DOWNSTREAM NUTRIENT CHANGES THROUGH THE MACKENZIE RIVER DELTA AND ESTUARY, WESTERN CANADIAN ARCTIC

by

Craig A. Emmerton
Hon. Bachelor of Science, McMaster University 2002

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

In the
Department of Geography

SIMON FRASER UNIVERSITY

Spring 2006

APPROVAL

Name: **Craig A. Emmerton**

Degree: **Master of Science**

Title of Thesis: **Downstream nutrient changes through the Mackenzie Delta and Estuary, western Canadian Arctic**

Examining Committee:

Chair: **Dr. Nick K. Blomley**
Professor, Chair of Graduate Studies
Department of Geography

Dr. Lance F.W. Lesack
Senior Supervisor
Associate Professor of Geography

Dr. Warwick F. Vincent
Supervisor
Professor of Biology
Université Laval

Dr. William Quinton
Supervisor
Associate Professor of Geography and Environmental Studies
Wilfred Laurier University

Dr. Phil Hill
External Examiner
Research Scientist
Geological Survey of Canada

Date Defended/Approved: Apr. 6/06

ABSTRACT

The effect of the large lake-rich delta and freshwater-saltwater transition zone (FSTZ) on nutrients from the Mackenzie River was investigated during open water of 2003-2004. Water volume storage in the Mackenzie Delta at peak levels was estimated by quantitatively partitioning the landscape (via GIS analysis) into discrete floodplain lake, wetland and channel environments. A river and lake mixing model and biogeochemical sampling of upstream and downstream delta channels were used to estimate average nutrient composition of water outflow from the delta. Results showed that the delta was a sink for particulates and dissolved inorganic nutrients while dissolved organic matter was enhanced. The composition of river water across the FSTZ was investigated during a mid summer cruise in 2004. Results showed particulate, dissolved inorganic nutrient and dissolved organic carbon patterns typical of most estuaries while dissolved organic nitrogen and phosphorus increased across the FSTZ, atypical of most estuaries.

KEYWORDS: arctic; nutrients; delta; estuary; Mackenzie

To Lori and Bill.

ACKNOWLEDGEMENTS

I would first like to thank my senior supervisor Dr. Lance Lesack for the opportunity to work in Canada's North and for his guidance throughout my thesis. I would also like to thank Lance and Dr. Warwick Vincent for the opportunity to experience the Arctic Ocean during the ARDEX cruise of July 2004. I appreciated helpful comments and guidance from my examining committee, including Lance, Warwick, Dr. Bill Quinton and Dr. Philip Hill (external examiner). I also appreciate financial and logistical support from NSERC, NSTP, PCSP, Canada Research Chair program in aquatic ecosystems studies and the Department of Geography at SFU.

A special thanks goes to Les Kutny and staff at the Inuvik Research Center as this research would not be possible without their logistical support and occasional calls from stranded researchers in the delta! Invaluable help from George Lennie at the Water Survey of Canada in Inuvik was appreciated. Excellent field support from Canadian Helicopters made our helicopter sampling a relative breeze on the delta. The Captain and crew of the CCGS *Nahidik* provided outstanding assistance during the ARDEX cruise while fellow researchers provided helpful guidance and assistance. Further assistance in Inuvik was provided by DFO, Environment Canada, Gwich'in Renewable Resource Board and Western Arctic Adventures and Equipment. I must also acknowledge the graciousness of the people of the Town of Inuvik in granting my research on their land. Thank you to Ron Schade and staff at the Freshwater Institute for analyzing many of my water samples from the delta.

Thank you to the Lesack Lab (Catherine Febria, Jolie Gareis, Suzanne Tank, Adam Chateauvert) and Jenny Graydon for all of your advice and assistance during my time at SFU. Thanks go to field and lab assistants during my two field seasons in Inuvik: Shannon Turvey, Nicole Van der Wal and William Day of Inuvik. Thanks also to Dan Leitch and Scott Coughtrey for sampling help in May/June 2004 and to Dr. Max Bothwell for sampling assistance in July 2004. GIS support was graciously provided by

Walter Piovesan and Daniel Say at the SFU Map Library and Jasper Stoodley, Chris Bone and Daniel Stevens at SFU Geography. Thanks to Marcia and the rest of the SFU Geography staff.

Lastly, thank you to my family, Jenny and friends who kept me in good spirits during this long haul!

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GENERAL INTRODUCTION

The Mackenzie River Delta, in Canada's western Arctic, is the second largest in the Arctic Ocean Basin (approx. 13,000 km^2) and plays a critical role in controlling the coastal ecosystem of the western Arctic Ocean. Two distinct environments within the delta have the largest role in determining the type and magnitude of river nutrient fluxes to the Arctic Ocean. First, the delta's thousands of small floodplain lakes temporarily store river floodwaters during annual spring flooding and both add nutrients to and receive nutrients from floodwaters. Second, the delta's estuary links the Mackenzie River to Arctic Ocean waters and represents a region of considerable biogeochemical change. Each of these environments contributes to changing the original nutrient signature of the Mackenzie River inflowing to the head of the delta. Current knowledge of nutrient fluxes to the western Arctic Ocean from the Mackenzie River has mostly been based on sampling before the delta and estuary. This overlooks the important temporal and spatial changes in nutrients and sediment that occur as river water passes through each environment. The objective of this preliminary study was to address the effects of both the delta lakes and the estuary on modifying nutrient delivery to the Arctic Ocean.

In order to assess nutrient mass changes through the Mackenzie Delta, an accurate estimate of floodwater stored in delta lakes is required. Currently, little is known about the number, coverage and potential water stored in the delta lakes. This knowledge is of great importance as the vast majority of the lakes are flooded each spring and they potentially sequester and release important amounts of nutrients when connected to rivers. The objective of Chapter 1 was to use GIS software, digital topographic maps and standardized criteria to generate estimates of habitat composition, lake coverage and ultimately low and high water estimates of total water stored in delta lakes.

Downstream nutrient changes in the delta involved monitoring delta channels in space and time as well as the interaction between lakes and in delta channels. Three important components of the delta provided context for monitoring nutrient changes downstream. Inflowing rivers into the delta are relatively distinct chemically before entering a more mixed delta environment while lake environments dominate the mid delta and the delta mouth is influenced by heavy deposition and marine processes. Changes between these regions are expected to be substantial. Changes between lakes and channels, in concert with Chapter 1 results, provided a means to estimate the role of temporary lake storage on discharging ocean waters from the delta, termed the 'delta effects'. These programs were the basis of the Chapter 2 objective, which was to detect preliminary evidence of downstream nutrient changes in the delta and to quantify the role that the delta environment plays in influencing those changes.

In addition to nutrient changes through the delta, passage of river water into marine environments induces major changes in river material and is a key control on what is delivered to the coastal regions. This biogeochemical transition between full river water and full arctic marine water is currently poorly understood. The objective of Chapter 3 was to investigate the downstream and vertical biogeochemistry of the freshwater-saltwater transition zone of the Mackenzie Estuary. The large water, sediment and organic signature of the Mackenzie River was expected to exert a strong control throughout the estuary, especially considering the relatively small coastal shelf area at this location.

The Mackenzie River exerts strong controls on nutrient magnitude and distribution in the western Arctic Ocean and plays an important role in sustaining coastal ecosystems. With climate changes progressing in the arctic, nutrient delivery by the Mackenzie River may change and affect the sensitive coastal environment. Therefore, it is essential to investigate the current nutrient regimes in the Mackenzie River and the effect that its floodplain and estuary has on seaward fluxes.

1 AQUATIC HABITAT COMPOSITION, LAKE ABUNDANCE AND POTENTIAL WATER STORAGE IN THE MACKENZIE RIVER DELTA, WESTERN CANADIAN ARCTIC

1.1 Abstract

The complete landscape surface of the active Mackenzie Delta (13,135 km^2) was partitioned into discrete lakes (3,331 km^2), channels (1,744 km^2), wetlands (1,614 km^2) and non-wetted floodplain area (6,446 km^2) using standardized criteria via GIS analysis of 1:50,000 digital maps based on 1950s aerial photography. The census total of discrete lakes (49,046) is almost double the number, based on prior estimates. Based on the new information, total lake volume in the delta during the post river-flooding period is estimated as 5.4 km^3 and the volume of river water stored in the delta during peak water level is 25.8 km^3. Total water storage in the delta at peak water levels (31.2 km^3) thus is equivalent to about 37% of Mackenzie River flow (85.2 km^3) during the high-discharge period of delta break up. During this period, the stored river water can be envisioned in the form of a thin layer of water (2.3 m thick on average) spread out over 11,200 km^2 of lakes and flooded vegetation. This water is further exposed to 24 hour per day solar irradiance (arctic summer solstice) and thereby has significant potential to affect the composition of river water flowing to the Beaufort Shelf as the stored flood water recedes to the river channels after the flood peak.

KEYWORDS: arctic; delta; lakes; floodplain, Mackenzie

1.2 Introduction

Floodplain lakes are sites of significant biogeochemical change and variable water storage (Forsberg et al. 1988; Lesack et al. 1998). Biological uptake, sedimentation and other processes are normally enhanced in lake settings compared to turbulent and light-limited river water. Consequently, river floodwaters entering floodplain lakes can undergo significant nutrient chemistry changes driven primarily by reduced turbidity, increased light penetration and resulting biological activity. Arctic deltas are unique environments where these effects are intense due to substantial lake coverage, nearly continuous open water irradiation and an annual spring flood that is the dominant event to deliver water, nutrients and sediment to lakes (Lesack et al. 1998). Lakes in large arctic deltas typically number in the tens of thousands and together may play a large role in altering the nutrient chemistry of river floodwaters while in temporary spring storage. This interaction is an important process in maintaining the water and nutrient balances of individual lakes as well as the productivity of coastal regions that receives incoming freshwater nutrient fluxes.

The Mackenzie Delta, in Canada's western Arctic, is a lake-rich, ecologically sensitive environment (MRBC 1981). Its high latitude (67-70°N, 133-137°W) induces 7-8 months of ice cover before the open water season (June-October). Since the Mackenzie River flows northward from areas of relative warmth towards frozen northern regions, the spring freshet eventually encounters ice jams in the delta, resulting in peak water levels and wide scale flooding (Prowse 1986; Marsh and Hey 1989; Rouse et al. 1997; Lesack et al. 1998; Marsh et al. 1999). Delta lakes are subsequently flooded depending on their elevation and distance from river channels (Mackay 1963; Marsh and Hey 1989). This variable flooding (and subsequent recession) provides the primary nutrient supply to the delta plain and floodplain lakes and thus controls their ecological characteristics and ecosystem health (Lesack et al. 1998). The delta is expected to undergo environmental changes due to climate change pressures (Rouse et al. 1997). Specifically, these pressures are predicted to affect the timing and magnitude of the seasonal flood-pulse (Junk et al. 1989; Marsh and Lesack 1996) through earlier snowmelt, ice jam reduction and increased soil storage from thickening active layers. Each of these scenarios is expected to contribute to a lessening of the flood stage resulting in disconnection of the river with the delta plain and enhanced negative water balances in lakes of higher elevation and greater distance from river channels (Marsh and Lesack 1996). Nutrient chemistry of water discharging to the coastal Beaufort Sea may change as a result (Chapter 2).

The Arctic Ocean is the most river-influenced of the world's oceans (Opsahl et al. 1999). Rivers deliver considerable water and nutrient fluxes that exert strong controls on the productivity, salinity and water circulation in the Arctic Ocean (Aagaard and Carmack 1989; Holmes et al. 2001). Past investigations have attempted to characterize nutrient and water inputs from the largest rivers into the Arctic Ocean (Meybeck 1982; Telang et al. 1991; Cauwet and Sidorov 1996; Lara et al. 1998; Gordeev 2000; Lobbes et al. 2000; Holmes et al. 2001; Dittmar and Kattner 2003). It is apparent, however, that the effect of lake-rich deltas on discharging river water has been overlooked, despite significant connection with the delta plain and changes in lake chemistry during temporary spring flooding.

Understanding the influence of Mackenzie Delta on discharging waters to the western Arctic Ocean will require investigation of the coverage and volume of lakes over the delta plain. Sippel et al. (1992) demonstrated the importance of such information in the lake-rich Amazonian floodplain using aerial imagery and topographical maps. The authors provided estimates of flood inundation area, lake morphometry, lake enumeration and areal coverage within the floodplain. This information subsequently contributed to studies examining the role of the Amazon River floodplain in regional and global water and biogeochemical studies. Currently, little knowledge exists of lake water storage and coverage in the Mackenzie Delta. Mackay (1963) showed highest lake concentrations in the mid delta (30-50% coverage) and lower in the head and mouth areas of the delta (15-30% coverage). Marsh and Hey (1989, 1991) compiled an extensive survey of 132 lakes near Inuvik, NT cataloguing lake sill elevations, lake areas and estimates of lake size downstream in the delta. Marsh and Hey (1989, 1994) classified the flooding potential of lakes in the eastern delta and determined flooding depths of higher elevation lake and watershed areas. General lake density and enumeration sampling from topographical maps has been performed in the past with lake density estimates agreeing at ~25%

coverage over the delta plain along with enumeration estimates of ~25,000 lakes (Mackay 1963; Lewis 1988).

As part of a long-term investigation on the hydrology and limnology of lakes in the Mackenzie Delta (Lesack et al. submitted), the goal of our present study was to quantify the general habitat composition and fully census the lakes of the delta. This was achieved via a GIS analysis of the 1:50,000 digital map series available for the delta, based on extensive aerial photography performed during the 1950s. The "habitat layers" of the complete landscape surface in the delta were manually partitioned into discrete lakes, channels, wetlands and non-wetted floodplain area via standardized criteria. These results were used with other published information to assess the magnitude of potential water storage in the delta relative to Mackenzie River flow during the spring break up period and the plausibility of the hypothesis that the volume of river water moving through the delta is sufficiently high to potentially affect nutrient fluxes to the Beaufort Sea (Chapter 2). This study also represents a record of historical lake coverage in the delta that ought to facilitate future work addressing climate-induced loss of lake coverage already realized in other parts of the arctic landscape (Smith et al. 2005; Marsh et al. 2005).

1.3 Methods

1.3.1 Study area

The Mackenzie Delta lies at the end of the Mackenzie River at the Beaufort Sea in the western Canadian Arctic (Fig. 1.1). The delta is the second largest in the circumpolar arctic (after the Lena Delta) and is characterized by numerous anastomosing channels, small thermokarst lakes and wetlands that dominate the deltaic plain (Mackay 1963; Marsh et al. 1999). The delta plain is permafrost-influenced silt and sand covered by species of spruce (*Picea*), alder (*Alnus*), willow (*Salix*), birch (*Betula*), poplar (*Populus*), *Equisetum* and tundra species in the north above the treeline (Mackay 1963). About 90% of the delta's water supply is contributed by the Mackenzie River at Point Separation (Fig. 1.1) with minor contributions by the Peel River in the southwest (~8%) and others (Burn 1995). Floodplain lakes are generally small and shallow. Lakes are classed (Fig. 1.2) as being continuously connected to the river (no-closure), annually connected during flooding before disconnection (low-closure) and connected less than annually (high-closure). Lake flooding is determined by the sill elevation of the lake and water level of adjacent river channels. Most lakes are shallow enough to support substantial macrophyte growth (common species include *Potamogeton*, *Chara* and *Ceratophyllum*; Squires et al. 2002).

1.3.2 Software application and source data

Determination of lake coverage and other delta statistics was achieved using GIS software (ArcMap™, version 9.0, ESRI® 2004). Pre-digitized topographical maps at the 1:50,000 scale, which represented the entire delta area, were used and separated into upper, middle and lower delta regions (Fig. 1.3; Canada Centre for Topographic Information). Most aerial photography used to generate the maps was flown during the early 1950s, with the exception of some areas of interest such as settlements (Table 1.1). The topographical maps were cross-referenced with current satellite imagery (LANDSAT-5; July 2004) of the delta to verify their application to present conditions. After input into ArcMap™, polylines (lakes and channels as shaped lines) were converted to polygon features with recognized shapes with areas. All polygons were then distinguished as delta and non-delta entities using definitions by Hill et al. (2001; Fig. 1.4).

1.3.3 Lake and channel classification

Delta environments in the arctic are extremely complex systems of meandering rivers and adjacent lakes often directly connected to the channels and to each other. Thus, defining what an individual lake is (i.e. two separate lakes versus one lake with two bays) and what is a channel is not always straightforward. Therefore, objective criteria were developed to both separate lakes from channels and separate lakes connected with other lakes. Delineation of channels from lakes was straightforward with most showing obvious high length to width ratios and direct connection with other delta channels. Few cases arose where channels were quite short and wide and in such cases these were designated as channels if length was greater than width. Most lakes within the delta were obvious separate, unconnected entities. Lakes that were connected in long chains, had multiple 'bays' or had any characteristics not consistent with a completely closed shoreline were subjected to criteria that would determine if lakes were separate or the same waterbody. These criteria were developed partially based on the classification system as described by Sippel et al. (1992) in similar work in the Amazonian floodplain. Figure 1.5 shows that adjoining waterbodies were considered separate lakes if:

A. separated by a single line on a 1:50,000 topographical maps

B. separated by a connection that was longer than it was wide (i.e. a channel)

C. maximum lake length was more than twice the width of lake-river confluence

A 'connection' between two lakes was defined as where the width of the connection became consistent after reducing from each lake's maximum width (Fig. 1.5, B).

1.3.4 Delta statistical evaluation

Following separation from flowing channels and each other, lakes were counted and calculated for surface area and other descriptive statistics. Enumeration was performed by an inherent database generated by ArcMap™ for all separate polygons in a given layer. Polygon areas were determined through the application of a polygonal area VB script as provided by the ArcMap™ software. A sample of approximately fifty lakes, from various hard-copy topographical maps of the delta, was then taken and measured for area by planimeter and returned an average deviation of roughly +7% compared to the GIS calculation. Area calculations from a 132 lake set near Inuvik, NT (Marsh and Hey 1991) deviated roughly +3% compared to GIS calculations. Other layers were also crosschecked with results similar to the lake layer. Additional areal distribution and descriptive statistics were also generated (JMP® version 5.0.1.2, SAS Institute Inc. 2003). Delta-scale area and density measures were achieved with additional measures of total delta area using manual polygon generation within the ArcMap™ software to trace the delta boundaries in accordance with Hill et al. (2001). Lakes split at map borders were matched with its adjoining pair in all cases in order not to skew the enumeration, distribution and areal statistics.

1.4 Results

1.4.1 Composition of delta habitat

Active delta area - Analysis in ArcMap™ generated a 1950s era total delta area of 13,135 km^2, in close agreement with estimates by Hill et al. (1991) of 12,995 km^2. Changes in delta area were not considerable in the past half century in the delta based on visual comparison with current satellite photos. Delta area is dynamic and can change on an annual scale, especially between large flood events where erosion, ice scour and coastal deposition is enhanced. Sea level increase may also affect total area through coastal retreat (Hill et al. 2001) and increased mouth deposition due to the heightened base level. Sediment balance calculations by Carson et al. (1999) showed a continuing building process within the delta through point bar/overbank lake sedimentation and channel mouth deposition. Compared to erosional processes, deposition within the delta is roughly 40% higher, leaving a slow infilling of lakes and deposition at channel mouths as a result. However, over a relatively short period of geological time, delta change was not considerable (map versus satellite comparisons) and coastal erosion may have balanced any depositional gains within the delta as erosion rates have been observed to be significant (Macdonald et al. 1998). Two-thirds of incoming sediment from the Mackenzie River is transported to the offshore environment (Carson et al. 1999), thus substantial annual deposition is consumed by sub-aqueous delta and pro-delta regions, each not contributing to the surficial calculation of delta area. Delta building, consequently, is a slow process.

Habitat coverages - Habitat coverage in the delta was diverse (Fig. 1.6). Human influence in the 1950s was, and still is, largely absent in the delta area with the largest areal settlement, Inuvik, NT, not part of the delta by definition. Open water covered about 40% of the entire area, with floodplain lakes alone covering approximately 25% of the delta surface. Since aerial photographs, that were utilized to generate the topographical maps, were taken mostly in late summer (Table 1.1), the spring flooding period would certainly show a more extensive coverage of open water as around 95% of all lake area is inundated during a normal water year (Marsh and Hey 1994).

Understanding the coverage during the spring flood peak is an important consideration to mass flux studies since it is the largest single hydrological event in the delta and when large percentages of annual flows of water and material occur. Wetland and intermittent water are dynamic components in this coverage balance, but during lower flows they combined to cover about 12% of the delta. Wetlands are challenging to define in a delta environment since they are intermittent environments between open water and filled in lakes. The remaining 49% of delta coverage was non-wet terrestrial area comprised of levees, mud, sand and vegetated ground. Terrestrial coverage in the past half century did not appear to have changed dramatically likely due to the well-established vegetated coverage in the delta that is resistant to development of new lakes. Future disturbance of vegetation through fire, storm or human activity can be expected to jumpstart lake creation through ponding and subsidence due to permafrost melt.

Lake abundance - Floodplain lakes in the delta occur in extraordinary numbers, with our present census of 49,046 lakes being roughly double the number (25,000) estimated by earlier work (Table 1.2; Mackay 1963; Lewis 1988). Of this census, there are a significant number of water bodies that are quite small and collectively represent only a small amount of lake area. Starting from the largest lakes and progressively adding smaller ones, 99% of total lake area in the delta is accounted for by about 35,000 lakes 0.005 km^2 and larger and 99.9% of total lake area is accounted for by 45,000 lakes 0.0014 km^2 and larger (Fig. 1.7,1.8). Thus, even though the full number of water bodies is large relative to prior estimates, the number of lakes would still considerably exceed prior numbers if a size threshold cut-off point were applied to these results. A water body of 0.0014 km^2, for example, is small but never the less a significant sized water body in this system and typically is sufficiently deep (> 1.5 m) to not freeze to the bottom during winter. Average lake size increased seaward through the delta, progressing from 0.055 km^2 in the upper region to 0.072 km^2 in the mid-delta to 0.075 km^2 in the lower section. Lakes in the delta are mostly of thermokarst origin where heat from standing water melted ice-rich permafrost into taliks and subsidence ensued (Hill et al. 2001). Progression of smaller lakes in the upper delta toward larger lakes in the north is mainly a process related to levee height of channels and connection types of the lakes. Levees in the upper delta portion are higher due to increased riverine sediment loads in the region and increased distance and elevation from sea-level. This situation created a closed system for most lakes (Lewis 1988) where only annual overbank flooding supplied water, sediment and nutrients, leaving a negative water balance for the remainder of the open-water season. Toward the north of the delta, lakes tend to be larger due to shorter channel levees and increased exposure to summer storm surges from the Beaufort Sea (Marsh and Schmidt 1993; Jenner and Hill 1998). These mostly no-closure lakes are in constant connection with channels and maintain relatively stable water levels. Delta lakes averaged 0.058, 0.075 and 0.070 km^2 from east to west. Larger lakes in the mid delta may be attributed to the flooding influence of the large Middle Channel that diverts significant water amounts over the delta plain. Overall, mean lake area throughout the delta was 0.068 km^2, a smaller value than Hill et al. (2001) who estimated 0.12 km^2.

Habitat variability within the delta - Areal density of lakes and other habitat types varied from the head to the mouth of the delta (Fig. 1.6). Lake density was highest in the middle delta with a sharp decrease toward the tide-influenced regions. The middle delta is presumably the 'just right' situation where a balance of levee heights allows for larger connected lakes as well as many high-closure thermokarst lakes (Marsh and Hey 1989). Lake densities in the east, middle and west sections of the delta were remarkably stable at 26.2%, 24.2% and 26.4% of delta area respectively. This stability is surprising as higher lake densities would be expected nearer to the large Middle Channel, which would distribute floodwaters over a larger area and presumably create more lakes via permafrost subsidence. However, this may be offset due to large lake areas in this region. Channel density was highest in the lower delta, largely due to tidal and coastal processes that restrict lake building as well as branching of channels through relatively erosion prone landscapes. Wetland density through the delta increases from the upper delta (~2%) toward the coastal lower delta (~24%). This follows the gradual elevation track to sea level in the lower delta area where land is more easily inundated and connection with sea surges allows for pooling of water and development of wetland environments. Sediment deposition and lake connection is also highest in the lower portion of the delta (Carson et al. 1999; Hill et al. 2001), allowing for higher deposition rates and longer connection periods, and presumably more wetland creation. Terrestrial coverage was generally unchanged through the delta though highest densities were found in the delta head region where conditions for large open water bodies were restricted compared to other regions.

1.4.2 Delta water storage

The above information on delta area and areal composition of habitat types, in combination with other published information, provides a means for assessing the potential for Mackenzie River water storage in the delta and facilitating the assessment of the potential effect of the delta on riverine nutrient fluxes to the Arctic Ocean. Quantities of particular interest include (1) the total volume of water stored in lakes during the post-flooding period, (2) the volume of river-water going into temporary storage in the delta during the spring break up period when peak annual river flows occur, and (3) the volume of river-water flowing through the delta during the break up period. These volumes plus the parameters used for their estimation are summarized in Table 1.3.

The post-flooding estimate of total delta lake volume (5.35 km^3, Table 1.3, box cfgh in Fig. 1.9) is based on stratifying the delta into areas of No-closure, Low-closure and High-closure lakes, then obtaining the product of total lake area in each closure-class times the mean lake depth in each class. The stratification was done based on the relative fraction of total lake areas in each closure-class (Pipke 1996) and the approximation that the ratio of delta floodplain area (i.e. wetlands + floodplain) to lake area is 2.42 (Table 1.3). Average lake depth for each closure-class is based on measurements of 27 representative lakes in each class (81 lakes total), representing a random stratified sample from a complete swath of 2,700 lakes (Marsh et al. 1999) across the mid-delta.

River-water volume added to existing lakewater (11.7 km^3, Table 1.3) during an average peak flood (5.636 m asl over a 25 year record, Marsh and Hey 1989) was approximated as a rectangular water layer added to the average low-water volume of the lakes in each closure-class (box befc in Fig. 1.9). The area of this layer was taken as the low-water area of all lakes in each closure class. The difference in depth from the low-water point to the elevation of the next closure-class, in each of the classes, was averaged to estimate general mean depth for each closure class as a whole.

River-water volume on the floodplain (i.e. not on top of lakes) (14.1 km^3, Table 1.3) during an average peak flood was approximated as a rectangular water layer adjacent to the position of the water's edge of the lakes in each closure-class (box abcd in Fig. 1.9). The total area of this layer is the combined estimated area of not-wet floodplain plus wetlands associated with each closure class of lakes, with the flooded area in each class adjusted for average levee heights (Marsh and Hey 1994). At average peak water (5.636 m asl), the average height of levee tops are submerged in the case of no-closure and low-closure lakes (i.e 100% flooded). In the case of high-closure lakes, the fraction of floodplain area flooded (0.82) was estimated as the relative difference from the sill height of the high-closure class (4.0 m asl) to mean peak water level (5.636 m asl), versus the difference to the mean levee height for high-closure lakes (6.0 m asl, Marsh and Hey 1994). The difference in depth from the low-water point to the elevation of the next closure-class, in each of the classes, was averaged to estimate the mean maximum depth for the layer in each closure class. The mean depth for the layers in each closure-class was then taken as half the maximum depth (i.e. half of box abcd).

River-water volume added to existing delta channels (7.7 km^3, Table 1.3) during an average peak flood (5.636 m asl) was approximated as a rectangular water layer added to the average low-water level of the channels (1.231 m asl, Marsh and Hey 1989). Channel area was obtained directly from the GIS results and mean depth of the layer was the difference between average low-water and peak water (4.405 m).

The volume of Mackenzie river-water flowing through the delta during break up (85.2 km^3) is based on the product of the mean annual flow of the Mackenzie River (284 km^3,WSC 2005) times an estimate of the fraction of the annual flow volume that occurs during the delta break up period (0.30; see Discussion).

