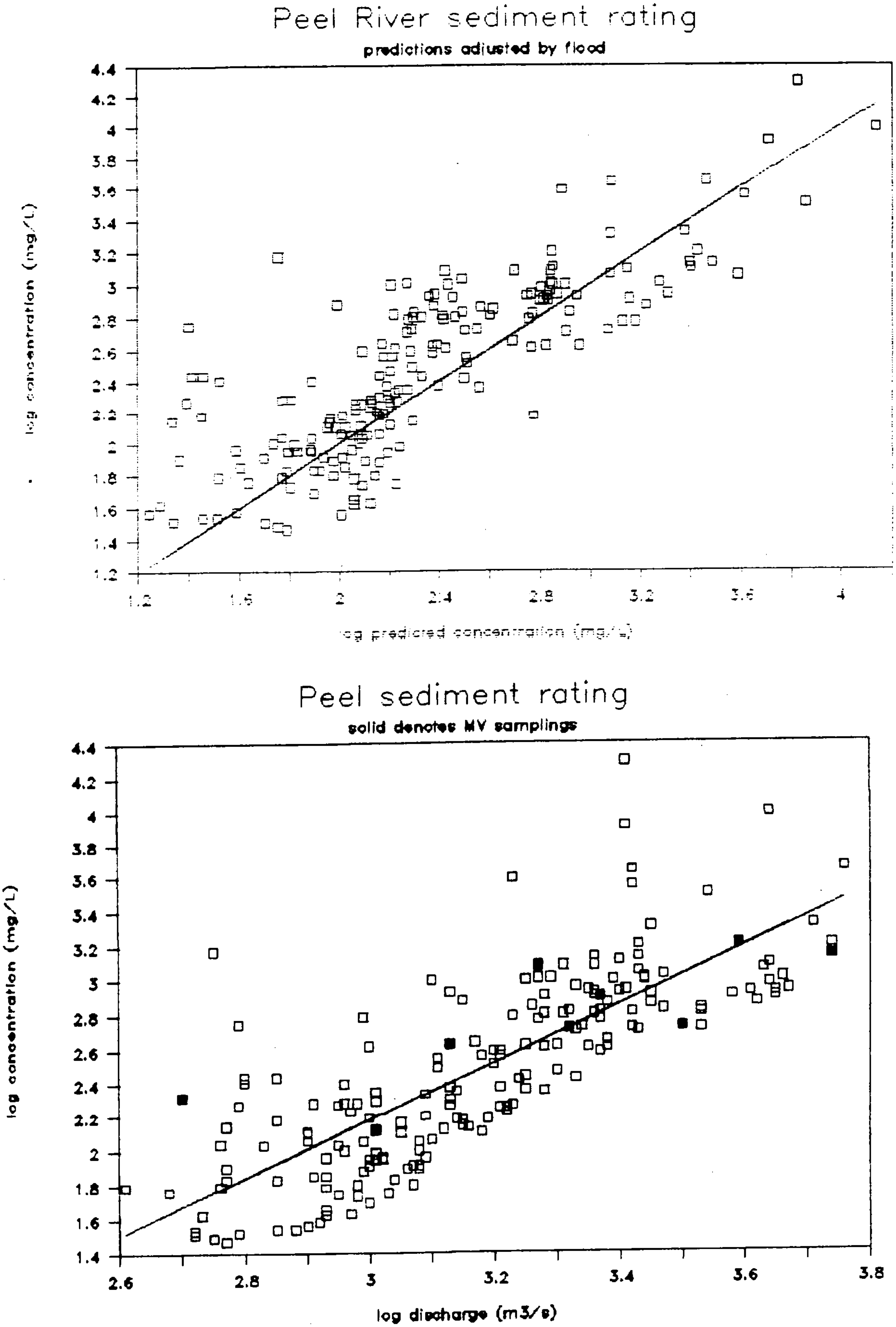

Peel sediment residuals 1988–90
labelled by steepness of rising limb
actual mg/L divided by predicted mg/L
days from start of flood
0
1
2
3
4
5
6
7
8
9
10
60
106
5
51
100
76
106
14
37
4
30
60
106
10
0
Peel sediment rating
before (0) and after (1) June 14
actual concentration (mg/L)
(Thousands)
adjusted predicted mg/L
(Thousands)
0
1
2
3
4
5