1.5 Discussion

1.5.1 Lake abundances and classification criteria

The increase in lake abundance, based on the present census, is at least partly related to the threshold criteria used to define a "countable lake". Random sampling of areas within each topographic map was performed to estimate the number of lakes added due to the separation criteria. A range of roughly 5,000-7,000 new lakes, or about 10-14% of the lake total, was added to the census based on successful criteria application. When compared to the 132 lake set near Inuvik, NT from Marsh and Hey (1989) this study also enumerated 132 lakes. This, however, included a balance of 5 occasions where the separation criteria altered the original set's lake identification, either adding lakes not recognized originally or consuming lakes that were not consistent with the separation criteria.

The significant benefit of this census is the complete partitioning of all area classified as "water" and thereby facilitating more precise estimates of water storage in the delta. Estimates of lake and floodwater storage in the delta based on 1950s aerial photography is applicable to present conditions considering the minimal habitat areal change in the delta based on comparisons with 2004 satellite imagery.

1.5.2 Uncertainties in delta water storage

While our results provide precise new estimates of habitat area in the Mackenzie Delta, these represent first order estimates of water volume storage in the delta. However, some elements of the analysis are conservative, and indeed adequate to make the case that the role of arctic river deltas on river flows to the Arctic Ocean ought to be further investigated (Chapter 2).

Average lake depths - The estimate of average lake depth in the delta, for example, warrants further explanation. The 81 lake-set on which the estimate was based consisted of three clusters of 27 lakes from each of the western, central and eastern areas of the swath and were selected as a representative sample for investigation of sedimentation rates (Marsh et al. 1999). Each 27-lake cluster was based on 9 lakes from each of the no-closure, low-closure and high-closure lake-classes. As lake-ice forms solutes are excluded from the ice matrix and are concentrated into the underlying liquid water (Lesack et al. 1991). The degree of concentration enhancement is in proportion to the volume of lake-water that freezes relative to the total lake volume and can be used to derive mean depth if the lake area is known (Pipke 1996). The lake depths measured in this study were indeed consistent with lake depths derived from the degree of solute concentration enhancement observed in these lakes in liquid water beneath the ice-cover during the winter (Pipke 1996). This data set also showed significant differences among the lake closure-classes that are consistent with our understanding of sedimentation patterns and thermokarst deepening of lakes in the delta (Marsh et al. 1999; Hill et al. 2001). Lake depths in no-closure lakes averaged 1.66 m, low-closure lakes averaged 1.37 m and high-closure lakes averaged 1.84 m. After weighting the lake depths in each closure-class by the average difference in lake areas among the classes (see below), the overall mean of 1.60 m was essentially identical to the arithmetic average of 1.63 m.

Other estimates of lake depths have been reported in the delta, though not based on a comparable level of representative sampling. Squires et al. (2002) estimated lake depth from mean measurements over the open water season on about 30 lakes in the Inuvik region of the delta. Mackay (1963) averaged 50 lake depths from the mid-western portion of the delta during the July-August period. The average of the lake-sets from these two studies is about 1.50 m and is reasonably close to the Pipke (1996) estimate. The variety of information on lake depths indicates the estimate used in this analysis ought to be reasonably close to the true value, but at present we do not have adequate information to assess whether there may be significant differences in lake depths either upstream or downstream from the central delta area where most work has been done in this system.

Area of delta flooded at peak flow - An important parameter in estimating this quantity is the fraction of the total delta area associated with each lake closure-class. The 81 lakes investigated by Pipke (1996) showed significant declines in the average lake areas from no-closure lakes (0.71 km^2) to low-closure lakes (0.29 km^2) to high-closure lakes (0.13 km^2). The assumption is that the area of delta floodplain associated with each of these classes is in direct proportion to the lake areas. This seems reasonable based on the fact that the fraction of the delta area represented by lakes is relatively constant in differing regions of the delta. This will be further examined in a future investigation.

A second assumption is that this estimate, based on the central delta, is also representative of the full delta. Marsh and Hey (1991) showed that the number of high-closure lakes (sill elevations higher than the average spring peak water levels) clearly declines from 33% in the central delta to 13% in the lower delta, but increases to 44% in the upper delta. This is fully consistent with the elevational gradient from downstream areas to upstream areas of the delta. Thus, true flooded area ought to be over-estimated in the upper delta, but will be under-estimated in the lower delta. As a first order estimate, the over and under estimates ought to offset one another and indicate the value used in our estimate is reasonable.

Average depth of the river-water layer in the delta - Our estimate of the river water volume going into temporary delta storage is relatively sensitive to our estimate of the average depth of the river-water layer in the delta at the time of peak water levels. While the average difference in water levels (4.405 m) between the spring peak during break up and low river levels during the summer is based on a reliable and long record (25 years) for Inuvik (Marsh and Hey 1989), the approximations represented in Fig. 1.9 represent significant assumptions. We are not aware of another approach to estimate water depths on the delta floodplain without an analysis of high-resolution floodplain topography (not presently available). Work by Marsh et al. (1999) suggests that basing the depth estimate on results from the Inuvik gauging station could underestimate the water layer thicknesses. Measurements during the spring break up of 1992 revealed that the water surface across the delta is not flat, showing a bulge of 0.7 to 1.6 m in the water surface of the middle channel relative to east and west channels during the period of rising water. It is possible that on average a higher portion of lakes in the middle of the delta may flood annually (Marsh and Hey 1989) and to a greater depth, than on the eastern or western sides. The spatial water level patterns need to be investigated, but it is a difficult problem that requires modeling the hydraulics of the system during a period of considerable ice-jamming and this has not yet been attempted anywhere that we are aware in a system of this scale.

Volume of Mackenzie flow during delta break up - For the purpose of this analysis we used 0.30 as the fraction of annual Mackenzie flow that occurs during break up, but the true fraction in fact is unknown. River flow cannot be directly measured for a period of nearly one month when the channel cross-sectional areas are unknown because they are filled with ice. Thus, relations between water level and flow cannot be established because extensive ice-jamming affects water levels to a greater degree than the volume of river flow. Based on examination of Mackenzie discharges during the 1990s above Arctic Red River (Fig. 1.1; primary inflow to the delta) in the Water Survey Canada database, about 15% of the annual river discharge is accounted for in the first 30 days from the time of initial rise in spring water level at the gauging station (roughly to the point of peak water level). The actual flow during this period was not measured, but estimated via patterns in upstream river flow. The true flow could be significantly higher than reported. If 15% is indeed the proportion of river flow that on average occurs up to peak water level (i.e. the rising limb of the annual hydrograph), that would mean the volume of water moving in and out of storage in the delta would be equivalent to 73% of the river flow (42.6 km^3) up to the high-water peak.

Overall, we are convinced the general uncertainties in this analysis are sufficiently limited to make a case that the effect of the Mackenzie Delta on its river flow is significant. If river flow to the Beaufort Shelf is important, flows during the break up period and flow interactions between the delta and river need to be investigated via hydraulic modeling.

1.5.3 Implications for riverine nutrient fluxes to the Beaufort Shelf

While the water storage volumes we have derived are not precise, they represent a useful foundation for assessing the potential scale of the effect that may occur on river-borne nutrients, as river water during the high flow period of spring break up passes through such a lake-rich delta system (Chapter 2). The investigation of several important mechanisms ought to be facilitated by our results. First, we have now quantified that roughly 5.4 km^3 of lake water has the opportunity to mix with 25.8 km^3 of river water during the break up period. Based on these volumes, the nutrient concentrations in the lakes per se would need to significantly differ from the concentration in river water to impart a strong “lake signature” to the nutrient content of the floodwater (either enhanced or diluted) that will eventually recede to the river.

On the other hand, the interaction of river water with the floodplain area beyond defined lake boundaries during the break up period represents a relatively large volume of water in contact with an extensive surface area of floodplain landscape. Prior work has documented the potential for floodwaters percolating in flooded vegetation to acquire significant concentrations of nutrients and DOC (Lesack et al. 1998, Lesack et al. submitted). The present results indicate that 25.8 km^3 of floodwater may spread out over 11,200 km^2 during a typical break up. Based on 25.8 km^3 of floodwater remixing with 54.0 km^3 of river water, the acquisition of nutrients to the floodwaters from the flooded vegetation and soils (or stripping from the flood water) would not have to be large to affect the overall content of river water when floodwaters recede to the river. In the case of some constituents such as DOC, TDN and TDP, the leaching effect from flooded vegetation could be substantial (Lesack et al. 1991, Lesack et al. submitted).

An additional consideration is that during storage in the delta, river water has considerable opportunity for photochemical reactions to occur using coloured dissolved organic matter as a substrate. The present results indicate 25.8 km^3 of flood water from the river effectively spreads out in a thin layer (2.3 m thick) over an area of 11,200 km^2, during a period of 24 hour day-length (within a couple weeks of the arctic summer solstice). Prior work has documented significant photo-bleaching of DOC and build up of H_2O_2 among lakes of the delta during periods near the solstice (Febria et al. submitted).

Overall, the water storage volumes derived from our present work can be used to generate testable hypotheses about each of the above mechanisms (Chapter 2).

1.5.4 Climate change and potential responses of the delta system

In a review of the effects of climate change on freshwater ecosystems of North America, Rouse et al. (1997) concluded that regional runoff will probably decrease because lowering of the permafrost table and associated increases in soil moisture capacity. This would likely be more important than the possibility of modestly enhanced precipitation. The review also concluded that decreased ice-cover thicknesses, longer ice-free seasons and smaller temperature gradients between southern and northern portions of drainage basins would lead to reduced ice-jamming and reduced flooding in large north-flowing rivers such as the Mackenzie. Taking that analysis further, Lesack et al. (submitted) concluded reduced ice-jamming and discharge in the Mackenzie will lead to overall reduced water levels in the Mackenzie Delta and reduced storage of river water during the high-flow period of spring break up. Evaporative losses, however, may be reduced with less water being stored in lakes where evaporative losses can be considerable (Lesack and Marsh 1996). A couple of recent papers have suggested that runoff in circumpolar north-flowing rivers discharging into the Arctic Ocean have increased over the last several decades (Peterson et al. 2002, Lammers et al. 2001). We have not based our analysis on the premise of increasing river discharge because the Mackenzie doesn't seem to fit with the other rivers (Peterson et al. 2002) and we are not yet convinced this analysis is generally plausible. A substantial portion of annual river discharge in the Mackenzie (potentially up to 30%) occurs during the spring break up period, when it is not possible to accurately measure discharge because of extensive ice-jamming in river channels and non-static channel cross-sections. While it is possible these other rivers may differ from the Mackenzie, we would be surprised if discharge measurements in the other circumpolar rivers during break up were not fraught with the same challenges as in the Mackenzie.

Major changes in the delta are a reality on an annual scale and are expected to increase under climate change scenarios (Marsh and Lesack 1996). Each habitat type in the delta, especially floodplain lakes, is expected to undergo changes beyond the usual interaction between annual erosion and sedimentation. The Mackenzie Delta is expected to undergo significant temperature rises of between 3-5 C according to global circulation models (Rouse et al. 1997). This is widely expected to decrease the ice content within the delta channels, thus providing weaker and less expansive ice jamming that jumpstarts stage rise and delta flooding. Additionally, due to the currently observed rise in sea level in the arctic (Proshutinsky et al. 2001) and increased erosion of thawing permafrost, sedimentation will likely increase in the delta as predicted in arctic rivers overall (Syvitski 2002). Each scenario should contribute to a greater rate of floodplain lake loss through the delta. A reduction in flood stage will restrict flooding to the lower elevation lakes closer to river channels and breached levees, leaving negative water balances to high elevation lakes (~33% of total lake numbers; Marsh and Hey 1989). Most high-closure lakes are relatively small in area and lake volume, thus they are increasingly susceptible to drying up between prolonged periods of non-flooding. Sedimentation in the lower lying lakes can be quite substantial during a typical year in the delta, often reaching several centimeters per annum (Marsh et al. 1999 and references within). With conditions where sedimentation may be enhanced (Syvitski 2002), lake infilling could dramatically increase. Inundation of the coastal delta lakes is possible with sea level rise, resulting in significant losses of typically large lakes in the delta. Permafrost reduction in the delta would promote a greater level of soil sequestration of water during the runoff period and even losses of lake volume through banks previously frozen and essentially impermeable, something already apparent in other arctic regions (Smith et al. 2005).

Wetland and channel coverage in the delta could become increasingly dynamic and unpredictable under a climate-warming scenario. Wetlands in the delta are mostly generated through abandoned channel and lake infilling and generally are at various stages of the processes. In an environment where more open water is expected to be lost, wetland coverage could substantially rise. Channels may expect reduced ice-scouring by ice-jamming, thus reducing bank and levee erosion during the flood period. Terrestrial coverage in the delta would be expected to expand, allowing for more coverage of large vegetation and more soil water retention.

Under typical climate warming scenarios in the delta, water content is expected to reduce drastically with feedbacks pointing towards more soil retention of water and more delivery of floodwaters to the ocean rather than to the floodplain. This may have important implications for aquatic habitat in the delta and their ecosystem structures as well as for the coastal Beaufort region. Reduced connection of river waters with the floodplain may have important implications for nutrient fluxes and contaminant sequestration.

1.6 Conclusions

Our lake census of the Mackenzie Delta has shown that lake abundance is nearly twice as high as previously thought, with about 45,000 lakes greater than 0.0014 km^2 in area accounting for 99.9% of total lake area in the system. The total water volume potentially stored in the delta at peak water levels (31.2 km^3) is a substantial volume relative to total Mackenzie River flow (85.2 km^3) during the high-discharge period of delta break up. During this period, the stored river water can be envisioned in the form of a thin layer of water (2.3 m thick on average) spread out over 11,200 km^2 of lakes and flooded vegetation and exposed to 24 hour per day solar irradiance (arctic summer solstice) (Lesack et al. submitted). We thus conclude the volume of river water moving through the delta during the spring break up period is a significant percentage of total flow to affect nutrient fluxes to the Beaufort Sea. These results are compelling evidence that water exchange between the delta floodplain and the river channel must be better quantified via hydraulic modeling, to correctly quantify riverine nutrient fluxes to the Beaufort Sea. Given that other work has indicated climatic warming will lead to reduced delta lake coverage and reduced ice jamming and water levels in the Mackenzie River (Rouse et al. 1997, Lesack et al. submitted), the present work suggests a concomitant reduction in river water stored in the delta during break up could also affect riverine fluxes of nutrients to the Beaufort.

1.7 References

Aagaard, K., and E.C. Carmack. 1989. The role of sea ice and other fresh-water in the arctic circulation. *Journal of Geophysical Research-Oceans* 94(C10): 14485-14498.

Burn, C.R. 1995. The hydrologic regime of Mackenzie River and connection of no closure lakes to distributary channels in the Mackenzie Delta, Northwest-Territories. *Canadian Journal of Earth Sciences* 32(7): 926-937.

Carson, M.A., F.M. Conly, and J.N. Jasper. 1999. Riverine sediment balance of the Mackenzie Delta, Northwest Territories, Canada. *Hydrological Processes* 13(16): 2499-2518.

Cauwet, G., and I. Sidorov. 1996. The biogeochemistry of Lena River: Organic carbon and nutrients distribution. *Marine Chemistry* 53(3-4): 211-227.

Dittmar, T., and G. Kattner. 2003. The biogeochemistry of the river and shelf ecosystem of the Arctic Ocean: a review. *Marine Chemistry* 83(3-4): 103-120.

Environmental Systems Research Institute, Inc. (ESRI)®. 2004. ArcMap™. Version 9.0 [computer program]. Environmental Systems Research Institute, Inc.®, Redlands, CA.

Febria, C.M., L.F.W. Lesack, J.A.L. Gareis, and M.L. Bothwell. 2005. Patterns of hydrogen peroxide among lakes of the Mackenzie Delta, western Canadian Arctic. Submitted: *Canadian Journal of Fisheries and Aquatic Sciences.*

Forsberg, B.R., A.H. Devol, J.E. Richey, L.A. Martinelli, and H. Dossantos. 1988. Factors controlling nutrient concentrations in Amazon floodplain lakes. *Limnology and Oceanography* 33(1): 41-56.

Gordeev, V.V. 2000. River input of water, sediment, major ions, nutrients and trace metals from Russian territory to the Arctic Ocean. The freshwater budget of the Arctic Ocean. Norwell, Mass., Kluwer. Editor E.L. Lewis.

Hill, P.R., S.M. Blasco, J.R. Harper, and D.B. Fissel. 1991. Sedimentation on the Canadian Beaufort Shelf. *Continental Shelf Research* 11(8-10): 821-842.

Hill, P.R., C.P. Lewis, S. Desmarais, V. Kauppaymuthoo, and H. Rais. 2001. The Mackenzie Delta: sedimentary processes and facies of a high-latitude, fine-grained delta. *Sedimentology* 48(5): 1047-1078.

Holmes, R.M., B.J. Peterson, A.V. Zhulidov, V.V. Gordeev, P.N. Makkaveev, P.A. Stunzhas, L.S. Kosmenko, G.H. Kohler, and A.I. Shiklomanov. 2001. Nutrient chemistry of the Ob' and Yenisey Rivers, Siberia: results from June 2000 expedition and evaluation of long-term data sets. *Marine Chemistry* 75(3): 219-227.

Jenner, K.A., and P.R. Hill. 1998. Recent, arctic deltaic sedimentation: Olivier Islands, Mackenzie Delta, North-west Territories, Canada. *Sedimentology* 45(6): 987-1004.

Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Can. Spec. Publ. Fish. Aquat. Sci. 106: 110-127.

Lammers, R.B., A.I. Shiklomanov, C.J. Vorosmarty, B.M. Fekete and B.J. Peterson. 2001. Assessment of contemporary arctic river runoff based on observational discharge records. *Journal of Geophysical Research-Atmospheres* 106(D4): 3321-3334.

Lara, R.J., V. Rachold, G. Kattner, H.W. Hubberten, G. Guggenberger, A. Skoog, and D. N. Thomas. 1998. Dissolved organic matter and nutrients in the Lena River, Siberian Arctic: Characteristics and distribution. *Marine Chemistry* 59(3-4): 301-309.

Lesack, L.F.W., P. Marsh, and R.E. Hecky. 1991. Ice cover growth and freeze-out of solutes in a Mackenzie Delta lake, p. 219-236. In T.D. Prowse and C.S.L. Ommanney [eds.], Northern hydrology: Selected perspectives. Environment Canada, NHRI Symp. 6, July 1990, Saskatoon.

Lesack, L.F.W., P. Marsh, and R.E. Hecky. 1998. Spatial and temporal dynamics of major solute chemistry among Mackenzie Delta lakes. *Limnology and Oceanography* 43(7): 1530-1543.

Lesack, L.F.W., M.M. Squires, P. Marsh, C.A. Emmerton, C.M. Febria, J.A.L. Gareis, A.J. Riedel, B.M. Spears, C.J. Teichreb, and M.L. Bothwell. 2005. Ecology of lakes in the Mackenzie River Delta: Potential responses to global change. Submitted: *Ecological Monographs*.

Lewis CP. 1988. Mackenzie Delta sedimentary environments and processes. Unpub. manuscript. Available at Environment Canada, Ottawa, K1A OH3, Canada.

Lobbes, J.M., H.P. Fitznar, and G. Kattner. 2000. Biogeochemical characteristics of dissolved and particulate organic matter in Russian rivers entering the Arctic Ocean. *Geochimica Et Cosmochimica Acta* 64(17): 2973-2983.

Macdonald, R.W., S.M. Solomon, R.E. Cranston, H.E. Welch, M.B. Yunker, and C. Gobeil. 1998. A sediment and organic carbon budget for the Canadian Beaufort Shelf. *Marine Geology* 144: 255-273.

Mackay, J. R. 1963. The Mackenzie Delta Area, N.W.T. Misc. Report 23, Ottawa: Geological Survey of Canada: 202 p.

Mackenzie River Basin Committee (MRBC). 1981. Mackenzie River Basin Study Report. A report under the 1978-81 Federal-Provincial Study Agreement respecting the water and related resources of the Mackenzie River Basin. 231 p.

Marsh, P., and M. Hey. 1989. The flooding hydrology of Mackenzie Delta lakes near Inuvik, NWT, Canada. *Arctic* 42(1): 41-49.

Marsh, P., and M. Hey. 1991. Spatial variations in the flooding of Mackenzie Delta lakes. Workshop on Mackenzie Delta: Environmental interactions and implications of development. Saskatoon, October 1989. Marsh P., Ommanney C.S.L. National Hydrology Research Institute, Saskatoon, Saskatchewan; 9-18.

Marsh, P., and M. Hey. 1994. Analysis of spring high water events in the Mackenzie Delta and implications for lake and terrestrial flooding. *Geografiska Annaler Series a-Physical Geography* 76(4): 221-234.

Marsh, P., and T. Schmidt. 1993. Influence of a Beaufort Sea storm-surge on channel levels in the Mackenzie Delta. *Arctic* 46(1): 35-41.

Marsh, P., and L.F.W. Lesack. 1996. The hydrologic regime of perched lakes in the Mackenzie delta: Potential responses to climate change. *Limnology and Oceanography* 41(5): 849-856.

Marsh, P., L.F.W. Lesack, and A. Roberts. 1999. Lake sedimentation in the Mackenzie Delta, NWT. *Hydrological Processes* 13(16): 2519-2536.

Marsh, P., M. Russell, and C. Onclin. 2005. The hydrology of lakes in the Western Candian Arctic – implications to proposed natural gas development. 15th International Northern Research Basins Symposium and Workshop, Lulea to Kvikkjokk, Sweden, 29 Aug. – 2 Sep. 2005.

Meybeck, M. 1982. Carbon, nitrogen, and phosphorus transport by world rivers. *American Journal of Science* 282: 401-450.

Opsahl, S., R. Benner, and R.M.W. Amon. 1999. Major flux of terrigenous dissolved organic matter through the Arctic Ocean. *Limnology and Oceanography* 44(8): 2017-2023.

Peterson, B.J., R.M. Holmes, J.W. McClelland, C.J. Vorosmarty, R.B. Lammers, A.I. Shiklomanov, I.A. Shiklomanov and S. Rahmstorf. 2002. Increasing river discharge to the Arctic Ocean. *Science* 298(5601): 2171-2173.

Prowse, T.D. 1986. Ice jam characteristics, Liard-Mackenzie rivers confluence. *Canadian Journal of Civil Engineering* 13(6): 653-665.

Pipke K.J. 1996. Under-ice methane accumulation in Mackenzie Delta Lakes and potential flux to the atmosphere at ice-out. M.Sc. Thesis: Simon Fraser University; 198 pp.

Proshutinsky, A., V. Pavlov, and R.H. Bourke. 2001. Sea level rise in the Arctic Ocean. *Geophysical Research Letters* 28(11): 2237-2240.

Rouse, W.R., M.S.V. Douglas, R.E. Hecky, A.E. Hershey, G.W. Kling, L. Lesack, P. Marsh, M. McDonald, B.J. Nicholson, N.T. Roulet, and J.P. Smol. 1997. Effects of climate change on the freshwaters of arctic and subarctic North America. *Hydrological Processes* 11(8): 873-902.

SAS Institute Inc. 2003. JMP®. Version 5.0.1.2 [computer program]. SAS Institute Inc., Cary, N.C.

Sippel, S.J., S.K. Hamilton, and J.M. Melack. 1992. Inundation area and morphometry of lakes on the Amazon River floodplain, Brazil. *Archiv Fur Hydrobiologie* 123(4): 385-400.

Smith, L.C., Y. Sheng, G.M. MacDonald, and L.D. Hinzman. 2005. Disappearing arctic lakes. *Science* 308: 1429.

Squires, M.M., L.F.W. Lesack, and D. Huebert. 2002. The influence of water transparency on the distribution and abundance of macrophytes among lakes of the Mackenzie Delta, Western Canadian Arctic. *Freshwater Biology* 47(11): 2123-2135.

Syvitski, J.P.M. 2002. Sediment discharge variability in Arctic rivers: implications for a warmer future. *Polar Research* 21(2): 323-330.

Telang, S.A., R. Pocklington, A.S. Naidu, E.A. Romankevich, I.I. Gitelson, and M.I. Gladyshev. 1991. Carbon and mineral transport in major North American, Russian Arctic, and Siberian rivers; the St. Lawrence, the Mackenzie, the Yukon, the Arctic Alaskan rivers, the Arctic Basin rivers in the Soviet Union, and the Yenisei. Biogeochemistry of major world rivers SCOPE (Chichester) 42: 75-104.

Water Survey of Canada (WSC). 2005. [Online]. Data products and services. Available: http://scitech.pyr.ec.gc.ca/waterweb/formnav.asp?lang=0.

1.8 Tables

Table 1.1 Maps identifiers and aerial photography dates upon which digital topographical files were based. NTS represents the Canadian National Topographical System for numbering topographical maps.

NTS NUMBER	MONTH	YEAR	NTS NUMBER	MONTH	YEAR
UPPER DELTA					
106M09	August	1950	106M15	August	1950
106M10	August	1950	106M16	August	1950
106M11	August	1952	106N13	Late June, August	1950
106M14	September	1984			
MIDDLE DELTA					
107B02	August	1950	107B10	August	1950
107B03	August	1950	107B11	August	1950
107B04	Late June	1954	107B12	August	1950
107B05	Late June	1954	107B13	Late June	1954
107B06	August	1950	107B14	August	1950
107B07	August	1988			
LOWER DELTA					
107C03	August	1950	107C11	August	1950
107C04	August	1950	107C12	August	1950
107C05	August	1950	117A09	Late June, August	1954
107C06	August	1950	117A15	August	1954
107C07	August	1950	117A16	Late June, August	1954
107C10	August	1950	117D01	August	1985

Table 1.2 Summary of descriptive statistics on lake areas in the Mackenzie Delta.

PARAMETER	RESULT
LAKE ABUNDANCE AND AREA:	
Lake Abundance	49,046
Total of Lake Areas	3330.9 km^2
Mean Lake Area	0.068 km^2
OTHER STATISTICS:	
Maximum Lake Area	42.7 km^2
Minimum Lake Area	$3.0x10^{-6}$ km^2
Median Lake Area	0.014 km^2
Variance of Lake Areas	10.9 km^2
Standard Deviation of Lake Areas	0.33 km^2
Standard Error of Lake Areas	0.002 km^2
Range of Lake Areas	42.7 km^2
Quartiles of Lake Areas	0.004 km^2

Table 1.3 Estimates of total water volume in lakes of the Mackenzie Delta, potential storage of river flow in the delta during annual peak water levels and parameters needed for estimation of water volumes.

PARAMETER	RESULTS
TOTAL DELTA AREA	**13,135 km^2**
Channels	1,744 km^2
Lakes	3,331 km^2
Wetlands (floodplain)	1,614 km^2
Non-wet floodplain	6,446 km^2

DELTA AREA AND LAKE VOLUME DURING LOW WATER (1.231 m asl)

	Floodplain Area (km^2)	Lake Areal Fraction	Lake Area (km^2)	Average Depth (m)	Water Volume (km^3)
No-closure	5,070	0.629	2,095	1.66	3.48
Low-closure	2,088	0.259	863	1.37	1.18
High-closure	911	0.113	376	1.84	0.69
TOTAL	8,060		3,331		**5.35**

WATER VOLUME ADDED TO LAKES DURING PEAK FLOOD (5.636 m asl)

	Flooded Area (km^2)	Base Water Elevation (m asl)	Maximum Depth Added (m)	Minimum Depth Added (m)	Average Depth Added (m)	Water Volume (km^3)
No-closure	2,095	1.231	4.405	4.136	4.271	8.95
Low-closure	863	1.50	4.136	1.636	2.886	2.49
High-closure	308	4.00	1.636	0	0.818	0.25
TOTAL	3,266					**11.69**

Table 1.3 (continued) Estimates of total water volume in lakes of the Mackenzie Delta, potential storage of river flow in the delta during annual peak water levels, and parameters needed for estimation of water volumes.

WATER VOLUME IN FLOODPLAIN DURING PEAK FLOOD (5.636 m asl)						
	Flooded Area (km^2)	Base Water Elevation (m asl)	Maximum Depth Added (m)	Minimum Depth Added (m)	Average Depth Added (m)	Water Volume (km^3)
No-closure	5,070	1.231	4.405	4.163	2.135	10.83
Low-closure	2,088	1.50	4.136	1.636	1.443	3.01
High-closure	745	4.00	1.636	0	0.409	0.30
TOTAL	7,902					**14.14**
WATER VOLUME ADDED TO CHANNELS DURING PEAK FLOOD (5.636 m asl)						
TOTAL	1,744	1.231			4.405	**7.68**
TOTAL DELTA STORAGE (plus channels) DURING PEAK FLOOD (5.636 m asl)						
TOTAL						**38.87**

Mean of spring peak water levels	5.636	m asl
Mean of summer low water levels	1.231	m asl
Area flooded	11, 168	km^2
Overall mean depth of flood-water	2.31	m
Flood-water volume	25.83	km^3
Lake-water volume	5.35	km^3

MACKENZIE DELTA RIVER FLOWS			
Mean annual flow	284	km^3	WSC (2005)
Fraction of flow during delta break up	0.30		
Estimated flow during delta break up	85.2	km^3	
Total flood-water storage in delta at peak flow (no channels)	31.2	km^3	

1.9 Figures

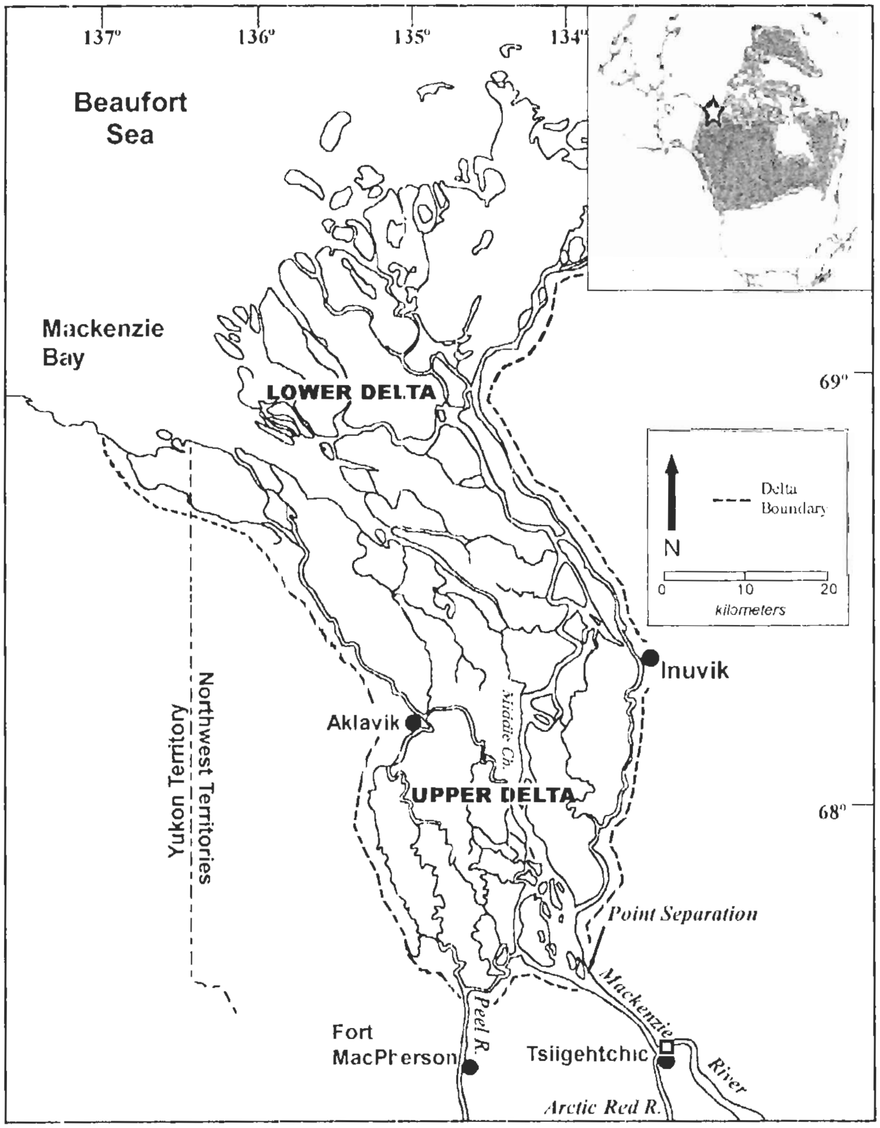

Figure 1.1 Map of Mackenzie Delta study area, Northwest Territories, Canada. The grey box indicates approximate location of the Mackenzie River above Arctic Red River Water Survey of Canada gauging station. Approximately 91% of all inflowing delta water is measured at this station.

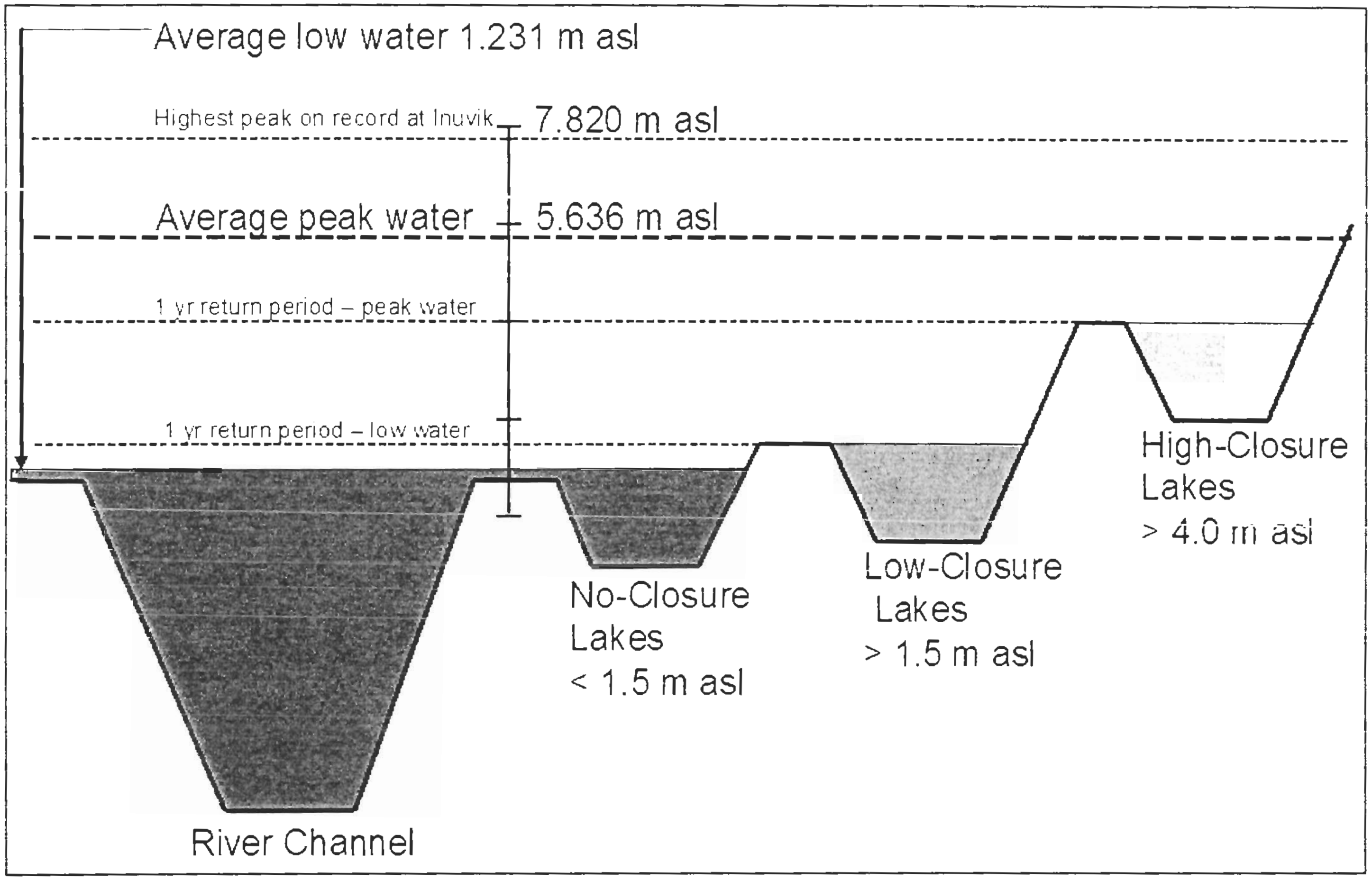

Figure 1.2 A schematic of the lake classification of the Mackenzie Delta along with lake sill elevations and flooding levels based on water levels at the Inuvik, NT gauging station (after Mackay 1963; Marsh and Hey 1989).

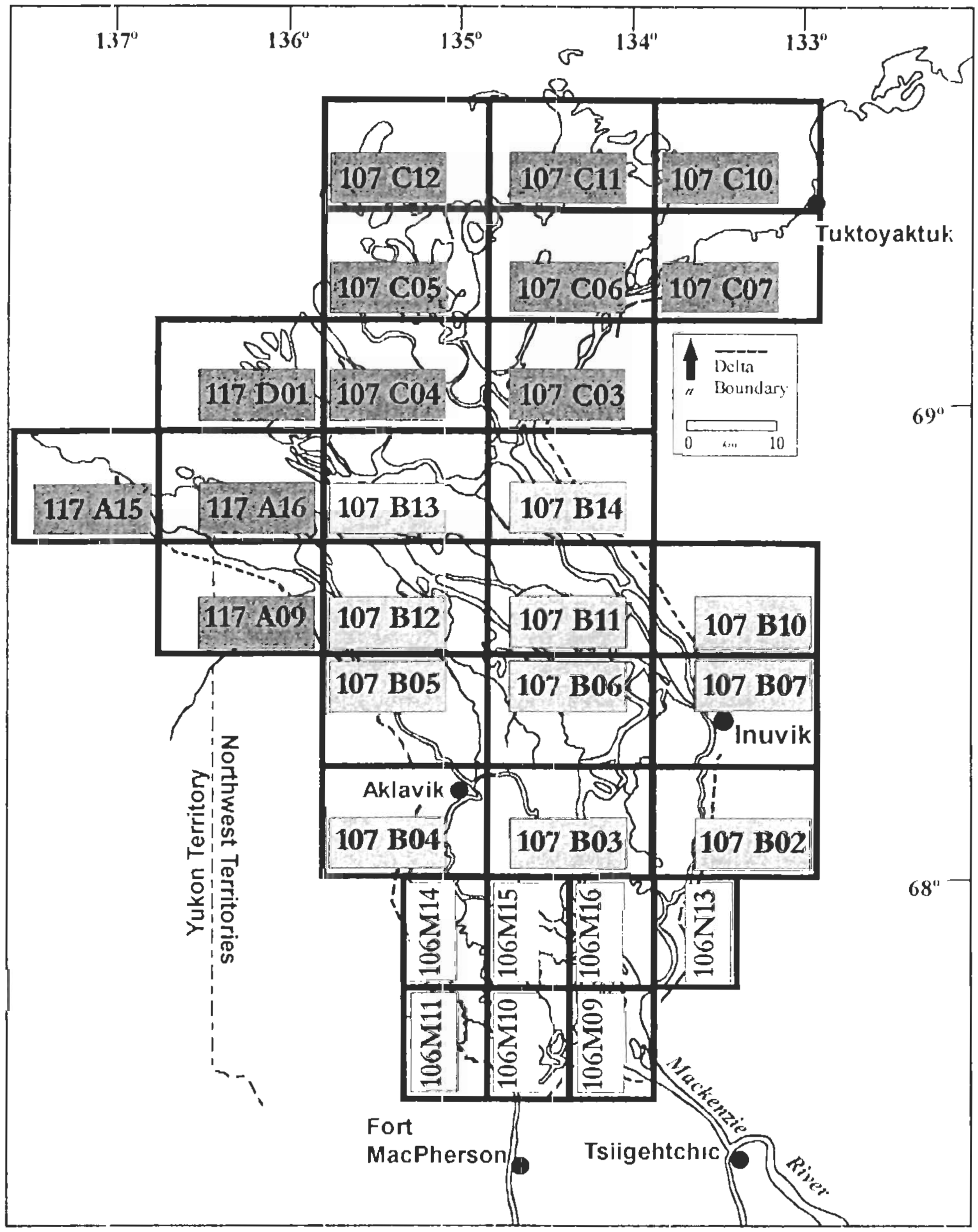

Figure 1.3 Coverage of digital topographical maps used in the delta study. Partitioning of delta regions in this study were as follows: white boxes represent the upper delta region, light grey the middle delta and dark grey the lower delta. Map labels are National Topographic System numbers from the Canadian Centre for Topographical Information.

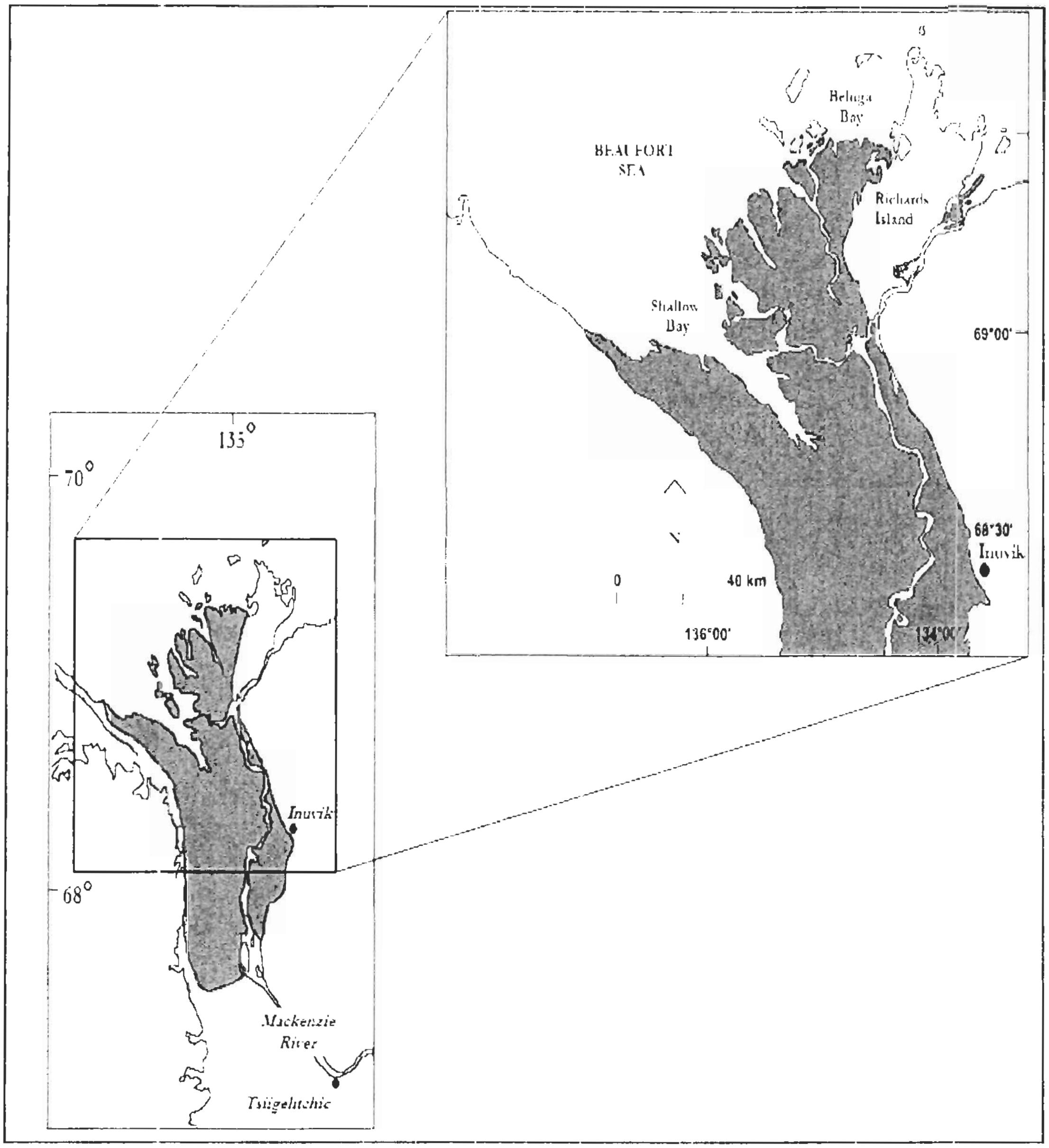

Figure 1.4 Delineation of the Mackenzie Delta landscape (modified from Hill et al. 2001). Dark grey indicates delta area used in the analysis.

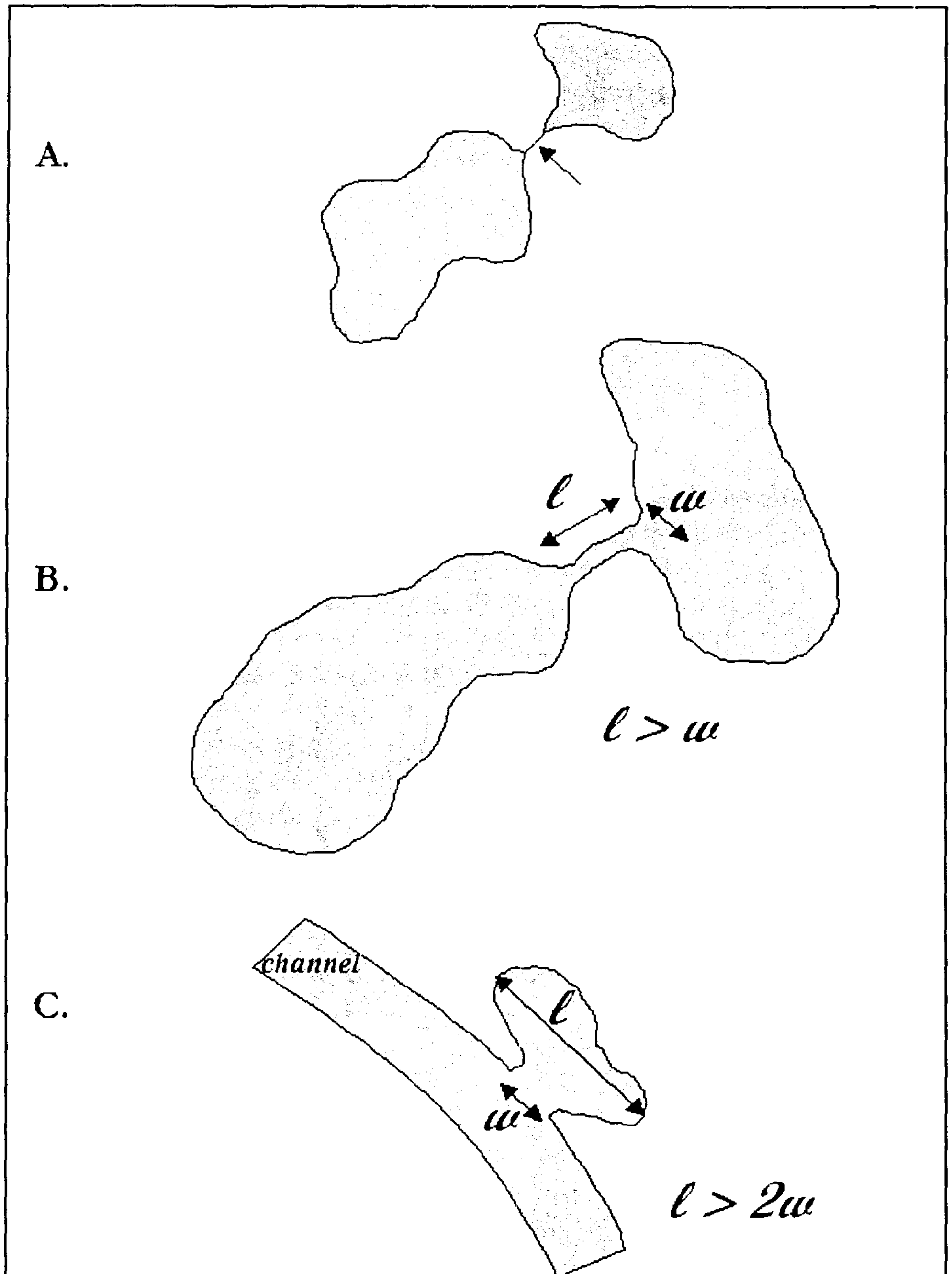

Figure 1.5 Lake classification criteria resulting in lake separation: (A) single connection line between lakes; (B) a connection longer than wide between lakes; (C) a connection between a lake and river that is shorter in width than half of the maximum lake length.

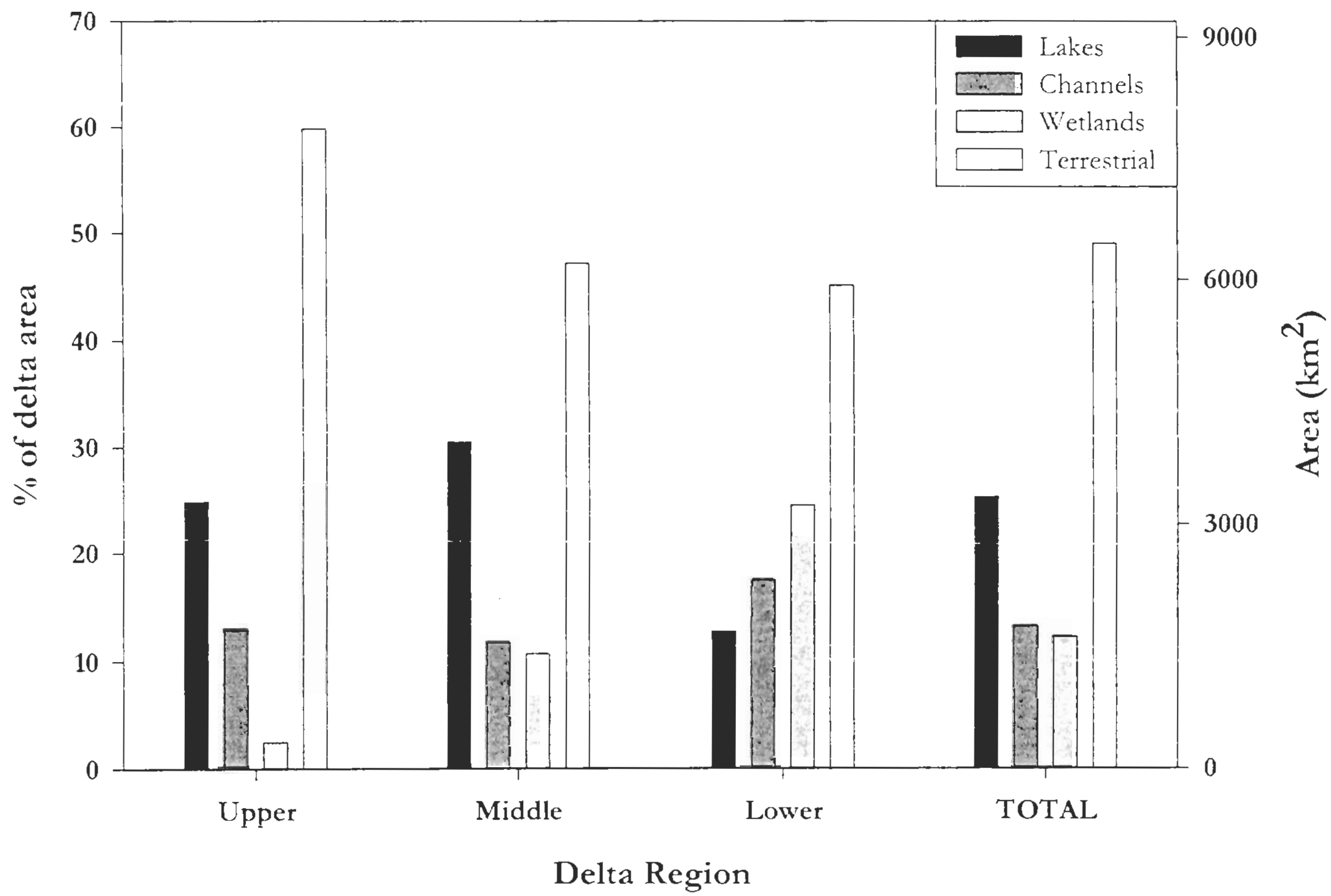

Figure 1.6 Percent and absolute habitat coverage in the Mackenzie Delta. Total delta area is 13,136 km^2.

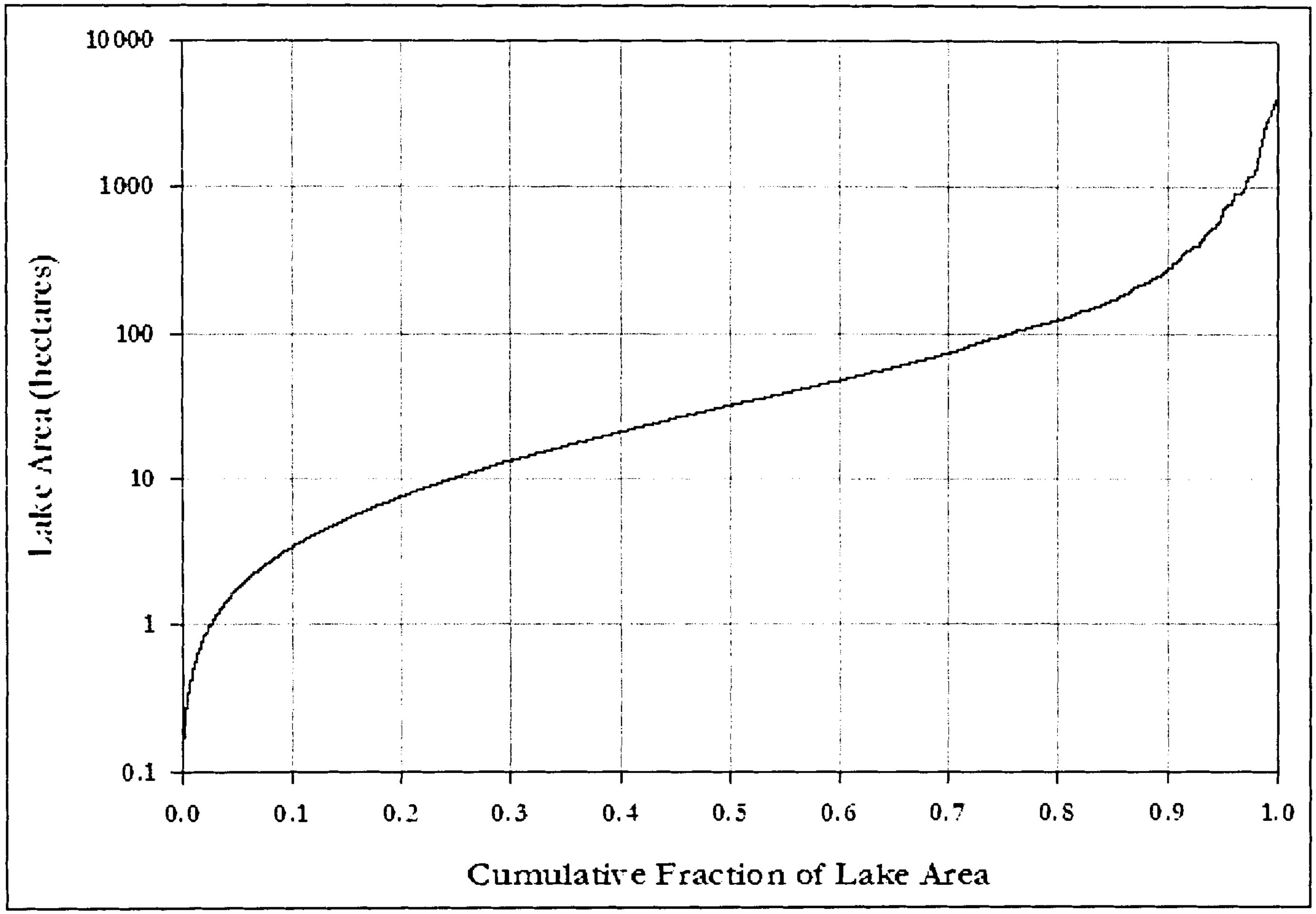

Figure 1.7 Lake size as a function of cumulative fraction of lake area in the Mackenzie Delta. Most lake area in the delta is provided by lakes larger than $0.01 km^2$.