FIGURE 4.5



Peel River sediment rating

predictions adjusted by flood

Peel sediment rating

solid denotes MV samplings

FIGURE 4.6

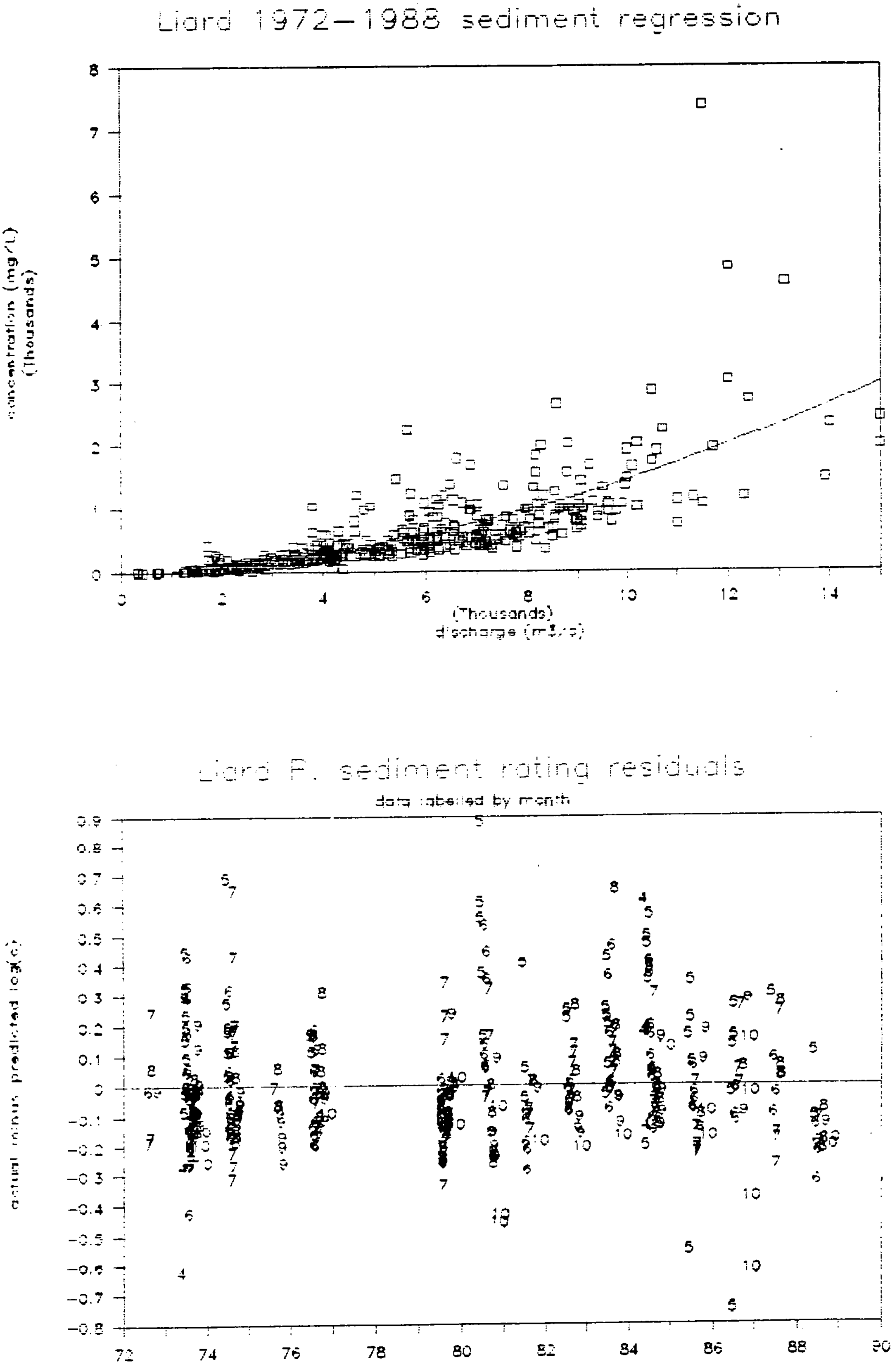

Liard 1972–1988 sediment regression
concentration (mg/L) (Thousands)
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
(Thousands) discharge (m3/s)
Liard R. sediment rating residuals
data labelled by month
actual minus predicted log(c)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
72
74
76
78
80
82
84
86
88
90