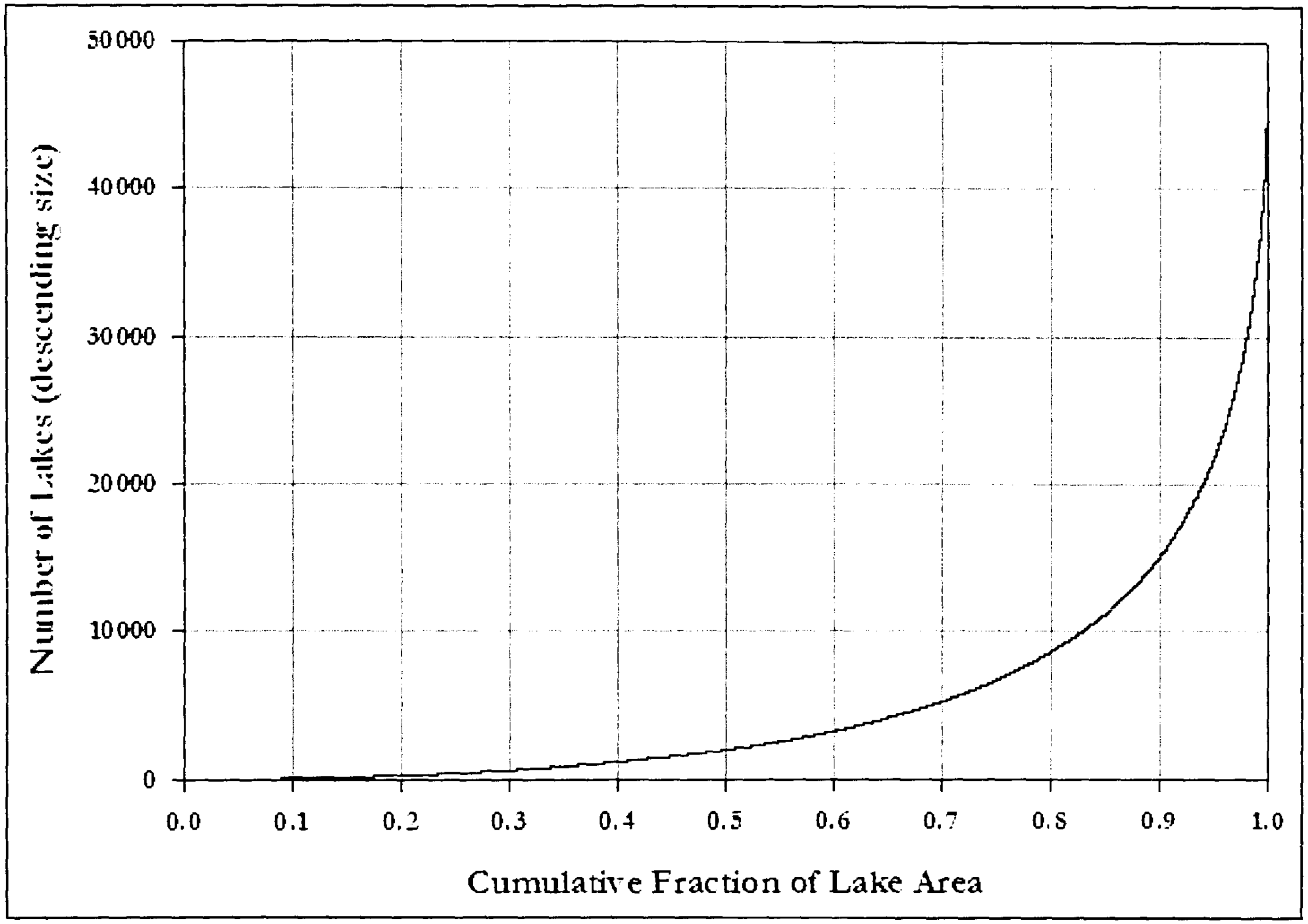

Figure 1.8 Lake counts ordered by descending lake size as a function of cumulative fraction of lake area. Lake counts are dominated by lakes of small area.

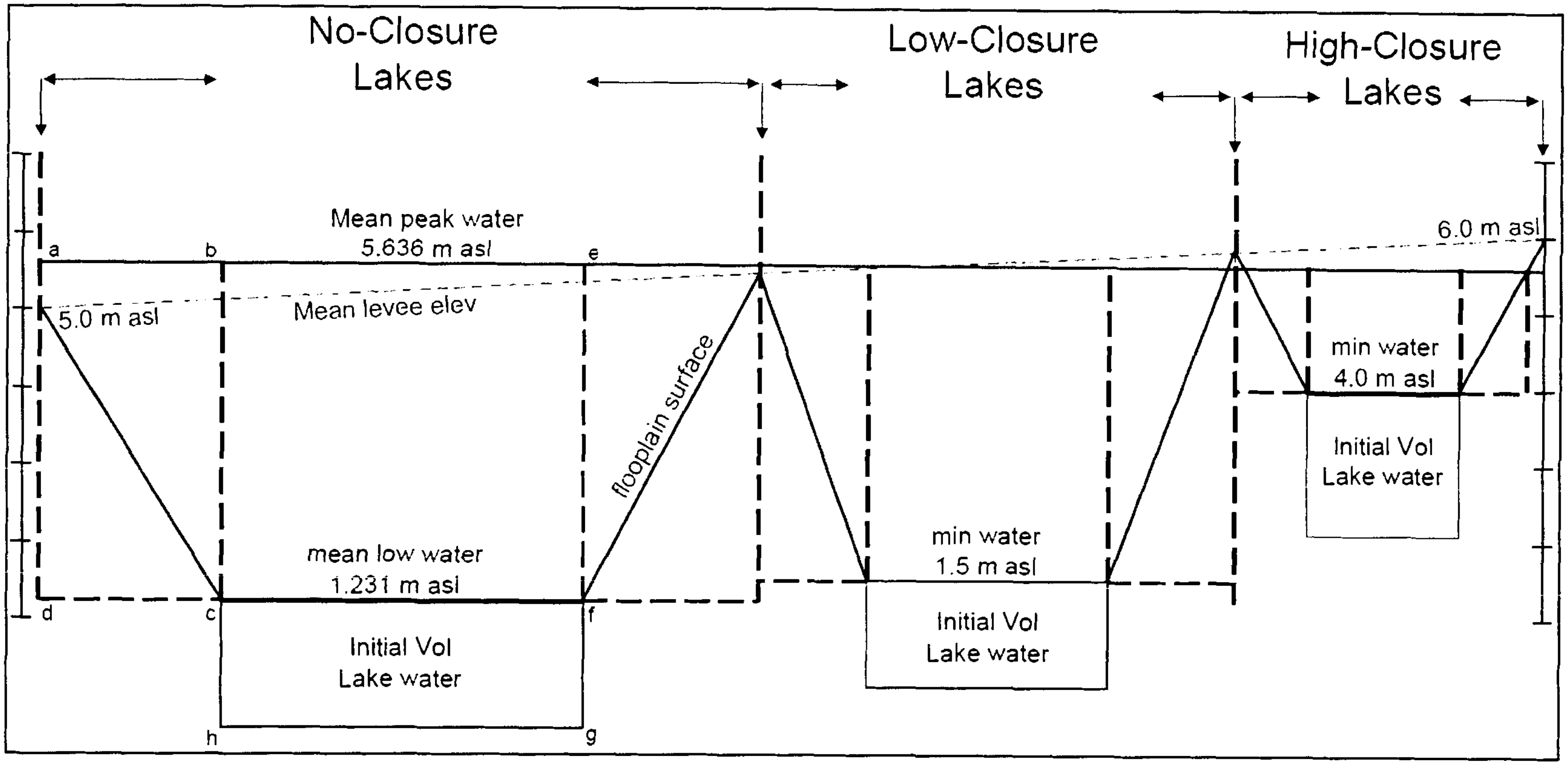

Figure 1.9 Conceptual model of potential water volume storage in no-closure, low-closure and high-closure lakes (box cfgh) (Marsh and Hey 1989) in the Mackenzie Delta, in river-water added to the lakes (box befc) and river-water on areas of the delta floodplain (box abcd) associated with each closure-class. Diagram is drawn to approximate vertical and lateral scales (each set of boxes represents total lake area in particular closure-class) and levee heights are derived from Marsh and Hey (1994).

2 CHANGES IN RIVER-BORNE NUTRIENTS DOWNSTREAM THROUGH THE MACKENZIE DELTA, WESTERN CANADIAN ARCTIC

2.1 Abstract

The effect of the Mackenzie Delta on riverine nutrient outflows to the Beaufort Shelf, historically measured upstream of the delta, was assessed during open water conditions of 2003 and 2004. The difference in nutrient content in river water from the inflow point of the upper delta to the outflow points of the distributary channels in the lower delta was measured 2 times during 2003 and 3 times during 2004 to assess whether nutrients moving through the delta behaved conservatively. A new estimate of the peak water storage volume for the delta (Chapter 1) permitted the development of a two-source mixing model (i.e. channel water versus lake storage) during the recession period of 2004. The model compared delta nutrient outflows from river water that did not go into lake storage with river water that remixed with water coming out of lake storage. Comparing the lumped volume-weighted mean concentrations between the two scenarios showed that prior to outflow from the delta, particle content (TSS, POC, PN, PP) and inorganic dissolved nutrients (nitrate, phosphate, silica, sulfate) were reduced, but total dissolved nutrients were enhanced apparently because organic forms of nutrients (dissolved organic nitrogen and phosphorus) were coming out of the delta.

KEYWORDS: arctic; delta; lakes; nutrients; Mackenzie

2.2 Introduction

The Mackenzie River Delta, in Canada's western Arctic, is expected to experience mean air temperature increases of 3-5°C as predicted by general circulation models (Moritz et al. 2002; Rouse et al. 1997). Warming and associated environmental responses have progressed in regions of the arctic (Mueller et al. 2003; Vincent and Pienitz 1996; Comiso 2003; Smith et al. 2005) and are expected intensify in the delta region. Warming-induced changes in the delta may have important consequences for the western Arctic Ocean as the Mackenzie River exerts strong controls on its productivity, salinity and water circulation (Opsahl et al. 1999; Holmes et al. 2001; Aagaard and Carmack 1989). One important climatic response of the delta may be a reduction in seasonal ice jams that facilitate widespread flooding of the ecologically sensitive delta area. This annual spring flood-pulse process (Junk et al. 1989) transports nutrient-laden water to the lake-rich floodplain and plays a critical role in sustaining the aquatic ecological health of the entire delta (Lesack et al. 1998). Consequently, this interaction with the floodplain plays an important role in determining the type and magnitude of nutrient fluxes delivered to the western Arctic Ocean.

Nutrient chemistry of large arctic rivers is an important indicator of basin change and largely controls the biological activity in estuaries and marine shelves (Holmes et al. 2001; Meybeck 1982). A general descriptive model of nutrient transport for the large Siberian and Mackenzie rivers can be described based on recent studies (Dittmar and Kattner 2003; Holmes et al. 2001; Lobbes et al. 2000; Gordeev 2000; Lara et al. 1998; Cauwet and Sidorov 1996; Telang et al. 1991; Meybeck 1982). Nutrient chemistry in the great arctic rivers follows a highly seasonal pattern that is controlled by their annual hydrological response (Vorosmarty et al. 2001). This response is characterized by three notable hydrograph stages during a water year (Fig. 2.1): (1) an extended ice-covered winter period of low flow (Burn 1995); (2) a dominant spring flooding event induced by snowmelt and local ice jamming (Prowse and Carter 2002); and (3) a post-flood recessional period with intermittent frontal precipitation (Burn 1995; Hill et al. 2001). This hydrological response contributes to nutrient characteristics quite different from world river averages (Meybeck 1982). Dissolved inorganic nutrient concentrations (nitrate, phosphate, silica and others) progress from a maximum in early spring due to flow dominance of nutrient-rich groundwater, to a minimum during the spring freshet period due to dilution (Cauwet and Sidorov 1996; Holmes et al. 2000). Ammonium is a notable exception to this model as snow and river ice are relatively high in ammonium and low in oxidized nutrients (Dittmar and Kattner 2003). Levels of inorganic nutrients in arctic rivers, however, are among the world's lowest (Meybeck 1982). Alternatively, dissolved organic nutrients (carbon, nitrogen, phosphorus) and particulates (carbon, nitrogen, phosphorus, total suspended solids) peak in correspondence with spring high water in arctic rivers. Snowmelt percolating through organic-rich taiga soils (Dittmar and Kattner 2003) and erosive runoff in their basins contributes to peak levels during freshet. Post flooding brings declines of organics and particulates as runoff is reduced. Each then progress towards a winter minimum where groundwaters, largely void of organics and particulates, dominate flow. Overall, organic matter content in arctic rivers is among the highest reported in world rivers (Dittmar and Kattner 2003) while sediment content is variable across arctic rivers. The biogeochemistry of large arctic rivers is normally variable without obvious downstream gradients (Lara et al. 1998; Millot et al. 2003; Gordeev et al. 2004), likely due to intense mixing, low temperatures and strong light limitation on primary producers. However, large changes may be observed when turbidity and water colour limitations decrease, such as in floodplain lakes.

River water entering and interacting with floodplains is expected to undergo chemical changes before drainage and discharge to the ocean. Such changes have been investigated in large temperate and tropical floodplains (Friedrich et al. 2003; Forsberg et al. 1988; Fisher and Parsley 1979; Maine et al. 2004; Vandenbrink et al. 1993; Vegas-Vilarrubia and Herrera 1993; Knowlton and Jones 2003), however few studies have looked at these processes in arctic delta floodplains. Arctic deltas could have substantial effects on incoming river floodwaters due to the relatively high density of lakes in their floodplains compared to other regions (Emmerton et al. submitted; Sippel et al. 1992). In the Mackenzie Delta, lakes cover about one quarter of its total area and about 95% of that area is flooded during an average discharge year. Further, it is estimated that lakes mix with and store as much as one-third of all incoming river water during the flooding period (Emmerton et al. submitted). Since delta lakes are important temporary reservoirs during the flooding period, their shallow and low energy environments are expected to affect the biogeochemistry of river waters. Suspended particles rapidly settle out in the lakes, depositing particle-bound nutrients as well as reducing light attenuation through the water column. Attenuation is further decreased as coloured dissolved organic carbon (CDOC) is photobleached by the nearly 24 hr irradiation during the arctic summer (Febria et al. submitted). With increased light availability, primary production increases and inorganic nutrients are often reduced to below analytical detection limits. Organic matter within the lakes has several fates including losses through decomposition and heterotrophic uptake to addition from production-related releases and decomposition of particulate organic matter (i.e. macrophytes). Floodwaters interacting with previously non-wetted delta plain have also been observed to strip organic nutrients from the floodplain (Lesack et al. submitted).

Processes that modify river nutrients in arctic deltas can either add or sequester nutrients bound for coastal ecosystems. These mechanisms are susceptible to climate change pressures through such processes as reduced flood events and floodplain connection, increased sediment loads and altered nutrient cycles in the watershed. With such effects likely progressing, it is essential to understand the current magnitude of these controlling mechanisms through the Mackenzie Delta before potential changes. Current studies of arctic rivers have largely overlooked the effect of lake rich deltas on discharging river water, despite their potentially large controlling effects (Emmerton et al. submitted). In the lower Mackenzie River, the most extensive nutrient surveys have occurred at the Mackenzie above Arctic Red River discharge station before the delta (Fig. 2.2; Table 2.1), thus overlooking the effects that the delta may have on seaward water. This study investigated preliminary evidence of nutrient changes through the Mackenzie Delta. The major objectives were:

1. To test the hypothesis that river nutrients transported through the Mackenzie Delta will deviate from conservative behaviour as annual river floodwater returns to the delta channels from temporary storage in the delta lakes and floodplain. Nutrient concentrations in river water at the lower end of the delta are expected to either: (a) increase via recovery of nutrient-enhanced water, or (b) decrease via recovery of nutrient-depleted water, as a result of biogeochemical processes (particle sedimentation,

biological uptake and releases of nutrients and photo-bleaching of coloured DOC) changing the composition of the river water while temporarily stored in the delta.

2. To assess the hypothesis that the Mackenzie Delta has a measurable effect on the flux of riverine nutrients exported to the Arctic Ocean (Beaufort Shelf) during the hydrograph recession period of open-water (delta effect).

2.3 Methods

2.3.1 Study area

The Mackenzie Delta (approx. 68-69°N 134-137°W) lies downstream of the historical mouth of the Mackenzie River, extending northward into the Beaufort Sea in Canada's western Arctic (Fig. 2.2). The delta is the second largest in the circumpolar arctic (approx. 13000 km^2; after the Lena) and can generally be divided into upper, middle (Inuvik-Aklavik section) and lower portions (Fig. 2.2; together termed 'delta' unless otherwise stated). The delta is characterized by numerous anastomosing channels, wetlands and floodplain lakes that combine to cover almost half of the deltaic plain (Emmerton et al. submitted; Marsh et al. 1999; Mackay 1963). The balance of the delta plain is permafrost-influenced silts and sands. Vegetation in the delta plain consists of species of spruce (*Picea*), alder (*Alnus*), willow (*Salix*), birch (*Betula*), poplar (*Populus*) and *Equisetum* (Mackay 1963) and tundra species exist above the treeline. Most lakes are shallow enough to support significant macrophyte growth (common species include *Potamogeton*, *Chara* and *Ceratophyllum*) (Squires and Lesack 2003). About 90% of the delta's water is supplied by the Mackenzie River at Point Separation (Fig. 2.2) with minor contributions by the Peel River in the southwest (~8%) and others (Burn 1995). The high latitude of the delta results in 7-8 months of ice cover each year. Since the Mackenzie River flows from areas of relative warmth towards frozen northern regions, the spring freshet encounters ice dams in the delta environment, resulting in peak water levels and widescale flooding in late May and early June (Prowse 1986; Lesack et al. 1998; Rouse et al. 1997; Marsh and Hey 1989; Marsh et al. 1999). Floodplain lakes are generally small and shallow (<10 ha, <4m) and have been classified by lake elevation and connection to adjacent rivers (Mackay 1963; Marsh and Hey 1989) (Fig. 2.3): (1) lakes connected to river water less than annually are termed 'high closure' (33% of all lakes); (2) lakes connected during annual flooding before cutting off from the river are termed 'low closure' (55%); (3) lakes continuously connected to the river are termed 'no closure' (12%). This flooding gradient results in various biogeochemical, biological and physical gradients across delta lakes (Febria et al. submitted; Squires and Lesack 2003; Lesack et al. 1998).

2.3.2 Sampling programs and field methods

Two 'snapshot' sampling programs were performed to investigate nutrient patterns through the channels of the Mackenzie Delta (Objective 1).

Delta Surveys - Three transects based on work by Carson et al. (1999) were chosen to cross the delta width at its inflow, mid-reach and mouth river channels in order to detect nutrient changes through the delta. A total of 19 sites (Fig. 2.2,#1) were sampled from helicopter floats twice during 2003 (01-Aug., 18-Aug.) and three times during 2004 (14-Jun., 17-Jul., 15-Aug.), with the 14-Jun. survey essentially sampling early water recession in the delta. Sites were catalogued by GPS to ensure consistency between surveys (Table 2.2). All samples were collected approximately mid-channel as surface grab samples using clean, site-rinsed 1L HDPE bottles. During the 5-hour survey period, samples were stored in cool and dark conditions until return to the laboratory.

Mass Balance Survey - A nutrient mass balance survey was conducted on the Mackenzie River East Channel to investigate mass flux changes in nutrients downstream within the river. Three sites (Fig. 2.2,#2; Table 2.2) were selected with sufficient spatial separation to observe changes. The survey was performed on 20-Jul. 2004 by boat with instantaneous discharge measured and water collected at each site. Instantaneous discharge was measured at each site by boat using a differential GPS Acoustic Doppler Profiler from Water Survey Canada (Inuvik). Water was collected at midpoint and quartile distances of the channel width using clean, site-rinsed 2L LDPE bottles. Both surface and column-integrated samples were taken and all data was pooled by site. All samples were subsequently stored in dark and cool conditions during transit to the laboratory.

Two sampling programs were performed to assess measurable nutrient effects of delta lakes on river water in temporary storage during the peak to low water period (Objective 2).

River weekly sampling - Weekly samples were collected from the delta's three inflow rivers (Fig. 2.2,#3; Table 2.2) during the 2004 open water season from 02-Jun. to 09-Aug. for the Mackenzie and 10-Jun. to 09-Aug. for the Arctic Red and Peel rivers. Water was sampled from the Mackenzie, Arctic Red and Peel rivers as near-shore, surface grabs. Samples were directly collected into clean, site-rinsed 2L LDPE bottles, being careful not to collect stirred river bottom sediments. All samples were then stored in dark and cool conditions during transit to the laboratory.

***Delta lakes weekly sampling* -** A group of 6 lakes (Table 2.2,2.3; Fig. 2.4) representing the 3 lake classifications (Fig. 2.3) have been a prior focus for many biogeochemical and ecological studies in the delta (Anema et al. 1990a,b; Squires and Lesack 2003; Febria et al. submitted). The 2004 open water season resulted in the flooding of all lakes except for Dock Lake, which had not been flooded since at least the 2001 open water season. Nutrients were collected weekly from each site from 03-Jun. to 07-Aug. Lake samples were collected by boat using a clean, vertically oriented Van Dorn water sampler at mid-column. Delta lakes have well-mixed water columns post ice cover (Lesack et al. 1991), thus mid-column samples were accepted as representative of the entire lake volume. Dock Lake samples were collected as surface grabs from shore. All samples were transferred on-site to clean, site-rinsed 2L LDPE bottles and stored in cool and dark conditions during transit to the laboratory. Samples were collected at approximately the same location within each lake week to week.

2.3.3 Water sample analysis

Upon return from the field, samples were immediately passed through Whatman GF/C filters. GF/C filtration was chosen to be consistent with historical delta datasets as well as to more efficiently deal with the relatively high sediment loads of the Mackenzie River. Samples were rigorously shaken per 100mL of filtrate to ensure suspension of settled sediments and an overall well-mixed sample. Sample filtrate was partitioned for separate analyses into either clean 60mL or 125mL HDPE bottles rinsed with filtrate. Samples were partitioned for: nitrate (NO_3^-) and common anions (Cl^-, SO_4^{2-}); soluble reactive silica (SRSi); total dissolved organic carbon (TDOC); coloured dissolved organic carbon (CDOC); total dissolved nitrogen and phosphorus (TDN/TDP); and soluble reactive phosphate and ammonium (SRP, NH_4^+). CDOC was further filtered through 0.22 m membrane filters before analysis. Total suspended solids (TSS) were measured using pre-combusted GF/C filters (16 hrs. @ 500°C) while oven-dried GF/C filters were used for particulate organic carbon, nitrogen and phosphorus (POC, PN, PP). Table 2.4 describes nutrient preservation and analysis methods used.

2.3.4 Delta effect mixing model

Recent work has approximated the total volume of inflow river water that is added to and drained from delta lakes during the open water season (Emmerton et al. submitted). This allows for estimates of floodwater temporarily stored in lakes as a proportion of total flow. During lake storage, many nutrients will undergo changes via physical and biological processes, thus nutrient masses can be considerably different when lakes drain river water back to delta channels after flood peak. To quantify the effect that lake processes have on nutrient masses before drainage, a 'delta effect' mixing model was developed. The analysis covered the period from peak to low water levels in the delta (3-Jun. to 15-Aug.-2004; 60% of 2004 discharge) and utilized weekly measures from lakes and inflow rivers. Masses delivered by the inflow rivers without influences of the delta lakes (MR; Equation 1) were compared to masses delivered by the lake drainage portion and remaining river water portion together (MDE; Equation 2):

Nutrient mass delivered to Arctic Ocean by inflow rivers without delta lake drainage effects (MR):

(1) $MR = VR * CR$

Where VR is the volume of inflow water to the delta
CR is flow weighted average nutrient concentration of inflow rivers

Nutrient mass delivered to Arctic Ocean by inflow rivers with delta lake drainage effects (MDE):

(2) $MDE = (Vf*Cf) + (Vr*CR)$

Where Vf is the volume of water in storage within the three lake classes to be returned to river channels
Cf is the flow weighted average concentration of lake water returned to river channels from the three lake classes
Vr is the volume of river water flowing through delta channels excluding water that went into delta lake storage (VR-Vf)

Inflow river water volumes (VR) were calculated daily from discharge measurements at the final Water Survey of Canada stations on each inflow river (Mackenzie, Arctic Red, Peel) before entrance to the delta (Water Survey of Canada

2005). The mean nutrient concentration from the three rivers (CR) was calculated by averaging the measurement period data for each river and calculating a flow-weighted average. Missing data in the Arctic Red and Peel rivers on 3-Jun. were ignored considering only 8% of the total inflowing river water originated from those rivers during the measurement period. Total lake drainage volumes (Vf) were based on summing the differences between high and low storage volume estimates in each of the three lake types (Emmerton et al. submitted). The average nutrient concentration from the three lake classes (Cf) was calculated by averaging summer nutrient concentrations in each lake class and flow-weighting an overall average.

2.4 Results

2.4.1 Seasonal nutrient patterns of the Mackenzie River

Though occurring after the Mackenzie River flood peak, weekly river sampling in 2004 was performed sufficiently close to peak water and was assumed to be representative of peak conditions (lake sampling near Inuvik was performed at peak water at that location) (Fig. 2.5). One under ice sample (via auger) and one breakup period sample were also collected to delineate some water characteristics during the rising limb of the hydrograph, though results are not assumed to be well representative of rising limb conditions (see below). Nutrient patterns during the flood peak period were of particular interest within this study as the year's largest fluxes of river material occurred during this time. Combined with high fluxes, the arctic summer solstice provided nearly continuous, relatively strong irradiance to the region, further affecting nutrient contents.

Nutrient results from the Mackenzie River followed the general pattern observed in other arctic rivers (Dittmar and Kattner 2003) (Fig. 2.6). Both particulates and dissolved organics were high during peak discharge and sharply declined after the flood. Lower water peaks occurred during the summer due to precipitation (mid July) and a coastal storm surge which raised water levels throughout the delta (end July; Chapter 3). Dissolved organic phosphorus was low throughout the year showing only small increases during the flood peak. Excluding ammonium and SRP, inorganic nutrients were at a minimum during peak flooding and generally increased afterwards. Ammonium and SRP were highly variable throughout the sampling period. Intermittent concentration peaks were also attributed to local hydrological events mentioned previously. Total nitrogen and phosphorus reflected the dominance of particulate N and P within their measures while total dissolved N and P were generally stable throughout the year, representing a general composition split between organic and inorganic forms.

2.4.2 Assessment of nutrient changes in delta channels – delta surveys

Particulates - Particulates through the delta (Fig. 2.7) were highly variable with both increases and decreases observed among the different particulate measures. During the June survey, POC and PN each increased in concentration at downstream transects relative to the inflow rivers while TSS and PP decreased from inflow to the mid transect and increased at the mouth transect. The July 2004 survey showed steady decreases between all sites among each measure while nearly all August surveys for each particle measure showed decreases from inflows to the mid transect before increasing at the mouth transect.

Dissolved organic matter (DOM) - A sharp seasonal change in TDOC was observed in the delta as the early recession survey had 60% higher levels than low water surveys of 2004 (Fig. 2.8). Changes through the delta were not strong, showing rather stable downstream behaviour during all surveys. Results were similar for coloured DOC. Since TDOC patterns were generally stable between transects, its proportion of TOC was largely controlled by POC patterns (Fig. 2.9). CDOC decreased in space in relation to TOC only during the July survey as the other surveys had either increasing or stable CDOC levels. Each 2003 survey was higher in TDOC concentration than similar surveys in 2004, though neither showed strong changes through the delta.

Organic nitrogen showed a highly seasonal behaviour from early recession to later summer with the early recession having the highest organic nitrogen concentrations through the delta (Fig. 2.8). Similar to TDOC, stability downstream was observed during the early recession survey. However, lower water surveys in 2004 showed downstream DON additions, notably between the inflow and mouth transects. Late summer surveys of 2003 showed variable response in space through the delta and concentrations were as high as freshet surveys in 2004.

Organic phosphorus levels in the Mackenzie Delta channels were low and often below the analytical detection limit (0.050 μmol/L) (Fig. 2.8). Combined with high variability in samples taken from each transect, a confident assessment of DOP patterns in the delta could not be made. It would be expected that DOP behaviour would follow closely with DON, by showing an increase through the delta.

Dissolved inorganics - Nitrate concentrations during the early recession period of 2004 were generally unchanged through the delta from head to mouth, though a slight increase between the middle and mouth transects was observed (Fig. 2.10). A stripping effect was evident in the July survey between the middle and mouth transect with no considerable changes during August surveys. Late summer surveys of 2003 were markedly different in magnitude compared to 2004, despite similar time of year.

Ammonium through the delta was quite low in concentration except for selected sites during the early recession survey of 2004 (Fig. 2.10). Ammonium that was present was just above the analytical detection limit (0.5 μmol/L) and could not be confidently estimated in most cases. The first August survey of 2003 showed some evidence of removal through the delta.

Considerable addition of SRP was observed through the delta during the 2004 early recession survey (Fig. 2.10). July and August delta surveys in 2004 showed no differences spatially and were relatively low in concentrations in comparison to the freshet survey. Late summer surveys in 2003 were elevated in SRP compared to all 2004 surveys and increased between each transect in both surveys.

SRSi did not show discernable concentration changes through any delta survey (Fig. 2.10). There was some evidence of loss during the June 2004 survey between the inflow and middle transects, however the effect was not strong. SRSi increased over time between each survey during the 2004 season, though similar changes were not observed between the 2003 surveys.

Both sulphate and chloride showed large seasonal effects during the 2004 season (Fig. 2.10). Each ion progressed from minimum concentrations during the later freshet period to maxima during late summer in the delta. Increases between each survey in 2003 were also apparent. Sulphate and chloride concentrations through the delta remained relatively unchanged, however minor increases of sulphate were observed in the later summer surveys during both years and minor stripping effects were associated with chloride during the same time period.

Composite measures - Nitrogen composite measures (TDN, TN) represent a combination of other measures (TDN = DON+NO_3^-+NH_4^+; TN = PN+TDN).

Approximately two-thirds of the composition of TDN in the Mackenzie Delta was comprised of organic forms. Nitrate represented the balance of TDN with ammonium playing a relatively minimal role in the river water. TDN changes in space through the delta consequently showed a stable to slight addition pattern that mirrored organic nitrogen activity (Fig. 2.11). Particulate nitrogen represented about 60% of total nitrogen in the Mackenzie Delta during the early recession period (Fig. 2.11). Total nitrogen increased through the delta during early recession and was due to the stability of TDN and increases in particulate nitrogen. Post flood, the fraction of particulate nitrogen of TN reduced to about 50% yet it continued to characterize TN changes through the delta. DIN (NO_3^-+NH_4^+) was dominated by nitrate through the delta surveys.

Phosphorus composite measures (TDP, TP) represent a combination of other measures (TDP = DOP+PO_4^{3-}; TP = PP+TDP). Dissolved phosphorus was low in the Mackenzie Delta (Fig. 2.11) and DOP represented about 20% of all TDP over all delta surveys, showing little deviation between the early recession and lower water period. SRP consequently composed most of the TDP in the delta. With such low dissolved phosphorus concentrations in the delta, the bulk of total phosphorus was comprised of particulate phosphorus (Fig. 2.11). Over 95% of all phosphorus in the delta was in the particulate form, thus total phosphorus essentially behaved as its particulate form.

TOC (POC+DOC) showed minor downstream increases during early recession period before stabilizing during lower water.

Nutrients East to West - Not surprisingly, the Mackenzie River had the largest influence in the delta east to west, rather than the Arctic Red or Peel river inflows (Fig. 2.12). With large mean annual discharge differences between the Mackenzie (284 km^3/yr) and Arctic Red (5 km^3/yr) rivers, the Arctic Red River exerted little influence on the Mackenzie downstream of their confluence. The Peel River (22 km^3/yr) has a larger role in the delta than the Arctic Red River as it directly supplies the Peel Channel and others until the Aklavik Channel (Mackenzie water) joins downstream of Aklavik, NT to create the West and Hvatum channels. Thus, the Peel Channel was expected to have a large Peel River signature whereas West and Hvatum channels would have less of a Peel River signature.

Particulates (Fig. 2.12; TSS) were variable in concentration from east to west, showing no clear trends. Sites that sampled the Mackenzie River inflow and the Middle Channel through the delta were consistently the highest in concentration compared to other rivers and channels. The Mackenzie derives much of its sediment load from the Liard River, a mountain sourced river to the south with high sediment loads. Consequently, the Mackenzie had high concentrations compared to other rivers. The two eastern channels in the mid transect (East and Kalinek channels) were lowest in concentration overall which may have been due to the high lake density in the area or the influence of dilute waters from Campbell River draining from the large, clear Campbell Lake (Fig. 2.2 at southern box #2). The westernmost channels in the mouth transect were relatively high in 2003 and 2004 compared to the rest of the sites and may have been from rivers inflowing to the delta from the Richardson Mountains. These mountain streams are likely flashy systems with the potential to transport high sediment loads during summer storms.

All dissolved organics generally followed similar patterns as represented by TDOC (Fig. 2.12). TDOC was higher in the Mackenzie River inflow than either the Arctic Red or Peel Rivers. Both the Peel and Arctic Red rivers are sourced from the Mackenzie and Richardson mountain chains, draining high-grade areas where organic soil coverage is low compared to the taiga-rich basin from which the Mackenzie flows. Within the delta, the Mackenzie inflow mixed well throughout the delta, thus controlling the influence of the Peel River in the lower western channels. A high signature in the East Channel and adjacent Kalinek Channel was also observed compared to other sites which may be linked to wetlands on the eastern border or influences from rivers draining tundra regions (Rengleng River, Fig. 2.2 at first East Channel bend northward).

Nitrate (Fig. 2.12) and SRP were generally well-mixed throughout much of the delta channels though the westernmost sites were higher in each nutrient. This was likely due to the strong Peel River signature of nitrate and SRP that may be related to runoff processes through mountainous mineral soils that compose much of the Peel system. Other inorganic nutrients (SRSi, ammonium) did not show any clear trends east to west in the delta. Sulphate and chloride, alternatively, showed a strong Peel River influence in the western delta. The Peel River had low concentrations of chloride at the delta inflow and concentrations were low enough to compensate for elevated levels brought into the western delta from Mackenzie offshoot channels. Thus the Peel, Hvatum and West Channels were lower in chloride concentration than other delta channels. Sulphate was also different in the Peel River-influenced Peel, Hvatum and West channels. Inflow concentrations of sulphate from the Peel were higher than the Mackenzie, common in rivers from the cordillera, and thus controlled the western channels.

2003 vs. 2004 - Flow in the Mackenzie River was the key difference between the 2003 and 2004 open water seasons (Fig. 2.5). Discharge throughout the three open water months measured were on average 25% higher in 2003 than during the same period in 2004. On an annual scale, mean water flux from the Mackenzie was higher in 2003 (297 km^3) than the 32-year mean (284 km^3) while 2004 was among the lowest water years on record (251 km^3) (Fig. 2.5). This likely had profound effects on all measures between 2003 and 2004, which was observed across many of the nutrient measures. Particulates were elevated during the later summer surveys in 2003 compared to July levels in 2004, likely reflecting increased runoff and discharge induced by a rainier July and August 2003 compared to 2004 (Environment Canada 2005). August 2004 particulate levels were equal to or higher than August 2003 likely due to the storm surge event which raised water levels and likely entrained channel bank and floodplain particulates. The rainier July and August in 2003 and resulting runoff in the basin possibly explained dissolved organics patterns, as they were also quite high in 2003 compared to post flood measures in 2004, a relatively dry year. Dissolved inorganic nutrients were more variable between years. Nitrate was substantially lower in 2003 than 2004, which may have been a dilution effect during the higher flow year in 2003 from both surface runoff and larger lake discharges of nitrate depleted water. SRP levels in August 2003 were substantially higher than during the 2004 season, which may have been related to similar lake drainage processes as nitrate.

2.4.3 Assessment of nutrient changes in delta channels – mass balance survey

Results from the mass balance survey related well to findings from the July 2004 delta survey performed just days earlier. All particulates (Fig 2.13; TSS) decreased downstream in the East Channel and total N and P measures, dominated by particulates, also showed downstream decreases. Nitrate (Fig. 2.13: NO_3^-) also decreased downstream while SRP and chloride increased downstream. SRSi, sulphate remained stable downstream while ammonium was below analytical method detection at all sites. Dissolved organics all increased downstream in the East Channel, as represented by TDOC (Fig. 2.13; TDOC). Total dissolved N and P increased slightly downstream reflecting the high organic content of TDN and TDP.

Though the mass balance survey was a snapshot of nutrient masses in the East Channel, important discharge patterns were observed. Though the survey was performed in a relatively stable reach of the East Channel, large losses of discharge were observed downstream. From the upstream to downstream stations, the East Channel lost over 50% of its discharge. This discharge was likely redistributed to the Middle Channel from two small distributary channels during the study reach. This large drainage from an adjacent channel to the middle channel demonstrated the control of the Middle Channel on the mid eastern delta. Since the Middle Channel is most directly related to the inflowing Mackenzie River, it reflects the hydrology of the Mackenzie before the slower, smaller adjacent channels. Thus if water levels are falling in the Mackenzie River, the Middle Channel would fall quicker than other channels, creating head differences and subsequent flows from surrounding water ways. This is a reversal from flooding conditions where past work has determined that the middle channel is at a relatively higher water level compared to the rest of the delta (Marsh et al. 1999).

2.4.4 Quantification of the delta effect on inflowing nutrient fluxes – delta effect mixing model

Table 2.5 provides an example calculation of the delta effect model for TDOC.

Particulates - All particulate measures showed similar results from the model (Fig. 2.14; Table 2.6). A clear delta effect by floodplain lakes was observed as substantial reductions in particulates occurred when delta lake drainage was considered. Each measure decreased at least 10% compared to direct river levels during the measurement period with TSS decreasing by the largest margin (17%).

POC, PN and PP fractions of TSS (Fig. 2.15) were generally stable with delta lake effects.

Dissolved organic matter (DOM) - TDOC and CDOC were added to river water upon passage through the delta, though within measurable error (Fig. 2.16; Table 2.6). Additions of 15% and 11% of TDOC and CDOC respectively were observed when lake water was considered. More substantial additions were apparent for DON (46%) while the model revealed over a three-fold DOP increase when including lake additions.

Dissolved inorganics - Nitrate levels from delta inflow rivers were reduced by about 15% upon passage through the delta, based on model results (Fig. 2.17; Table 2.6). SRP (9%), SRSi (5%) and sulphate (7%) also showed losses due to the delta lake effect, though within calculated error of the river scenario. Results indicated that ammonium was a strong source through the delta, adding about 40% to river levels while chloride was conservative in behaviour through the delta.

Composite measures - Both total nitrogen and phosphorus appeared to decrease through the delta, though within error, possibly due to their dominant particulate compositions while total dissolved N and P increased reflecting high DON and SRP compositions, though also within error (Fig. 2.18,2.19; Table 2.6). Dissolved inorganic nitrogen was mostly comprised of nitrate and thus decreased through the delta under lake effects, while TOC was generally stable under each scenario, revealing a split in composition between DOC and POC (Fig. 2.18).

C:N:P ratios - Total C:N:P (Fig. 2.20) ratios all increased with the delta effect, though all within calculated error. Increases may have reflected the addition of organic carbon through the delta and the relative increase in DON compared to DOP. TOC:TN and TOC:TP increased above the Redfield ratio (106C:16N:1P), indicating a further influence of organic carbon from delta lakes. TN:TP increased to the Redfield ratio under delta lake effects. Particulate C:N:P ratios (Fig. 2.20) were more variable with decreases in POC:PN and increases of POC:PP and PN:PP with delta lake effects. POC:PN decreased toward the Redfield ratio, but was still well above 6.6. POC:PP was generally at the Redfield ratio while PN:PP was well below that value.

2.5 Discussion

2.5.1 The effect of the Mackenzie Delta on Mackenzie River nutrients

Particulates - Results from delta surveys and the mass balance survey revealed non-conservative, variable patterns of particulates through the delta during all periods. High variability during the early recession period reflected the intense erosive and depositional processes occurring. Erosive energy was high during the early recession due to channel ice scour and turbulent flow, while resuspension was elevated due to greater wetting contact with the floodplain and turbulence in shallow mouth areas. Deposition was also strong through sedimentation within lakes, wetlands, channels, levees and the vegetated plain. Post flood, river energy levels decreased and in-channel deposition exerted a much larger influence on the system and this was observed in all post-flood surveys. Most of this net deposition was assumed to occur in the mouth area of the delta, rather than in lakes that were mostly disconnected from the river at that point. The delta effect model showed that floodplain and lake sedimentation represented a strong particulate sink during the open water period, likely most intense during the early recession period. This matched well with a mass balance study by Carson et al. (1999) that estimated about 80% of all sediment delivered to the delta deposited within the floodplain and river channels. Though the model showed considerable deposition during the measurement period, depositional loss was likely underestimated. A portion of lake sedimentation was completed by the start of the analysis as substantial sedimentation occurred during the rising limb period when river waters initially entered the delta lakes. This was supported by TSS data from flooded lakes on 3-Jun. (54 mg/L) as compared to the adjacent Big Lake Channel (167 mg/L). If water collection was performed during the initial flooding period, the sites would likely be closer in concentration. The model also underestimated particulates because in-channel sedimentation was not accounted for, especially in the delta mouth region which has the highest depositional rate within the delta (Carson et al. 1999). This was supported by observed mean mouth transect concentrations from delta surveys (Table 2.6) which showed lower outflow concentrations than predicted by the delta model.

Increases of particulate organic fractions of TSS were apparent through the delta. The relatively high productivity within the delta and organic-rich particles in the floodplain were likely the main drivers of this organic enrichment of particles. Organic particles are plentiful in the delta floodplain with detritus accumulation from ample vegetation at lake and channel margins. Spring floodwaters entrain this material and are released upon lake drainage. Through the summer, dense macrophyte and *Equisetum* communities in and around lakes may also senesce and add to drainage waters. Lower increases in the particulate P fraction of TSS through the delta likely reflected general P limitation within freshwaters and uncertainties related to measuring P levels near detection.

Dissolved organic matter (DOM) - DOM was generally non-conservative through the delta during the open water season. The large seasonal differences in TDOC concentration was due to intense runoff during the freshet period that percolated through organic rich soils in the Mackenzie Basin. Active layer increase through the season and additional runoff is expected to drain below rich organic layers and reduce TDOC fluxes to waterways. TDOC outputs with delta lake effects were elevated with respect to the inflow river levels during the measurement period (Table 2.6). This was different from the discrete delta surveys which showed relative stability downstream through the delta. This may have been due to inherent differences between the season-long model and the 'snapshot' delta surveys. It may indicate in-channel processes such as absorption of lake TDOC onto river particles (Retamal et al. submitted), which would be overlooked by the model (same for all DOM). The addition of TDOC from the delta was likely most important during the flooding period as connection with the organic-rich floodplain and flushing of decomposed lake biota was highest and lake drainage was most intense. Post flood, lakes were increasing in TDOC due to high lake productivity, however fewer lakes were draining to delta channels during that time.

CDOC followed the same seasonal pattern as TDOC, however its relative proportion to TDOC decreased throughout the season at the Mackenzie at Arctic Red River and other sites. Additionally, during the July survey, the proportion of CDOC declined downstream through the delta. It is not apparent in this study if proportional losses of CDOC over time and downstream were due to reduced watershed inputs of

CDOC (and subsequent additions of dilute lake water) or from photobleaching losses within delta lakes. If photobleaching was strong in the delta, than most intense losses would be expected near the solstice period when CDOC was relatively high in lake and river waters and irradiance was most intense. The model, unfortunately, could not resolve CDOC losses as it was dominated by high lake levels of CDOC during the early recession period, leaving any photobleaching losses indiscernible.

DON was generally not conservative downstream as strong additions through the delta were observed. The delta effect model showed that DON increased 1.5 times through additions from delta lakes during the summer season (Table 2.6). During the early recession period, downstream concentrations through the delta were generally stable however seasonal results from the model contrasted with these discrete surveys in a similar fashion to TDOC. Post flood, delta surveys and the mass balance survey showed increases of DON through the delta, which was attributed to lake drainage of organic-rich water. Organic rich lake water likely reflected the dissolution of particulate organic matter from algae and macrophytes and the release of dissolved organic material as by-products of primary production. This addition was most pronounced after flooding due to primary production increases near the summer solstice (after the June delta survey) due to reduced light attenuation and water temperature increases. Dissolved organic phosphorus was generally low in river waters and high in lakes similar to DON and considerable lake additions were observed (3 fold increase through the delta), attributed to similar processes as DON.

Dissolved inorganics - Minimal downstream changes of nitrate during the early recession delta survey may have been related to the water temperature in delta lakes. Temperatures in the lakes did not drastically increase until the week of the early recession survey, likely limiting biological uptake of nitrate. Consequently, levels in the lakes were steady and similar to river water. Connection with the delta plain during the flooding period would not be expected to generate substantial inputs of nitrate to the system as it is not efficiently sequestered in the soils. When lake temperatures increased, uptake of nitrate by phytoplankton was intense and the delta surveys and the mass balance survey showed downstream reductions. This intense uptake of nitrate began during the time of the June delta survey and its effects were not observed due to the drainage time lag

(Appendix A). The July 2004 survey seemed to capture these lake nitrate losses. Lakes were still draining during July and the addition of nitrate depleted waters contributed to nitrate dilution in the river channels. This was apparent between the mid and mouth transects of the July survey and may have been due to the high lake densities in the middle delta, compared to the upper section. This period controlled overall nitrate behaviour in the delta as the delta effect model showed a stripping effect through the open water season. Delta rivers during August received little water from lakes as much of the drainage process was completed and likely explained stability seen through all August surveys. Nitrate losses within the river channels themselves were expected to be insignificant due to low productivity in the turbid river water, and this was supported by observed delta survey concentrations (Table 2.6) that were similar to predicted levels from the model.

Ammonium levels in rivers and lakes during the open water season were generally below analytical detection except for lake levels at the beginning of sampling period. High early season lake concentrations may have been attributed to relatively high levels of ammonium within snow runoff (Dittmar and Kattner 2003) and conditions where oxygen depletion over the winter would provide an environment for reduced forms of inorganic nitrogen. The flushing period of lakes would deliver relatively ammonium rich waters to the delta and load river levels, which was observed in the June 2004 delta survey. This flushing of ammonium-rich lakes seemed to control the delta effect model as ammonium mass was added to river waters over the measurement period. Similar to nitrate, when lake temperatures increased, loss of ammonium was observed in lakes bringing levels in lakes below detection for the rest of the season. This reflected its high demand in the aquatic environment, as it is the preferred form of nitrogen for algae growth. Though levels were below detection, ammonium would be expected to undergo a stripping effect in the rivers through the delta in similar fashion to nitrate through lacustrine uptake and redischarge of depleted waters back to the delta. Observed values from outflow channels suggested that the model substantially underestimated ammonium levels. This may have been attributed to the high variability of results common when the indophenol blue method is used (Holmes et al. 1999), or from real effects such as decomposition or ammonification within river channels.

SRP within flooded lakes was lost via uptake, similar to nitrate, during the summer solstice. Drainage of this dilute lake water resulted in losses through the delta according to the delta effect model. Delta surveys, however, showed an addition of SRP into river channels through the delta. Observed outflow rivers from the surveys also suggested that the model underestimated true levels (Table 2.6). This suggests an alternative source of SRP within the delta to compensate for the diluted waters draining from lake water storage. In-channel additions of SRP to river waters may have occurred due to SRP dissociation from particles with in the turbid river especially toward the mouth where salinity may have played a role (Fox et al. 1985). Wetland release of SRP may have also added to channel levels, as lakes sampled did not include large influences of wetlands that can occur through the delta. Additions of SRP may have been further enhanced in the East Channel as the mass balance survey showed a possible urban effect from Inuvik as its station showed a spike of SRP.

Soluble reactive silica was generally stable in space and time within the delta except for losses from low closure lakes, presumably related to uptake by diatom communities. This contributed to minor losses observed from the model results, however drainage from low closure lakes only represented about 20% of flow from all lakes over the measurement period and thus did not contribute largely to a delta effect. Observed river concentrations over the mouth transect fit well to model estimates suggesting that lake effects were a main control on SRSi additions through the delta (Table 2.6). Increases of SRSi over the season in delta channels were likely generated by drainage through deeper portions of the Mackenzie Basin soil profiles, usually higher in silica-based rocks (Guo et al. 2004).

Sulphate showed similar patterns to SRP as levels slightly decreased (5%) through the delta due to the delta lake effect, however channel concentrations actually increased through the delta (Table 2.6). This again suggests an alternative source of sulphate to the delta channels that may be related to wetland drainage, though little is known about sulphate in this system. Within the lakes, levels were generally stable in no closure lakes and decreased in others, possibly from sulphate reducing bacteria or production-related uptake. Chloride is normally conservative in aquatic environments, which was observed throughout the delta. There was virtually no delta effect from lakes and channel levels remained steady. Increases toward the mouth region were not observed as would be expected closer to the marine regions, though the Mackenzie plume normally restricts salinity intrusion.

C:N:P - Mackenzie River waters entering the delta were relatively impoverished in nitrogen and carried a strong terrestrial carbon signature in relation to the Redfield ratio. Carbon sources are strong through the Mackenzie Basin both in particulate and dissolved form, common in large rivers. Phosphorus is in adequate supply with TOC:TP levels at the Redfield ratio, though mostly in particulate form. Through the delta, nitrogen was added to outgoing waters but was still at limiting concentrations for coastal primary producers. The carbon signature also strengthened through the delta owing to the rich organic terrestrial environment of the delta as well as strong TDOC production in lakes during the open water season.

2.5.2 Limitations of nutrient flux estimates

Estimates of nutrient fluxes from large arctic rivers to the Arctic Ocean is a contentious issue mainly due to the uncertainty with measuring discharge with the influence of seasonal ice jams and complicated backflow conditions (Rouse et al. 1997). Based on the Mackenzie River at Arctic Red River hydrographs (Fig. 2.5), ice influence exists up to and often during the peak flood period in the Mackenzie. No solid estimates of the amount of flow passing during this period exist, though some estimates predict about 30% of the total annual flow (Emmerton et al. submitted). This measurement uncertainty during this high flow period and large associated errors restricts accurate estimates of water and nutrient fluxes from the Mackenzie and likely other arctic rivers. Uncertainty of flow during this period is further troublesome for nutrient flux estimates as many nutrients of interest increase with flow.

Two important issues limit calculation of full season nutrient fluxes from the Mackenzie River for 2003 and 2004 (including delta lake effects). First, 2003 data is only available for July and August and did not include measurements from the important flooding period when nutrient fluxes are at their maximum. Second, both 2003 and 2004 datasets did not include samples from the rising limb of the annual hydrograph. It is difficult to sample the thalweg of the Mackenzie correctly during this period due to ice effects, which do not allow for safe sampling. Accurate flow measurement is also complicated by ice influences as described earlier. The rising limb of the hydrograph also represents a period where delta effects could be substantially different from the recession period. During this time, initial flushing of delta lakes and floodplain likely transports over-wintered lake water (high in dissolved constituents) and larger fractions of accumulated organic material from the previous senescence period. Under-ice sampling during the winter low flow period was also absent. The Mackenzie River maintains relatively higher flows during the winter period compared to other large arctic rivers since it receives water from three large lakes. Water chemistry during the winter period could be quite different from open water chemistry, thus annual flux estimates are limited by the absence of this data. Though limitations in flux estimates do exist in this study, these results provide descriptive and quantitative preliminary evidence that river water chemistry through the delta is altered before discharge to the ocean.

2.5.3 Climate change implications

Climate change scenarios have predicted a reduction of freshet flooding within the delta due to reduced ice damming of rivers and associated flooding (Rouse et al. 1997). Results from the delta effect model showed that lakes can have a substantial controlling effect on nutrient fluxes discharging to the western Arctic Ocean. With reductions of seasonal flooding predicted, lake flooding and drainage is expected to decline. This may have implications for organic fluxes, which were a strong source from delta lakes during the flooding period, or for particulates and inorganic nutrients, which were largely sinks in delta lakes. Under a climate change scenario, runoff is expected to decrease throughout the Mackenzie Basin due to permafrost loss and associated increase in soil storage capacity. Reduction in runoff would be expected to reduce flow as well as inorganic and organic nutrient fluxes from the surface. The Mackenzie would also be expected to have a proportionally higher groundwater influence within its waters during the open water season, which would likely increase inorganic nutrient contents. Combining above scenarios, most fluxes would likely decline due to lower discharges from the Mackenzie. Organic nutrient fluxes would likely be further affected through reduced additions from floodplain lakes and from freshet runoff. This may have implications for coastal heterotrophic communities which use organics as a food substrate as well as all organisms in the water column that depend on organics as a 'sunscreen' for UV light. Inorganic nutrients would likely increase in the Mackenzie under a climate change scenario due to a decline in uptake losses in delta lakes and increases from higher groundwater proportions during the open water season. With reduced runoff, SRP and SRSi may be negatively affected as they are mostly added from watershed geology whereas ammonium is strongly sequestered in soils and nitrate generally passes through the watershed and is dominantly precipitation related. Groundwater is normally enriched in inorganic nutrients, especially in arctic watersheds (Dittmar and Kattner 2003) and would likely contribute a larger portion in Mackenzie flow under reduced runoff and greater soil water sequestration scenarios. Sediment fluxes would likely increase as temperature-induced effects would increase sediment supplies to rivers (Syvitski 2002), offsetting any declines experienced from reduced runoff. Future changes in each of these fluxes could have large effects on the productivity of delta and coastal ecosystems.

2.6 Conclusions

This preliminary study has demonstrated that the Mackenzie Delta plays a large role in altering incoming Mackenzie River water for all measured nutrients and supports the hypothesis that nutrients will behave non-conservatively through the delta. Delta lakes and the floodplain play an important role in these changes by either sequestering nutrients from or adding nutrients to delta river waters. It appears that measuring concentrations and estimating fluxes to the western Arctic Ocean from the Mackenzie River before the delta will likely overestimate particulates and inorganic nutrients and underestimate organic nutrients. Other controls within river channels may also play a role in changing nutrient contents before coastal delivery. Future work should focus on mass balance changes between individual lakes and adjacent river channels to better focus actual exchanges of nutrients between each environment. Greater focus on the rising limb of the Mackenzie hydrograph also needs to be addressed, specifically ice-influenced hydrology and nutrient behaviour.