FIGURE 4.7

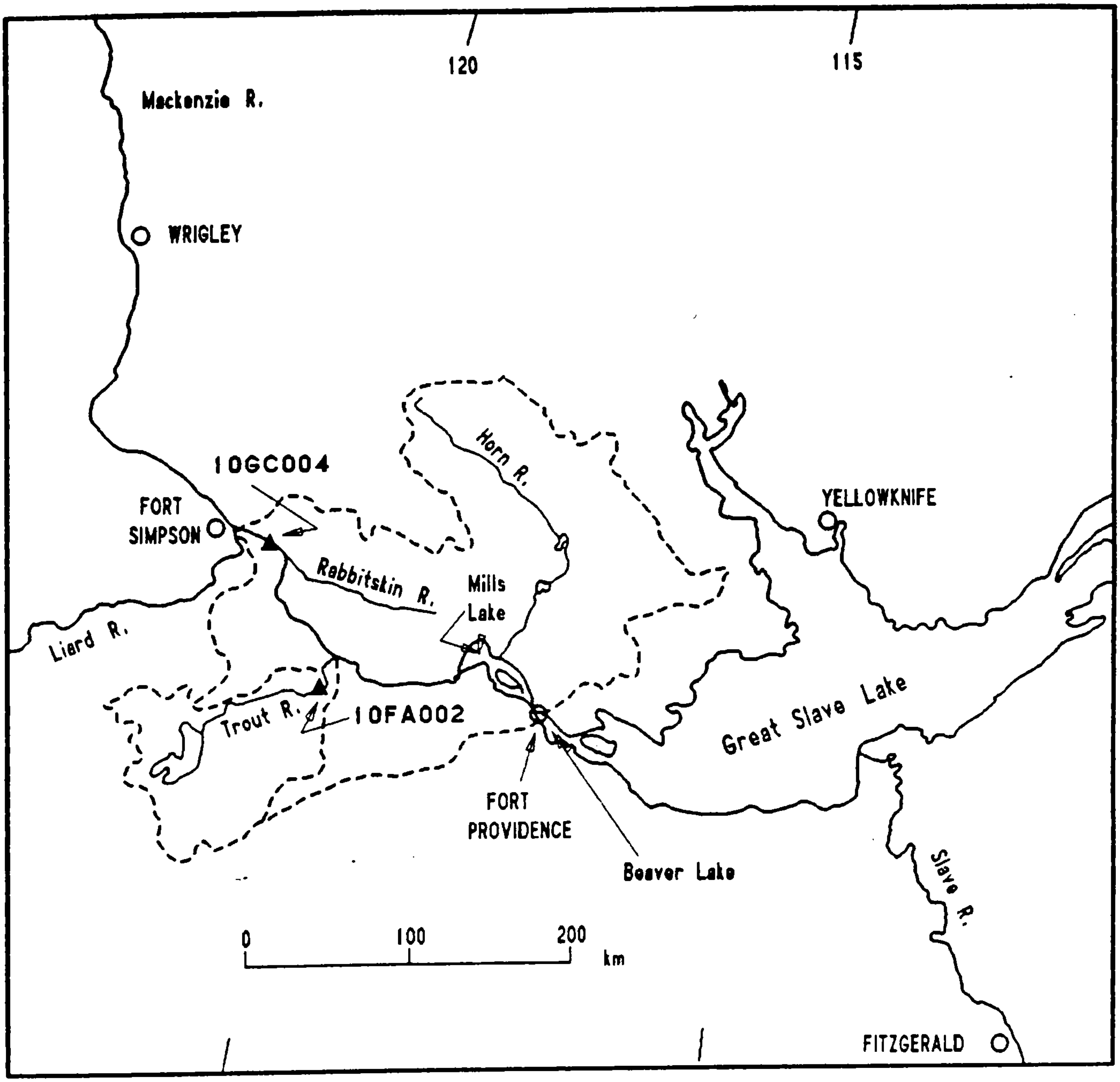


FIGURE 5.1

MACKENZIE RIVER DRAINAGE BASIN :
FORT PROVIDENCE TO FORT SIMPSON

LIBRARY
CANADA CENTRE FOR INLAND WATERS
867 LAKESHORE ROAD
BURLINGTON, ONTARIO, CANADA
L7R 4A6