2.7 References

Aagaard, K. and E.C. Carmack. 1989. The role of sea ice and other fresh-water in the arctic circulation. *Journal of Geophysical Research-Oceans* 94(C10): 14485-14498.

Anema, C., R.E. Hecky, E.J. Fee, D. Nernberg and S.J. Guildford. 1990a. Water chemistry of some lakes and channels in the Mackenzie Delta and on the Tuktoyaktuk Peninsula, N.W.T., 1985. *Canadian Data Report of Fisheries and Aquatic Sciences* 726: 1-73.

Anema, C., R.E. Hecky, S. Himmer and S.J. Guildford. 1990b. Water chemistry of some lakes and channels in the Mackenzie Delta and on the Tuktoyaktuk Peninsula, NWT., 1986. *Canadian Data Report of Fisheries and Aquatic Sciences* 729: 1-63.

Brunskill, G.J., D.M. Rosenberg, N.B. Snow, G.L. Vascotto, and R. Wageman. 1973. Ecological studies of aquatic systems in the Mackenzie-Porcupine drainages in relation to proposed pipeline and highway developments. Canada Task Force, North. Oil Develop. Envir. Comm., II. Report 73-41. 345 pp.

Burn, C.R. 1995. The Hydrologic Regime of Mackenzie River and Connection of No Closure Lakes to Distributary Channels in the Mackenzie Delta, Northwest-Territories. *Canadian Journal of Earth Sciences* 32(7): 926-937.

Carson, M.A., F.M. Conly and J.N. Jasper. 1999. Riverine sediment balance of the Mackenzie Delta, Northwest Territories, Canada. *Hydrological Processes* 13(16): 2499-2518.

Cauwet, G. and I. Sidorov. 1996. The biogeochemistry of Lena River: Organic carbon and nutrients distribution. *Marine Chemistry* 53(3-4): 211-227.

Comiso, J.C. 2003. Warming trends in the arctic from clear sky satellite observations. *Journal of Climate* 16: 3498-3510.

Dionex Corporation. 1991. Dionex DX-300 gradient chromatography systems user's manual release 01. Dionex Corportation, Sunnyvale California.

Dittmar, T. and G. Kattner. 2003. The biogeochemistry of the river and shelf ecosystem of the Arctic Ocean: a review. *Marine Chemistry* 83(3-4): 103-120.

Droppo, I.G., D. Jeffries, C. Jaskot and S. Backus. 1998. The prevalence of freshwater flocculation in cold regions: A case study from the Mackenzie River Delta, northwest territories, Canada. *Arctic* 51(2): 155-164.

Emmerton, C.A., L.F.W. Lesack and P. Marsh. 2005. Aquatic habitat composition, lake abundance, and potential water storage in the Mackenzie River Delta, western Canadian Arctic. Submitted: *Water Resources Research.*

Environment Canada. 2001. EcoAtlas©. Version 2001_1_601_AR2. [CD-ROM]. Environment Canada, Government of Canada.

Environment Canada. Environment Canada (Env. Canada). [Online]. Past weather data. Available: http://www.weatheroffice.ec.gc.ca/ [2005].

Fee E.J., R.E. Hecky, S.J. Guildford, C. Anema, D. Mathew and K. Hallard K. 1988. Phytoplankton primary production and related limnological data for lakes and channels in the Mackenzie Delta and lakes on the Tuktoyaktuk Peninsula, NWT. Canadian Technical Report of Fisheries and Aquatic Sciences, 1614, v + 62p.

Febria, C.M., L.F.W. Lesack, J.A.L. Gareis and M.L. Bothwell. Patterns of hydrogen peroxide among lakes of the Mackenzie Delta, western Canadian Arctic. Submitted: *Canadian Journal of Fisheries and Aquatic Sciences*.

Fox, L. E., S.L. Sager and S.C. Wofsy. 1985. Factors controlling the concentrations of soluble phosphorus in the Mississippi Estuary. *Limnology and Oceanography* 30(4): 826-832.

Friedrich, J., C. Dinkel, E. Grieder, S. Radan, D. Secrieru, S. Steingruber and B. Wehrli. 2003. Nutrient uptake and benthic regeneration in Danube Delta lakes. *Biogeochemistry* 64(3): 373-398.

Forsberg, B.R., A.H. Devol, J.E. Richey, L.A. Martinelli and H. Dossantos. 1988. Factors controlling nutrient concentrations in Amazon Floodplain lakes. *Limnology and Oceanography* 33(1): 41-56.

Fisher, T.R. and P.E. Parsley. 1979. Amazon lakes: Water storage and nutrient stripping by algae. *Limnology and Oceanography* 24(3): 547-553.

Gordeev, V.V. 2000. River input of water, sediment, major ions, nutrients and trace metals from Russian territory to the Arctic Ocean. *The freshwater budget of the Arctic Ocean*. Norwell, Mass., Kluwer.

Gordeev, V.V., V. Rachold and I.E. Vlasova. 2004. Geochemical behaviour of major and trace elements in suspended particulate material of the Irtysh River, the main tributary of the Ob river, Siberia. *Applied Geochemistry* 19: 593-610.

Guo, L., J.Z. Zhang and C. Gueguen. 2004. Speciation and fluxes of nutrients (N, P, Si) from the upper Yukon River. *Global Biogeochemical Cycles* 18(1).

Hill, P. R., C. P. Lewis, S. Desmarais, V. Kauppaymuthoo and H. Rais. 2001. The Mackenzie Delta: sedimentary processes and facies of a high-latitude, fine-grained delta. *Sedimentology* 48(5): 1047-1078.

Holmes, R.M., A. Aminot, R. Kerouel, B.A. Hooker and B.J. Peterson. 1999. A simple and precise method for measuring ammonium in marine and freshwater ecosystems. *Can. Journal of Fisheries and Aquatic Sciences* 56(10): 1801-1808.

Holmes, R.M., B.J. Peterson, V.V. Gordeev, A.V. Zhulidov, M.Meybeck, R.B. Lammers and C.J. Vorosmarty. 2000. Flux of nutrients from Russian rivers to the Arctic Ocean: Can we establish a baseline against which to judge future changes? *Water Resources Research* 36(8): 2309-2320.

Holmes, R. M., B.J. Peterson, A.V. Zhulidov, V.V. Gordeev, P.N. Makkaveev, P.A. Stunzhas, L.S. Kosmenko, G.H. Kohler and A.I. Shiklomanov. 2001. Nutrient chemistry of the Ob' and Yenisey Rivers, Siberia: results from June 2000 expedition and evaluation of long-term data sets. *Mar. Chemistry* 75(3): 219-227.

Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Can. Spec. Publ. Fish. Aquat. Sci. 106: 110-127.

Knowlton, M. F. and J. R. Jones. 2003. Connectivity influences temporal variation of limnological conditions in Missouri River scour lakes. *Lake and Reservoir Management* 19(2): 160-170.

Lara, R.J., V. Rachold, G. Kattner, H.W. Hubberten, G. Guggenberger, A. Skoog and D.N. Thomas. 1998. Dissolved organic matter and nutrients in the Lena River, Siberian Arctic: characteristics and distribution. *Marine Chemistry* 59(3-4): 301-309.

Lesack, L.F.W., R.E. Hecky, and P. Marsh. 1991. The influence of frequency and duration of flooding on the nutrient chemistry of Mackenzie Delta lakes. *In* Environmental Interactions and Implications of Development, Proceedings of the Workshop on the Mackenzie Delta. Saskatoon, Sask., 17–18 October 1989. NHRI Symposium 4, National Hydrology Research Institute, Environment Canada, Saskatoon, Sask. pp. 19–36.

Lesack, L.F.W., P. Marsh and R.E. Hecky. 1998. Spatial and temporal dynamics of major solute chemistry among Mackenzie Delta lakes. *Limnology and Oceanography* 43(7): 1530-1543.

Lesack, L.F.W., M.M. Squires, P. Marsh, C.A. Emmerton, C.M. Febria, J.A. Gareis, A.J. Riedel, B.M. Spears, C.J. Teichreb, and M.L. Bothwell. Ecology of lakes in the Mackenzie River Delta: Potential responses to global change. Submitted: *Ecological Monographs*.

Lobbes, J.M., H.P. Fitznar and G. Kattner. 2000. Biogeochemical characteristics of dissolved and particulate organic matter in Russian rivers entering the Arctic Ocean. *Geochimica Et Cosmochimica Acta* 64(17): 2973-2983.

Mackay, J.R. 1963. The Mackenzie Delta Area, N.W.T. *Misc. Report 23, Ottawa: Geological Survey of Canada*: 202 p.

Maine, M.A., N.L. Sune and C. Bonetto. 2004. Nutrient concentrations in the Middle Parana River: effect of the floodplain lakes. *Arch. Hydrobiol.* 160(1): 85-103.

Marsh, P. and M. Hey. 1989. The flooding hydrology of Mackenzie Delta lakes near Inuvik, Nwt, Canada. *Arctic* 42(1): 41-49.

Marsh, P., L.F.W. Lesack and A. Roberts. 1999. Lake sedimentation in the Mackenzie Delta, NWT. *Hydrological Processes* 13(16): 2519-2536.

Meybeck, M. 1982. Carbon, nitrogen, and phosphorus transport by world rivers. *American Journal of Science* 282: 401-450.

Millot, R., J. Gaillardet, B. Dupre and C. J. Allegre. 2003. Northern latitude chemical weathering rates: Clues from the Mackenzie River Basin, Canada. *Geochimica Et Cosmochimica Acta* 67(7): 1305-1329.

Moritz, R.E., C.M. Bitz and E.J. Steig. 2002. Dynamics of recent climate change in the arctic. *Science* 297(5586): 1497-1502.

Mueller, D.R., W.F. Vincent and M.O. Jeffries. 2003. Break-up of the largest arctic ice shelf and associated loss of an epishelf lake. *Geophysical Research Letters* 30(20): 2031.

Opsahl, S., R. Benner and R.M.W. Amon. 1999. Major flux of terrigenous dissolved organic matter through the Arctic Ocean. *Limnology and Oceanography* 44(8): 2017-2023.

Prowse, T.D. 1986. Ice jam characteristics, Liard-Mackenzie rivers confluence. *Canadian Journal of Civil Engineering* 13(6): 653-665.

Prowse, T.D. and T. Carter. 2002. Significance of ice-induced storage to spring runoff: a case study of the Mackenzie River. *Hydrological Processes* 16(4): 779-788.

Retamal, L., W.F. Vincent, C.L. Osburn and C. Martineau. 2006. Comparison of the optical properties of dissolved organic matter in two river-influenced coastal regions of the Canadian Arctic. Submitted: *Estuarine and Costal Shelf Science.*

Reeder, S. W., B. Hitchon and A.A. Levinson. 1972. Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada-I. Factors controlling inorganic composition. *Geochimica Et Cosmochimica Acta* 36: 825-865.

Rouse, W.R., M.S.V. Douglas, R.E. Hecky, A.E. Hershey, G.W. Kling, L. Lesack, P. Marsh, M. McDonald, B.J. Nicholson, N.T. Roulet and J.P. Smol. 1997. Effects of climate change on the freshwaters of arctic and subarctic North America. *Hydrological Processes* 11(8): 873-902.

Shimadzu Corporation. 2004. TOC-V CPH/CPN total organic carbon analyzer user's manual. Shimadzu Corporation, Kyoto, Japan.

Sippel, S.J., S.K. Hamilton and J.M. Melack. 1992. Inundation area and morphometry of lakes on the Amazon River floodplain, Brazil. *Archiv Fur Hydrobiologie* 123(4): 385-400.

Smith, L.C., Y. Sheng, G.M. MacDonald and L.D. Hinzman. 2005. Disappearing arctic lakes. *Science* 308: 1429.

Squires, M.M. and L.F.W. Lesack. 2003. The relation between sediment nutrient content and macrophyte biomass and community structure along a water transparency gradient among lakes of the Mackenzie Delta. *Canadian Journal of Fisheries and Aquatic Sciences* 60(3): 333-343.

Stainton, M.P., M.J. Capel and F.A.J. Armstrong. 1977. The chemical analysis of freshwater, 2nd edition. Canada Fisheries and Mariane Services Miscellaneous Special Publication 25.

Strickland, J.D., and T.R. Parsons. 1972. A practical handbook of seawater analysis. Bull. Fish. Res. Board Can. 167: 310.

Telang, S.A., R. Pocklington, A.S. Naidu, E.A. Romankevich, I.I. Gitelson and M.I. Gladyshev. 1991. Carbon and mineral transport in major North American, Russian Arctic, and Siberian rivers; the St. Lawrence, the Mackenzie, the Yukon, the Arctic Alaskan rivers, the Arctic Basin rivers in the Soviet Union, and the Yenisei. *Biogeochemistry of major world rivers SCOPE (Chichester)* 42: 75-104.

Vandenbrink, F.W.B., J. Deleeuw, G. Vandervelde and G.M. Verheggen. 1993. Impact of hydrology on the chemistry and phytoplankton development in floodplain lakes along the lower Rhine and Meuse. *Biogeochemistry* 19(2): 103-128.

Vegas-vilarrubia, T. and R. Herrera. 1993. Effects of periodic flooding on the water chemistry and primary production of the Mapire systems (Venezuela). *Hydrobiologia* 262(1): 31-42.

Vincent, W.F. and R. Pienitz. 1996. Sensitivity of high-latitude freshwater ecosystems to global change: Temperature and solar ultraviolet radiation. *Geoscience Canada* 23(4): 231-236.

Vorosmarty, C.J., L.D. Hinzman, B.J. Peterson, D.H. Bromwich, L.C. Hamilton, J. Morison, V.E. Romanovsky, M. Sturm and R.S. Webb. 2001. The hydrologic cycle and its role in arctic and global environmental change:A rationale and strategy for synthesis study. Fairbanks, AK, Arc. Res. Consortium of the U.S.

Water Survey of Canada (WSC). 2005. [Online]. Data products and services. Available: http://scitech.pyr.ec.gc.ca/waterweb/formnav.asp?lang=0.

Whitehouse, B. G., R. W. Macdonald, K. Iseki, M. B. Yunker and F. A. McLaughlin. 1989. Organic-carbon and colloids in the Mackenzie River and Beaufort Sea. *Marine Chemistry* 26(4): 371-378.

2.8 Tables

Table 2.1 Past biogeochemical studies at the Mackenzie River mouth and delta channels.

AUTHOR	LOCATION*	(FREQUENCY) DATES	CONSTITUENTS MEASURED
Environment Canada 2001	Mackenzie-ARR Mackenzie-ECI	(Monthly) 1970-2003 (Monthly) 1971-1973	TN, PN, TDN, NH_4^+, NO_3^-, TC, TOC, TIC, POC, TDC, HCO, DIC, TP, TIP, PP, TDP, PO_4^{3-}, $Si(OH)_4$, SO_4^{2-}, Cl^-, conductivity, water T
Millot et al. 2003	Mackenzie-ARR	(1x) Aug.-1996	TSS, TDS, NO_3^-, DOC, HCO_3^-, $Si(OH)_4$, Cl^-, SO_4^{2-}, Sr^{2+}, Mg^{2+}, Ca^+, K^+, Na^+, pH
Droppo et al. 1998	Mackenzie-ARR Mackenzie-ECI Mackenzie-WC	(1x) 28-Jul., 9-Sep.-1993 (1x) 23-Jun.,27-Jul.,7-Sep.-1993 (1x) 23-Jun.,29-Jul.,8-Sep.-1993	TSS, POC, DOC, SO_4^{2-}, Cl^-, Mg^{2+}, Ca^+, K^+, Na^+, water T, conductivity, pH
Telang et al. 1991	Mackenzie-ARR	(biweekly) May-1981,1982 (biweekly) Oct.-1982-Sep.-1983	TN, PN, TDN, NO_3^-, TC, TIC, TOC, POC, DOC, PO_4^{3-}, $Si(OH)_4$, SO_4^{2-}, Cl^-, Mg^{2+}, Ca^+, K^+, Na^+, alkalinity, conductivity, turbidity, colour, pH, water T
Anema et al. 1990a	Mackenzie-ECI	(biweekly) Jun.-Sep.-1985	TSS, PN, TDN, PP, POC, TIC, DOC, HCO_3^-, TDP, $Si(OH)_4$, SO_4^{2-}, Cl^-, Fe, Mg^{2+}, Ca^+, K^+, Na^+, pH, alkalinity, conductivity, water T, Chl-a

Table 2.1 (continued) Past biogeochemical studies at the Mackenzie River mouth and delta channels.

AUTHOR	LOCATION*	(FREQUENCY) DATES	CONSTITUENTS MEASURED
Anema et al. 1990b	Mackenzie-ECI	(biweekly) Jun.-Sep.-1986	Same as Anema et al. 1990a, pH
Whitehouse et al. 1989	Mackenzie-ECK	(1x) Sep. 1987	POC, DOC
Fee et al. 1988	Mackenzie-ECK	(2x weekly) Jun.-Sep.-1985,1986	TIC, pH, water T, conductivity, CHL-a, DO, primary production
Brunskill et al. 1973	Mackenzie-ARR Mackenzie Delta Peel-Ft. MacP.	(Monthly) Jun.-Sep.-1971 (Monthly) Mar.-Sep. 1972	TSS, PN, TDN, PP, POC, HCO_3^-, TDP, $Si(OH)_4$, SO_4^{2-}, Cl^-, Mg^{2+}, Ca^+, K^+, Na^+, pH, conductivity, DO, water T,
Reeder et al. 1972	Mackenzie-ARR	(1x) Aug.-1969	TSS, TDS, NO_3^-, TOC, HCO_3^-, PO_4^{3-}, B, Mn, Fe, Ni, Cu, Zn, U,F, $Si(OH)_4$, Cl^-, SO_4^{2-}, Sr^{2+}, Mg^{2+}, Ca^+, K^+, Na^+, water T, conductivity, pH

*Locations: Mackenzie-ARR: Mackenzie River above Arctic Red River, upstream of delta
Mackenzie-ECI: Mackenzie River, East Channel, middle delta near Inuvik, NT
Mackenzie-ECK: Mackenzie River, East Channel, lower delta above Kugmallit Bay
Mackenzie-WC: Mackenzie River, West Channel, middle delta near Aklavik, NT
Mackenzie Delta: Mackenzie Delta, several channels
Peel-Ft. MacP.: Peel River near Fort MacPherson, NT

Table 2.2 Locations of delta surveys, mass balance survey and weekly sampling during open water sampling of 2003 and 2004.

SITE	NORTH	WEST
DELTA SURVEY – INFLOW TRANSECT		
Mackenzie River @ Point Separation	67° 36.156′	134° 04.445′
Mackenzie River above Arctic Red River	67° 28.151′	133° 41.381′
Arctic Red River near mouth	67° 25.562′	133° 46.737′
Peel River above Fort MacPherson	67° 19.341′	134° 51.854′
DELTA SURVEY – MID DELTA TRANSECT		
East Channel @ Inuvik	68° 19.587′	133° 40.950′
Kalinek Channel	68° 23.637′	133° 58.157′
Middle Channel	68° 17.730′	134° 22.599′
Aklavik Channel	68° 12.883′	134° 46.238′
Peel Channel	68° 12.942′	135° 05.817′
DELTA SURVEY – MOUTH TRANSECT		
Middle Channel above Reindeer Channel	68° 50.574′	134° 37.794′
East Channel	68° 59.613′	134° 38.816′
Middle Channel at Langley Island	69° 02.735′	135° 01.913′
Reindeer Channel	68° 58.042′	135° 01.758′
Kipnik Channel	68° 44.219′	135° 01.156′
Crooked Channel	68° 40.228′	134° 57.441′
Napoiak Channel	68° 33.161′	134° 46.071′
Jamieson Channel	68° 33.167′	135° 16.394′
Hvatum Channel	68° 38.124′	135° 39.587′
West Channel	68° 38.394′	135° 44.312′
MASS BALANCE SURVEY		
Upstream	68° 07.876′	133° 48.261′
Inuvik	68° 28.495′	133° 45.515′
Downstream	68° 33.333′	133° 57.794′
INFLOW RIVERS SURVEY		
Mackenzie River above Arctic Red River	67° 28.151′	133° 41.381′
Arctic Red River near mouth	67° 25.562′	133° 46.737′
Peel River above Fort MacPherson	67° 19.341′	134° 51.854′
6 LAKES SURVEY		
129	68° 18.279′	133° 50.673′
80	68° 19.399′	133° 52.324′
87	68° 19.047′	133° 52.435′
280	68° 19.248′	133° 50.378′
56	68° 19.385′	133° 50.785′
Dock	68° 18.847′	133° 42.954′

Table 2.3 Lake statistics from 6 lake set sampled in this study.

LAKE	FLOODING CATEGORY	AREA (Ha)	AVERAGE DEPTH (m)	SPRING SILL ELEVATION (m)
129	No closure	316.6	1.29	2.363
80	No closure	19.3	1.52	2.631
87	Low closure	3.9	1.31	3.389
280	Low closure	2.4	1.64	3.838
56	High closure	3.1	1.08	4.623
Dock	High closure	0.5	2.23	5.169

Table 2.4 Water sample preservation and analysis methods for all river and lake sampling programs.

ANALYSIS	PRESERVATION	ANALYSIS METHOD
NO_3^-, Cl^-, SO_4^{2-}	Frozen	Dionex DX-300 ion chromatography (Dionex Corporation1991)
SRSi	Refrigerated	Acid molybdate spectroscopy (Strickland and Parsons 1972)
PO_4^{3-}	Refrigerated (<24hrs)	Molybdate blue spectroscopy (Strickland and Parsons 1972)
NH_4^+	Refrigerated (<24hrs)	Indophenol blue spectroscopy (Strickland and Parsons 1972)
TDOC	Frozen	Shimadzu TOC-V_{CPH} (Shimadzu Corporation 2004)
CDOC	Refrigerated	Spectrophotometry at 330nm. A=2.303 d/r where: A-absorbance coefficient; d-absorption @ 330nm; r-cell path length (cm)
TDN/TDP	Refrigerated	Acid photo-oxidation (Stainton et al. 1977)*
TSS	None	Gravimetric (Stainton et al. 1977)
POC, PN	Oven dried/sealed	Rapid Analysis Elemental CHN analyser (Stainton et al. 1977)*
PP	Oven dried/sealed	Filter digestion/molybdate blue spectroscopy (Stainton et al. 1977)*

*samples analysed by the Freshwater Institute, Fisheries and Oceans Canada (DFO)

Table 2.5 Sample calculations of delta effect model (TDOC) during the 03-Jun to 15-Aug sampling period. Mass fluxes displayed as volume-weighted concentrations for comparison purposes.

NO DELTA EFFECTS (rivers only)				
	MAC	ARR	PR	**Total**
River flow volume (km^3)	94.1	1.7	5.8	**101.6**
Average concentration (μmol/L)	324	159	140	-
River mass flux (mol*10^6)	30482	262	804	**31549**

Volume-weighted concentration (μmol/L): **311**

WITH DELTA EFFECTS (rivers and lakes)				
	NC	LC	HC	**Total**
Lake flow volume (km^3)	15.7	3.8	0.2	**19.8**
Average concentration (μmol/L)	528	612	807	-
Lake mass flux (mol*10^6)	8300	2350	169	**10819**
River flow volume less volume to lakes (km^3)	-	-	-	**81.7**
Volume-weighted river concentration (μmol/L)	-	-	-	**311**
River mass flux (mol*10^6)	-	-	-	**25402**
Lake+river mass flux (mol*10^6)	-	-	-	**36221**

Volume-weighted concentration (μmol/L): **357**

MAC – Mackenzie River above Arctic Red River
ARR – Arctic Red river near mouth
PR – Peel River above Fort MacPherson
NC – No closure lakes
LC – Low closure lakes
HC – High closure lakes

Table 2.6 Delta effect model results for selected nutrients during the 2004 water recession period. Observed values are based on seasonal means of the mouth transect from 2004 delta surveys (*measured in mg/L; measured in m^{-1}).

NUTRIENT	VOLUME-WEIGHTED MEANS NO DELTA EFFECTS (µmol/L)	VOLUME-WEIGHTED MEANS WITH DELTA EFFECTS (µmol/L)	DELTA LAKE EFFECT (%) (added to river (+) or stripped in lakes (-))	DELTA LAKES (nutrient sink or source)	OBSERVED (µmol/L)
PARTICULATES					
TSS	126*	104*	-17	Sink	77*
POC	347	296	-15	Sink	251
PN	17.6	15.8	-11	Sink	14.7
PP	3.4	2.9	-16	Sink	2.3
DOM					
TDOC	311	357	15	Source	323
CDOC	7.9	8.8	11	Source	8.55
DON	4.5	6.6	46	Source	5.9
DOP	0.01	0.03	228	Source	0.02
INORGANIC NUTRIENTS/IONS					
NO_3^-	5.8	4.9	-15	Sink	4.8
NH_4^+	0.17	0.23	40	Source	0.62
SRP	0.08	0.07	-10	Sink	0.09
SRSi	57.4	54.3	-5	Sink	54.1
SO_4^{2-}	446	416	-7	Sink	487
Cl^-	199	201	1	Conservative	197

Table 2.6 (continued) Delta effect model results for selected nutrients during the 2004 water recession period. Observed values are based on seasonal means of the mouth transect from 2004 delta surveys (*measured in mg/L; measured in m^{-1}).

NUTRIENT	VOLUME-WEIGHTED MEANS		DELTA LAKE EFFECT (%) (added to river (+) or stripped in lakes (-))	DELTA LAKES (nutrient sink or source)	OBSERVED (µmol/L)
	NO DELTA EFFECTS (µmol/L)	WITH DELTA EFFECTS (µmol/L)			
COMPOSITE MEASURES					
TN	27.8	26.2	-6	Sink	26.0
TDN	10.2	11.6	14	Source	11.3
TP	3.5	3.0	-14	Sink	2.4
TDP	0.06	0.08	37	Source	0.11
DIN	5.7	5.0	-13	Sink	5.4
TOC	658	653	-1	Sink	574
C:N:P RATIOS					
TOC:TN	22.9	23.2	1	Conservative	22.2
TOC:TP	207.4	346.1	40	Increased	258.5
TN:TP	9.6	15.0	36	Increased	11.8
POC:PN	19.4	17.7	-10	Decreased	16.6
POC:PP	104.0	115.3	10	Increased	101.1
PN:PP	5.5	7.5	27	Increased	6.2

2.9 Figures

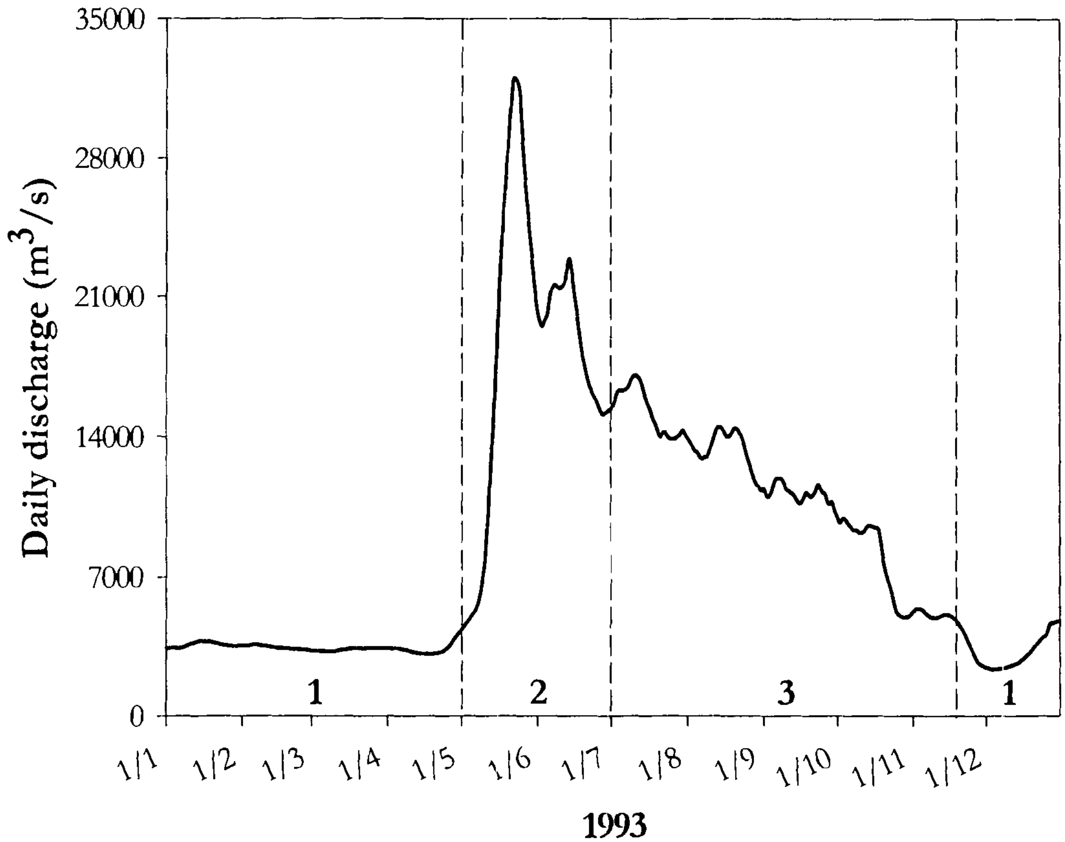

Figure 2.1 1993 daily discharge for the Mackenzie River above Arctic Red River WSC station. The 1993 hydrograph is the most representative of the 30-year average annual discharge of 284 km^3 for this station and represented 92% of all water to the Beaufort Sea from the Mackenzie system. General hydrological periods include: 1. Typical low flow period; 2. Flood period; 3. Recession period.

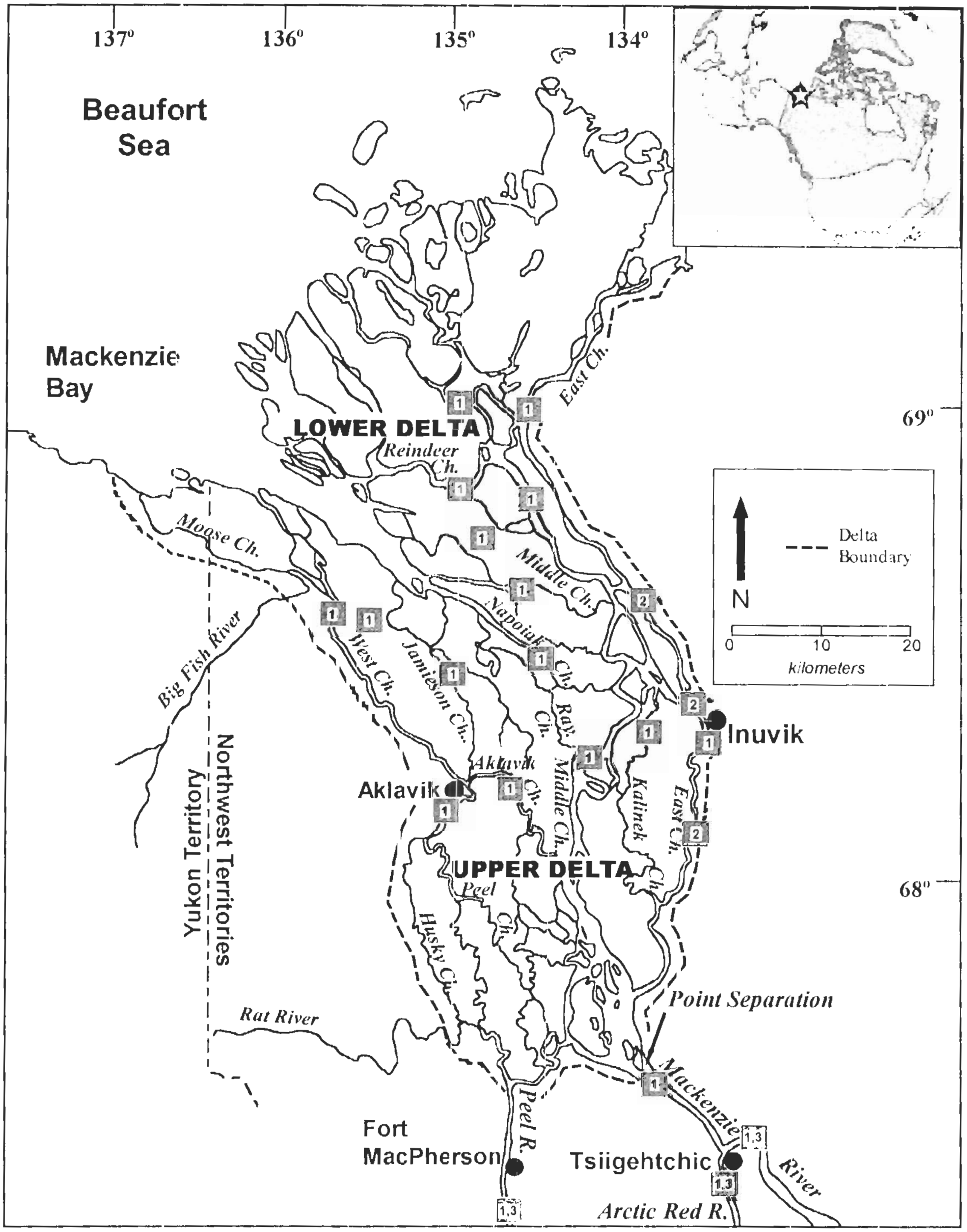

Figure 2.2 The Mackenzie Delta, NT, Canada. Grey boxes indicate a sampling location for each of the river sampling programs: (1) delta surveys; (2) mass balance survey; (3) weekly river sampling.

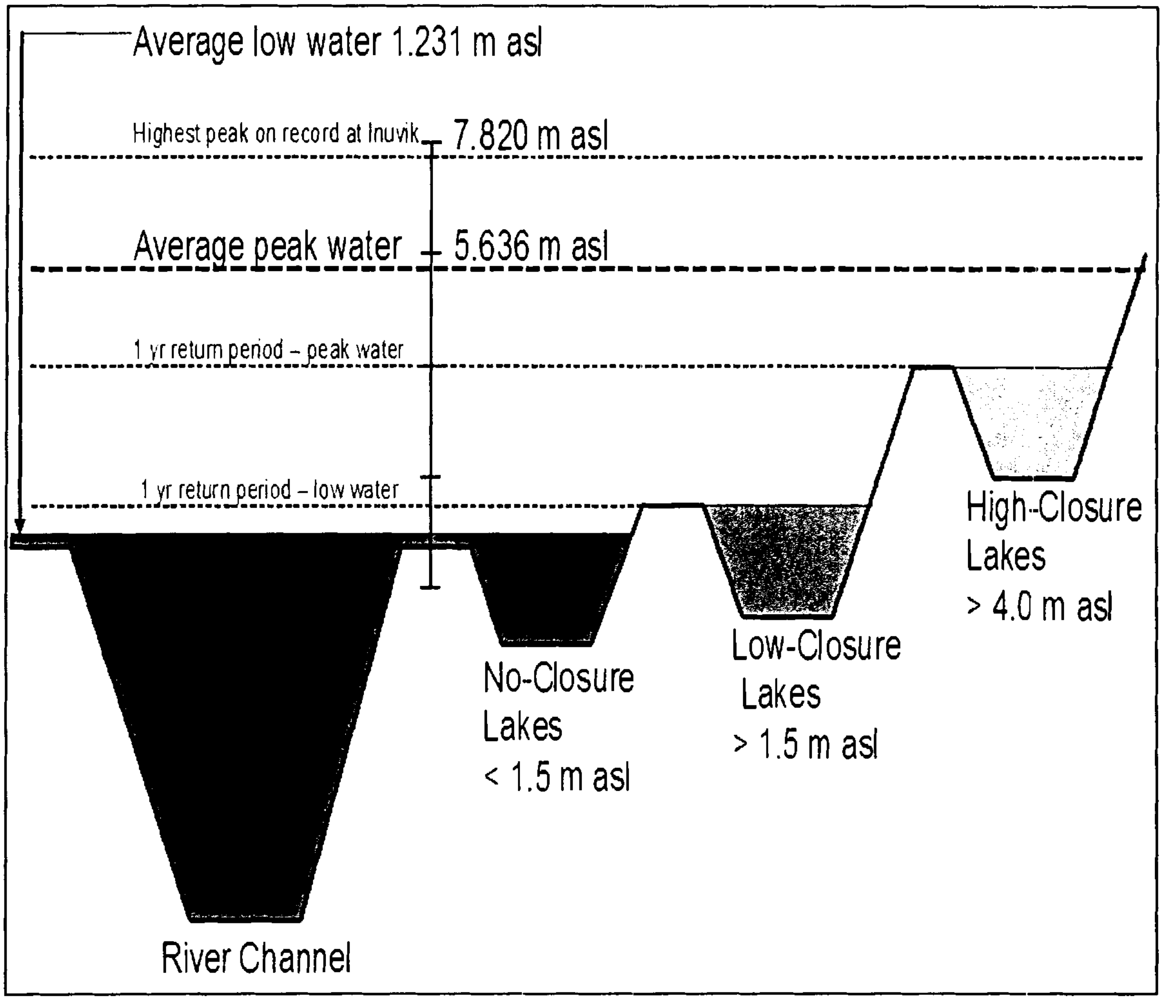

Figure 2.3 Sill elevation classification and flooding regime of delta lakes based on Mackay (1963) and Marsh and Hey (1989). Water levels are based on measurements at the Water Survey of Canada station on the East Channel at Inuvik.

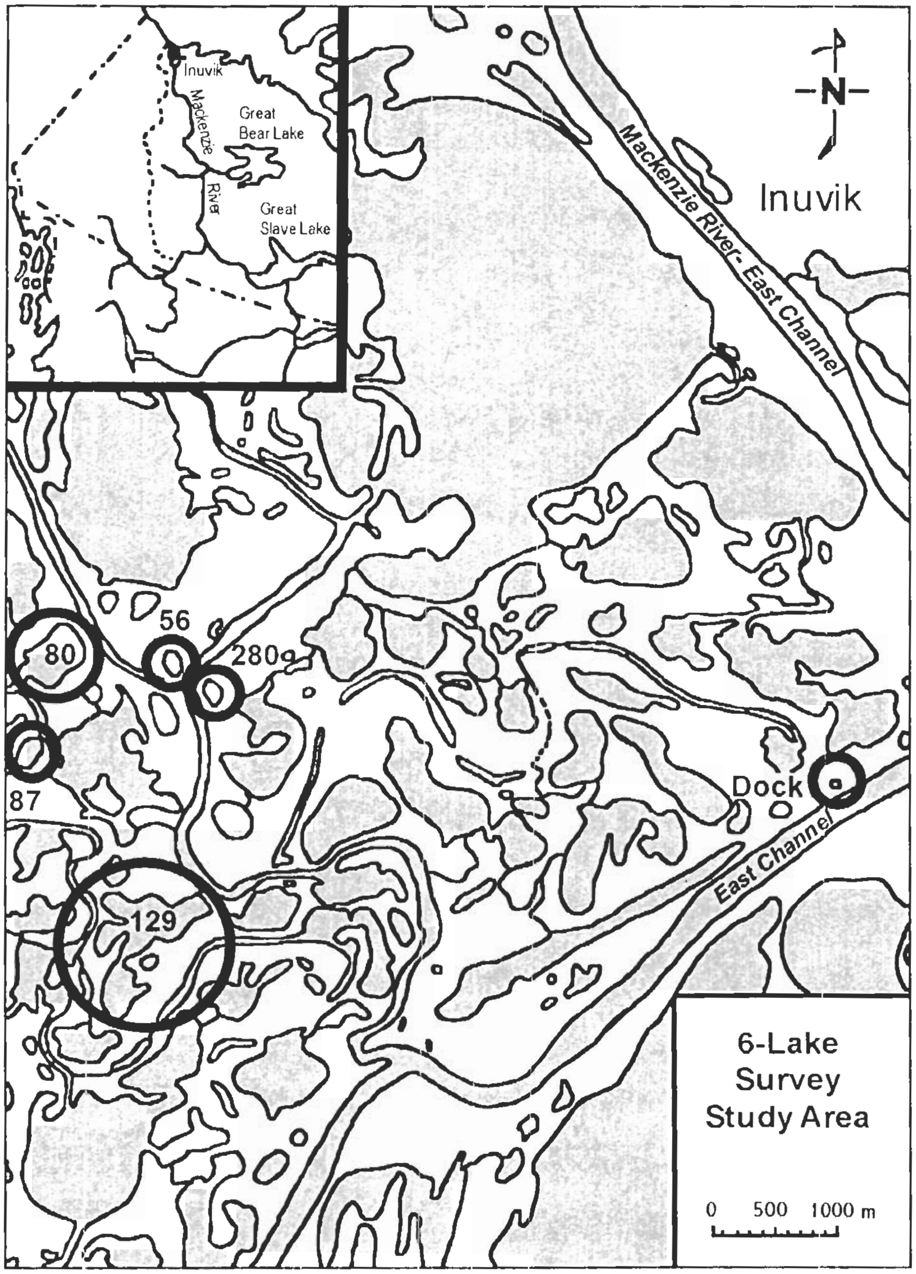

Figure 2.4 Study lakes representing each lake classification category by Mackay (1963) and Marsh and Hey (1989). Lakes 129 and 80 are no-closure lakes, lakes 87 and 280 are low-closure lakes and lakes 56 and Dock are high-closure lakes.

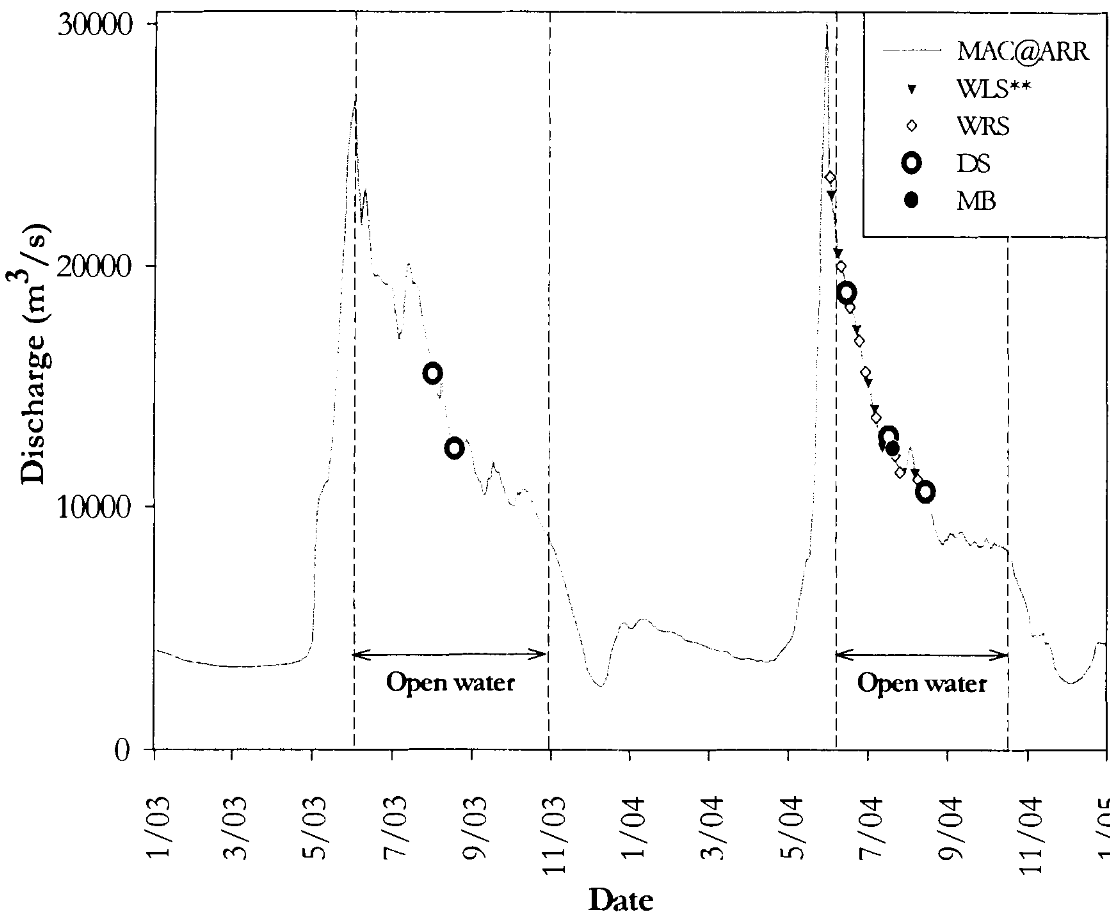

Figure 2.5 Mackenzie at Arctic Red River WSC station hydrograph 2003-2004 (MAC@ARR). Sampling program dates are indicated for both years. Note: 'WRS' and 'WLS' indicates timing of weekly river and lake sampling respectively; 'DS' indicates delta surveys; and 'MBS' indicates the mass balance survey. **Lake sampling was performed near Inuvik, NT downstream of this station and corresponded to the WSC station at Inuvik.

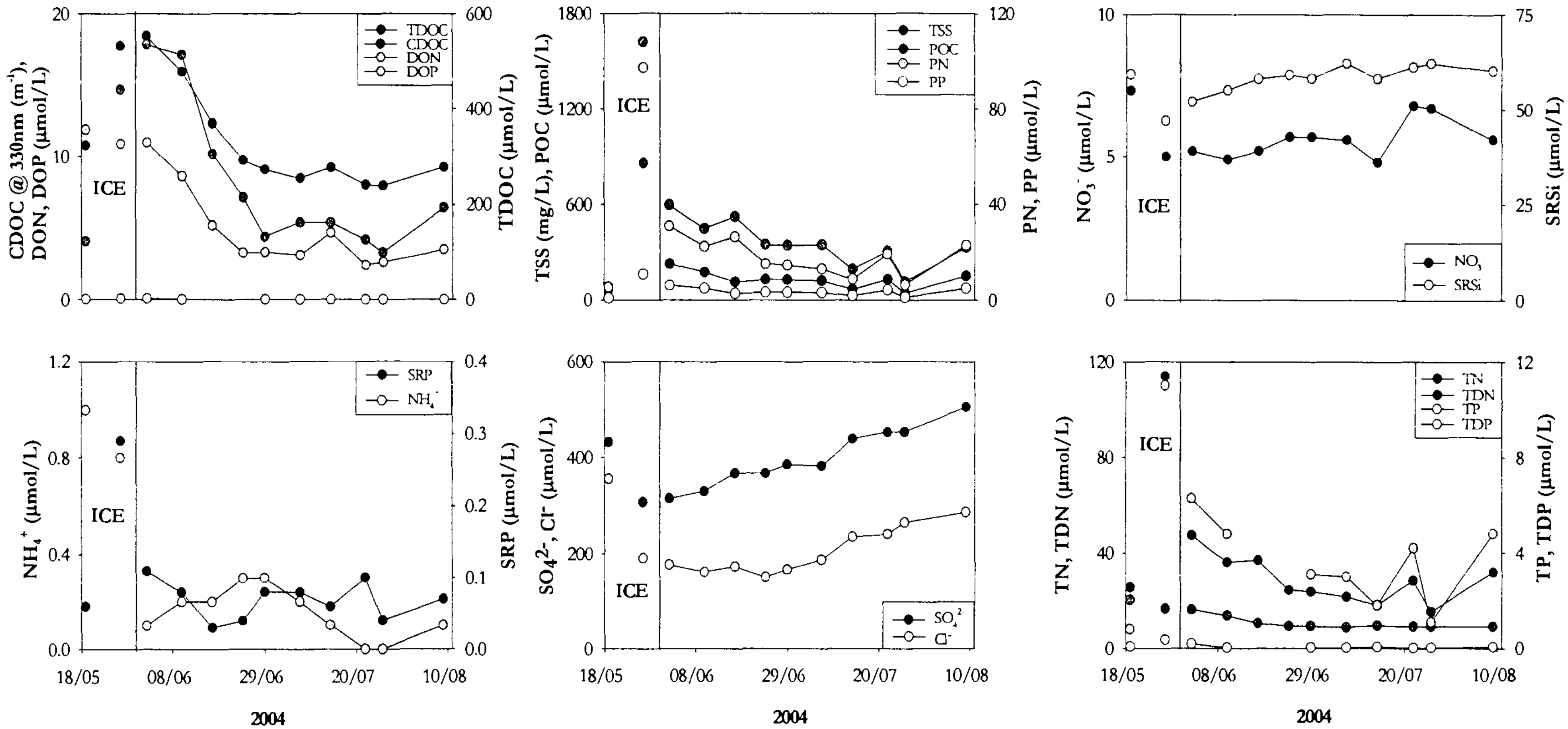

Figure 2.6 Weekly nutrient concentrations measured at the Mackenzie River at Arctic Red River during the 2004 open water season. Unconnected points indicate samples collected during the uncertain, ice-influenced rising limb portion of the hydrograph.

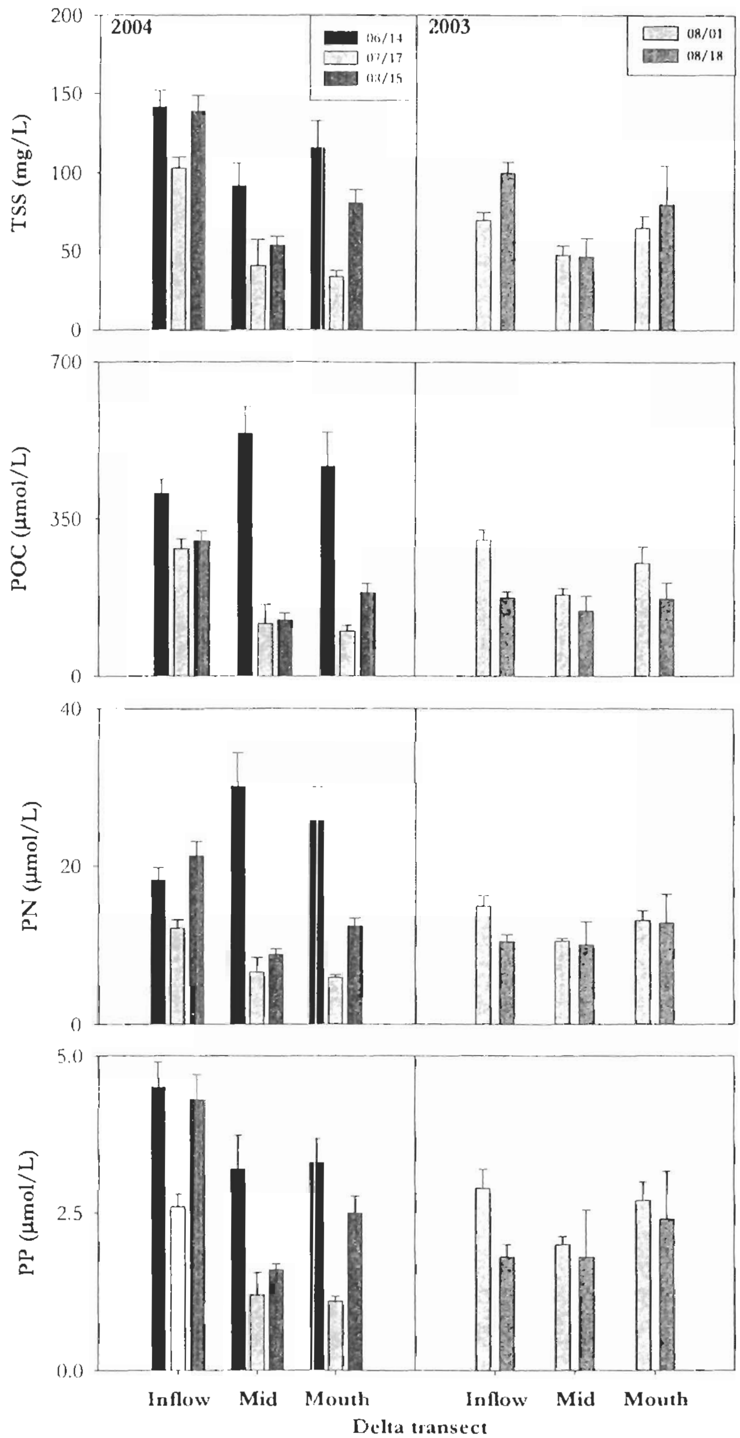

Figure 2.7 Particulate measures (TSS, POC, PN, PP) through Mackenzie Delta channels from the delta surveys. Error bars indicate flow weighted error in inflow transects and one standard error of the mean in the mid and mouth transects.

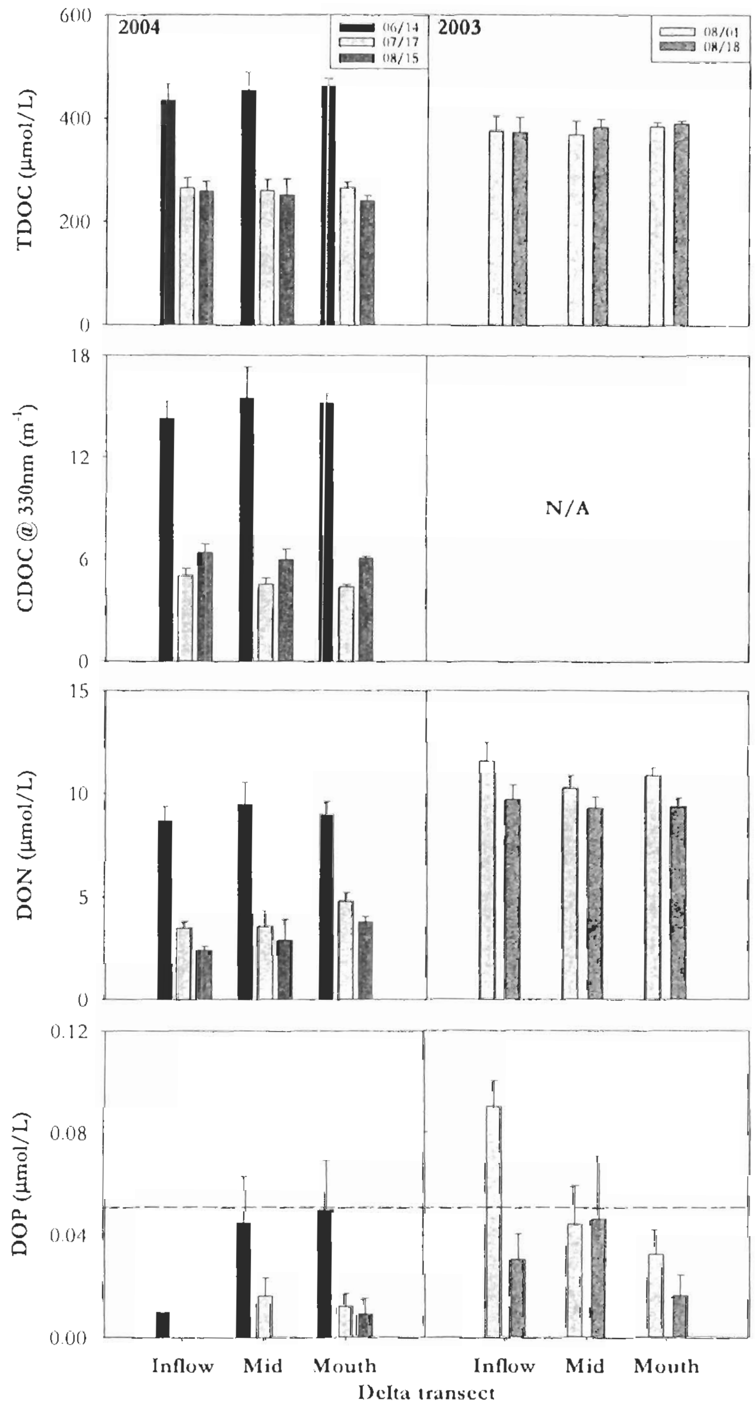

Figure 2.8 Dissolved organic matter measures through Mackenzie Delta channels from the delta surveys. Error bars indicate flow weighted error in inflow transects and one standard error of the mean in the mid and mouth transects. Dashed lines indicate limits of analytical detection.

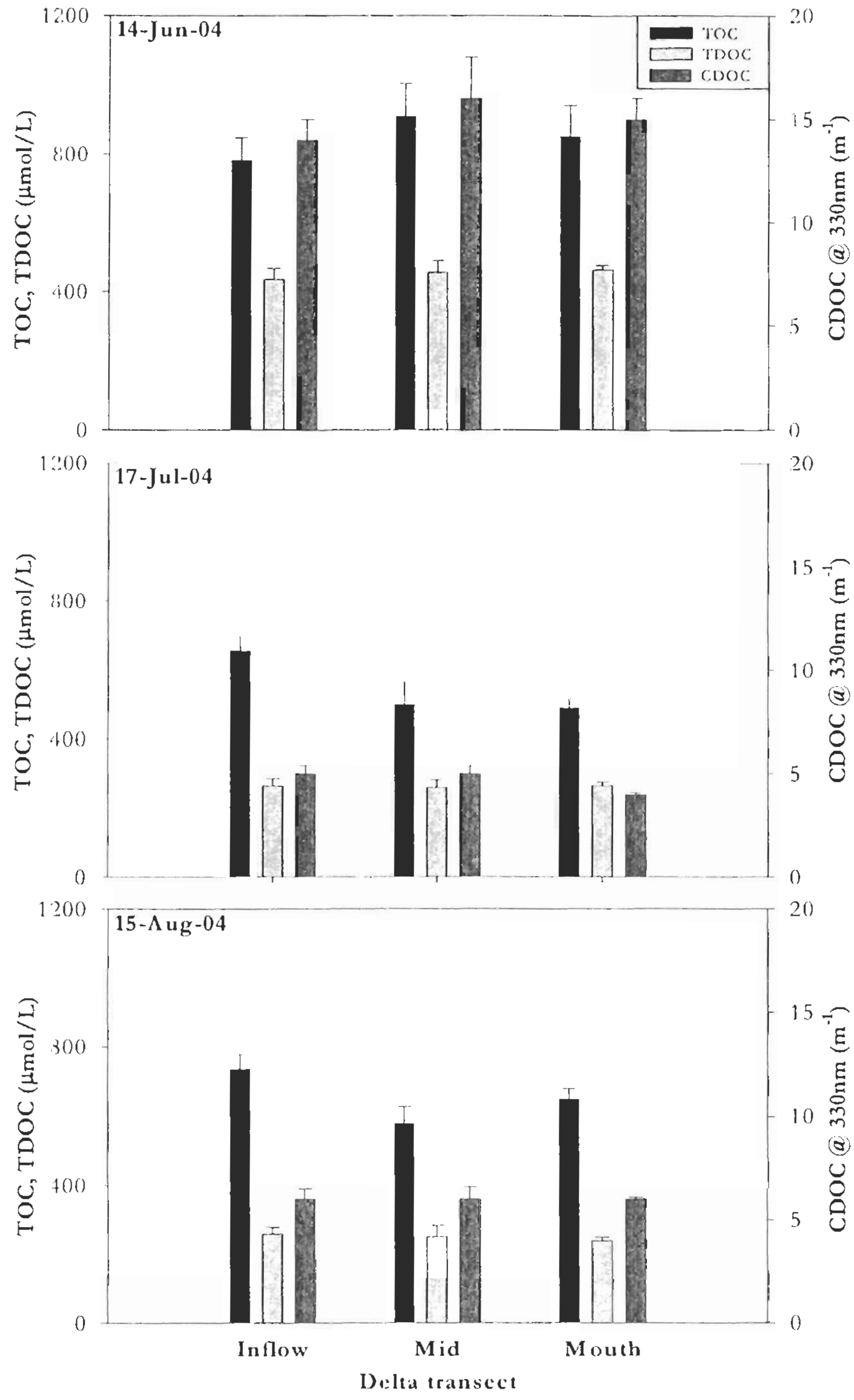

Figure 2.9 Total organic, total dissolved organic and coloured dissolved organic matter measures through Mackenzie Delta channels from the 2004 delta surveys. Error bars indicate flow weighted error in inflow transects and one standard error of the mean in the mid and mouth transects.

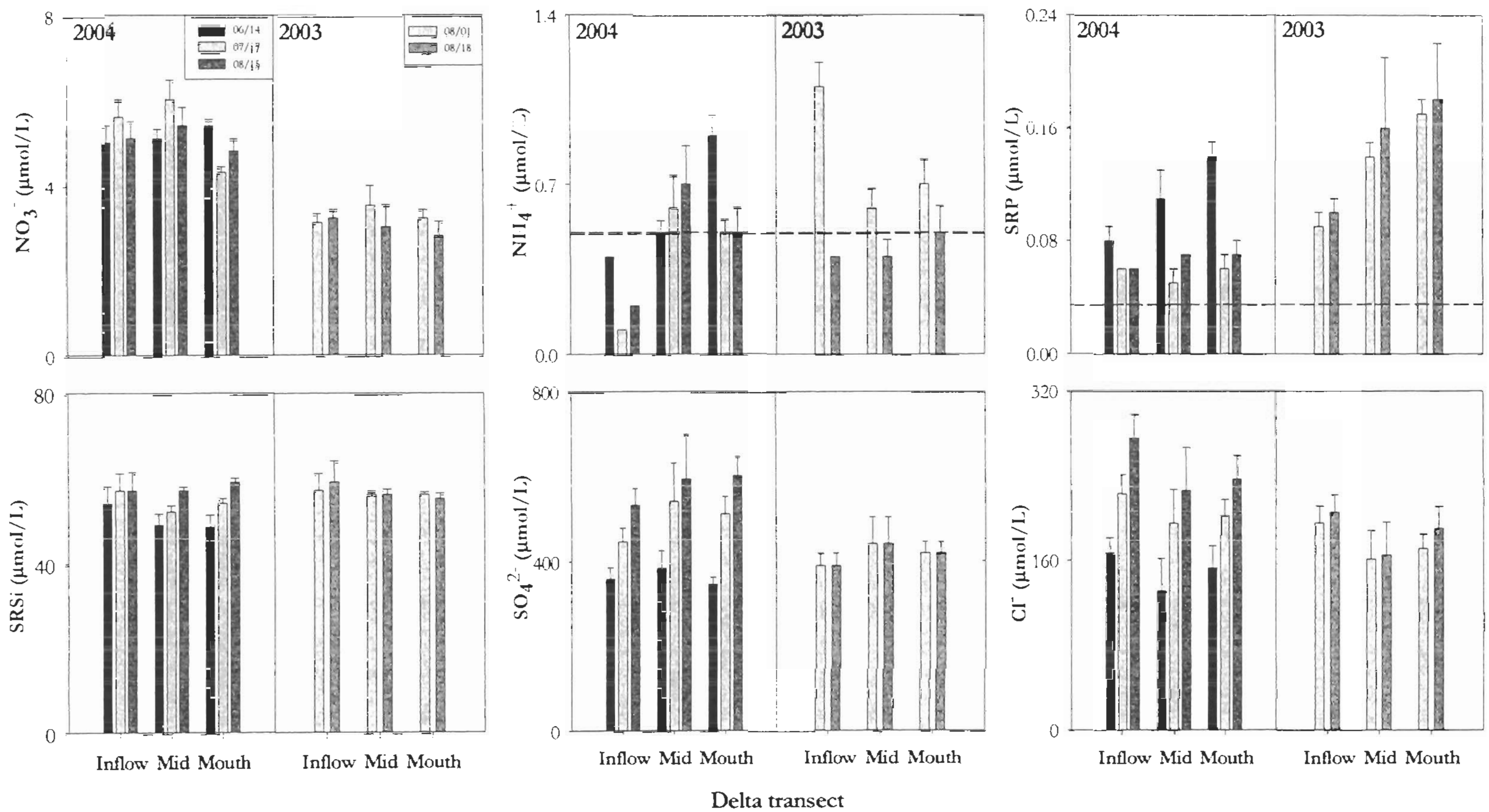

Figure 2.10 Inorganic nutrient measures through Mackenzie Delta channels from the delta surveys. Error bars indicate flow weighted error in inflow transects and one standard error of the mean in the mid and mouth transects. Dashed lines indicate limits of analytical detection

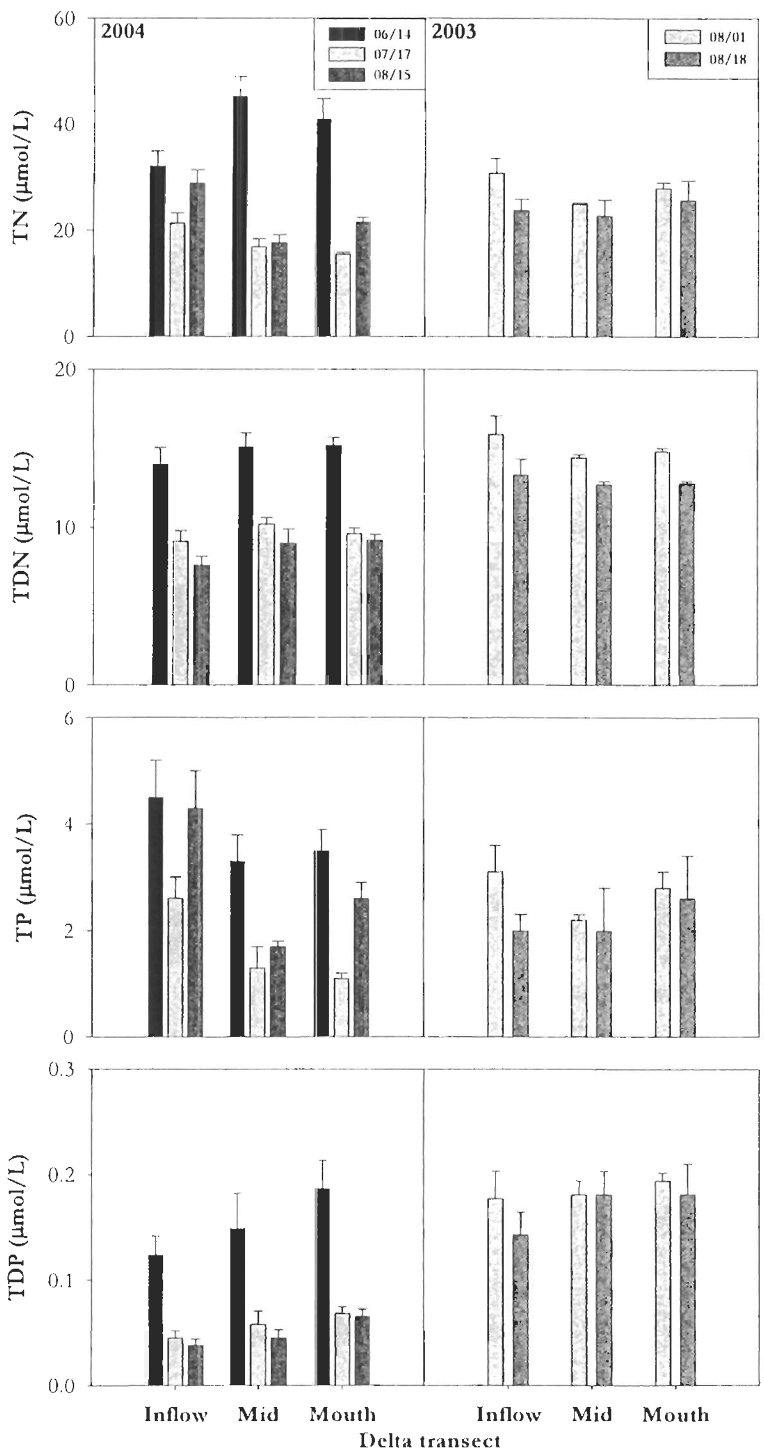

Figure 2.11 Composite measures through Mackenzie Delta channels from the delta surveys. Error bars indicate flow weighted error in inflow transects and one standard error of the mean in the mid and mouth transects.

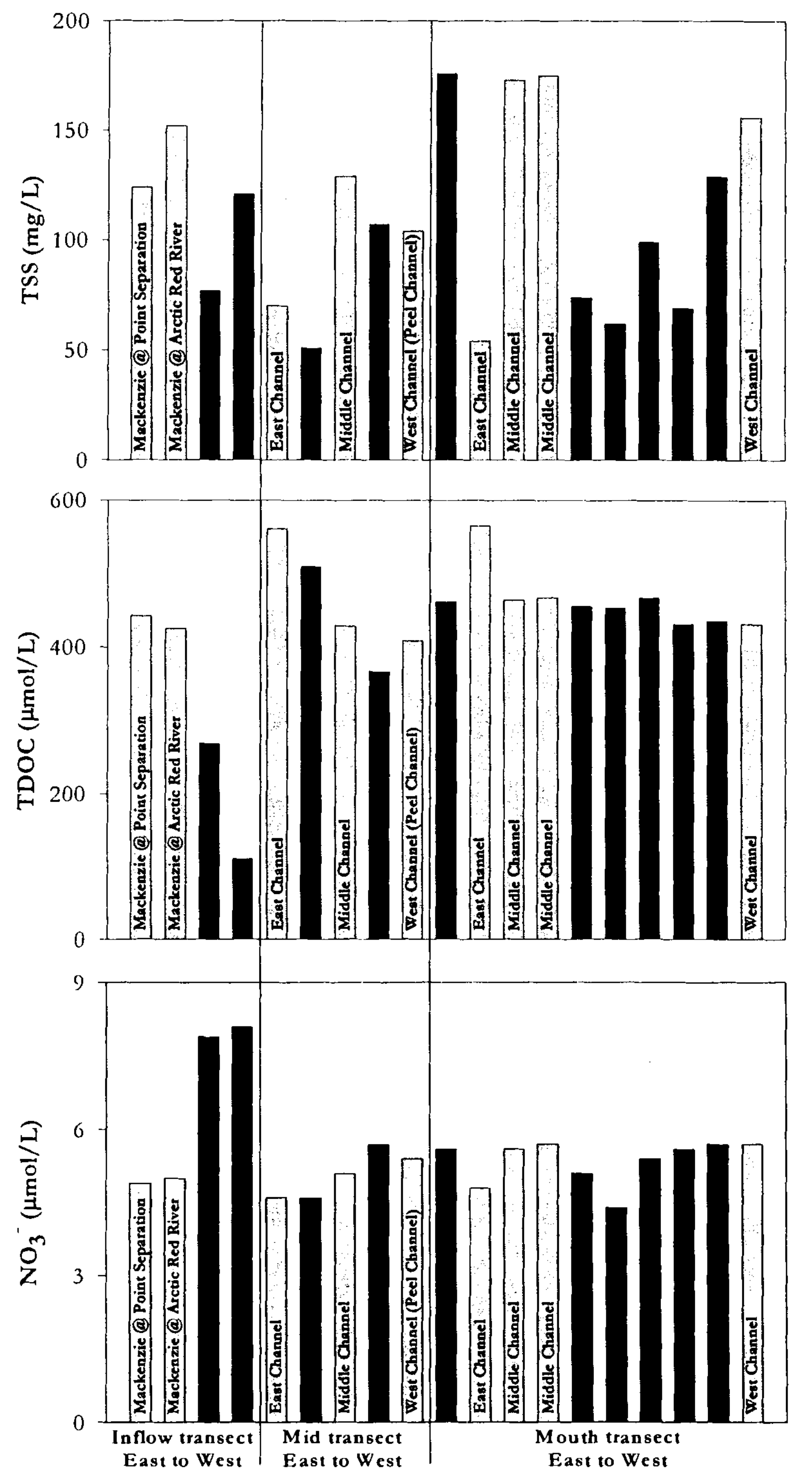

Figure 2.12 Selected nutrient measures east to west from the June 2004 early recession period delta survey. The grey bars indicate major delta rivers.

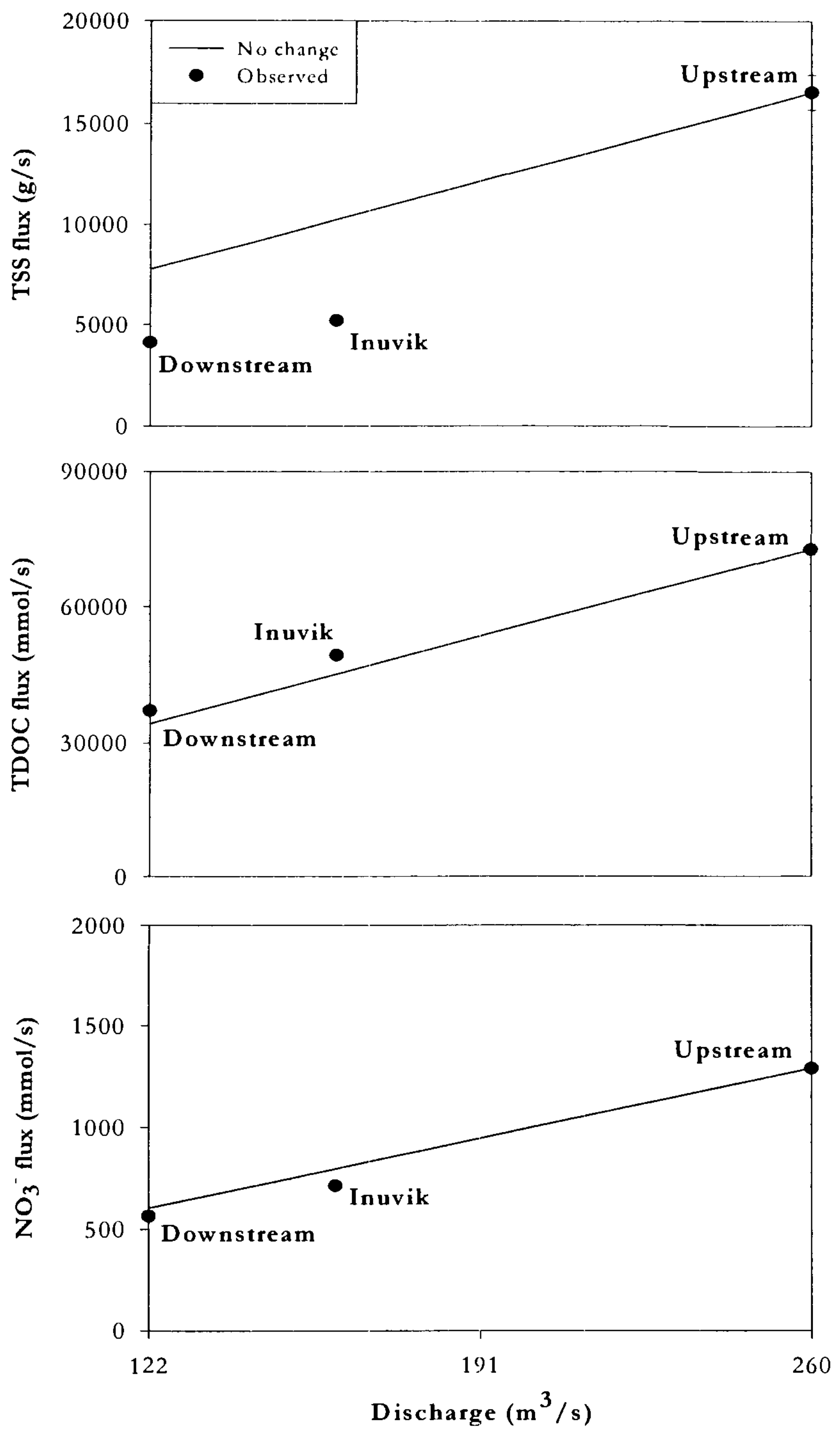

Figure 2.13 Mass balance survey results for TSS, TDOC and NO_3^-. The 'no change' line indicates theoretical conservative nutrient behaviour with discharge. Errors on observed measures indicate one standard error of the mean.

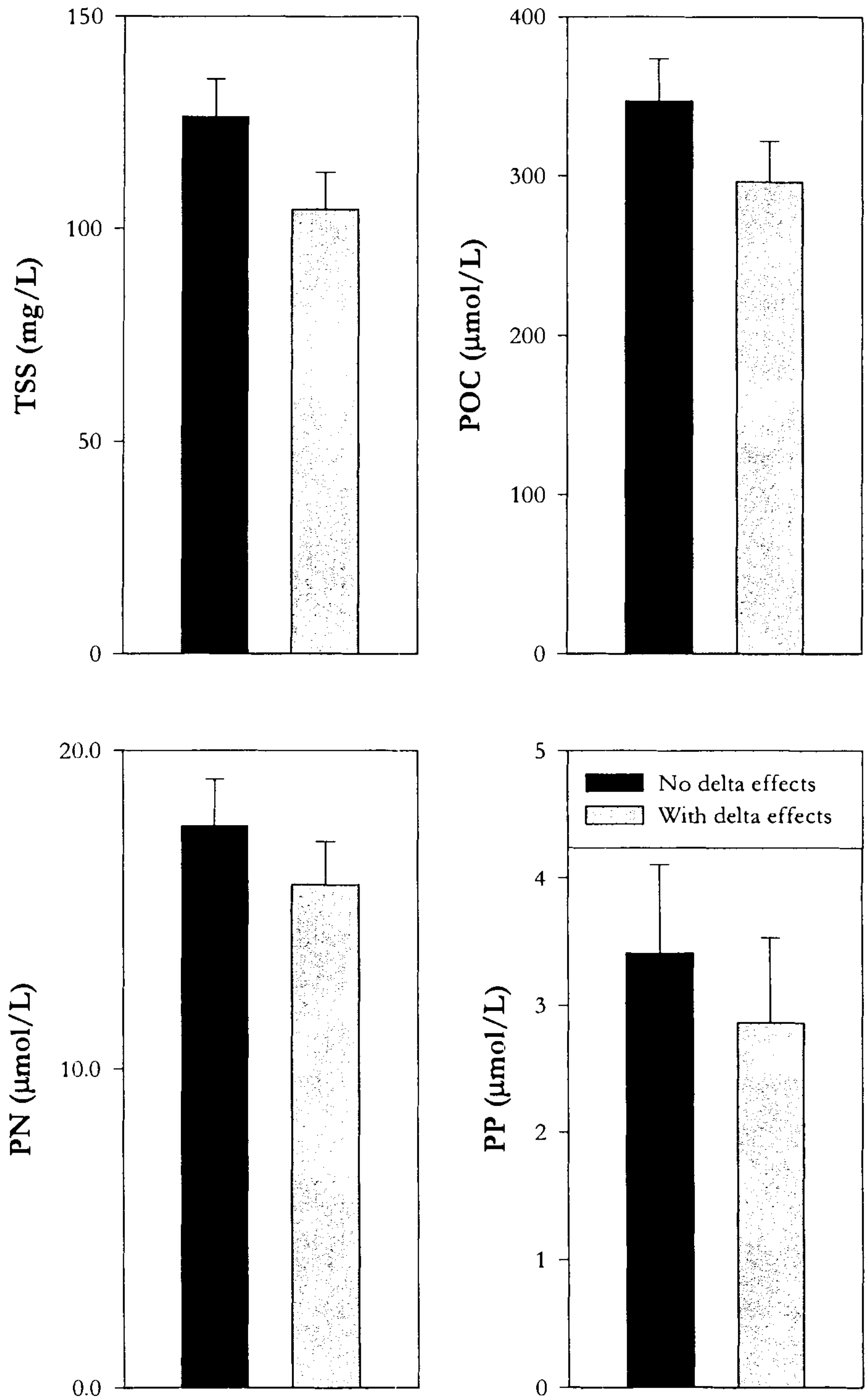

Figure 2.14 Delta effect model results for particulate measures (TSS, POC, PN, PP). Volume-weighted means based on a 3-Jun. to 15-Aug., 2004 measurement period. Error bars indicate flow weighted error.

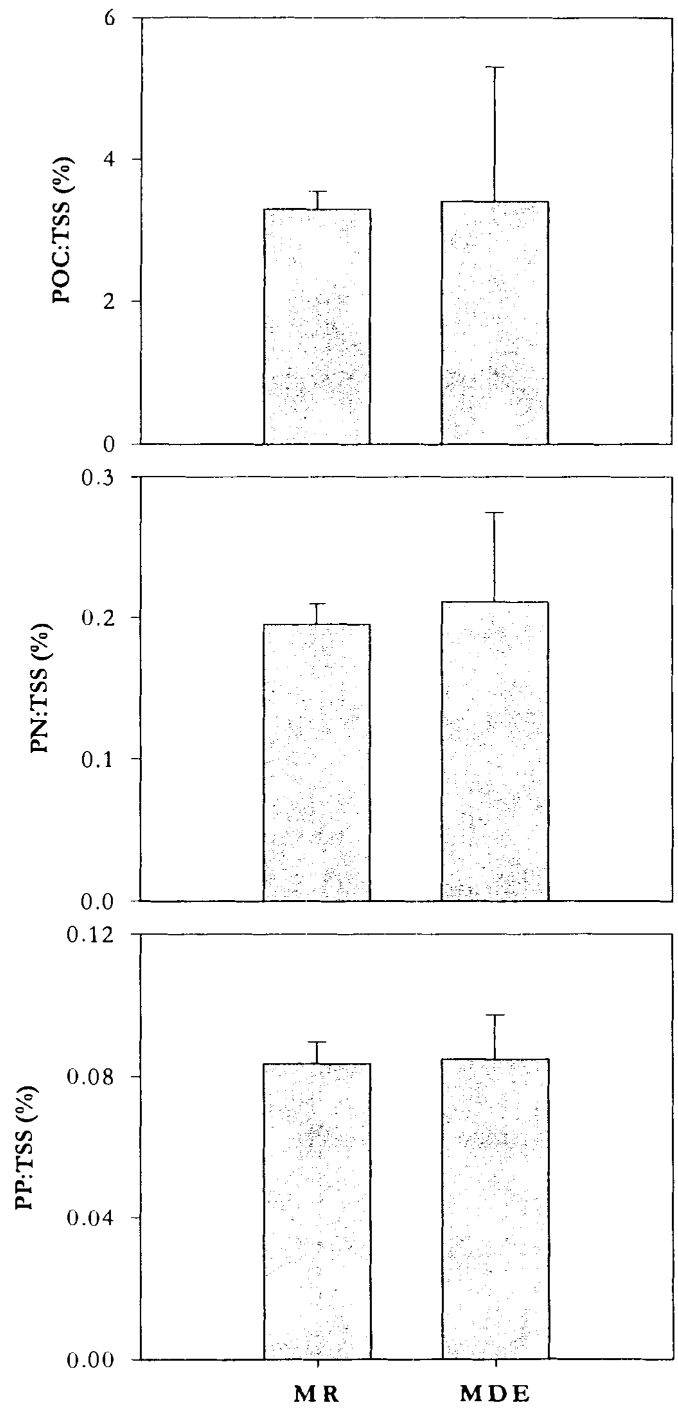

Figure 2.15 Delta effect model results for particulate measures (TSS, POC, PN, PP). Volume-weighted mean ratios based on a 3-Jun. to 15-Aug., 2004 measurement period. MR indicates 'no delta effects' scenario; MDE indicates 'with delta effects' scenario. Error bars indicate flow weighted error.

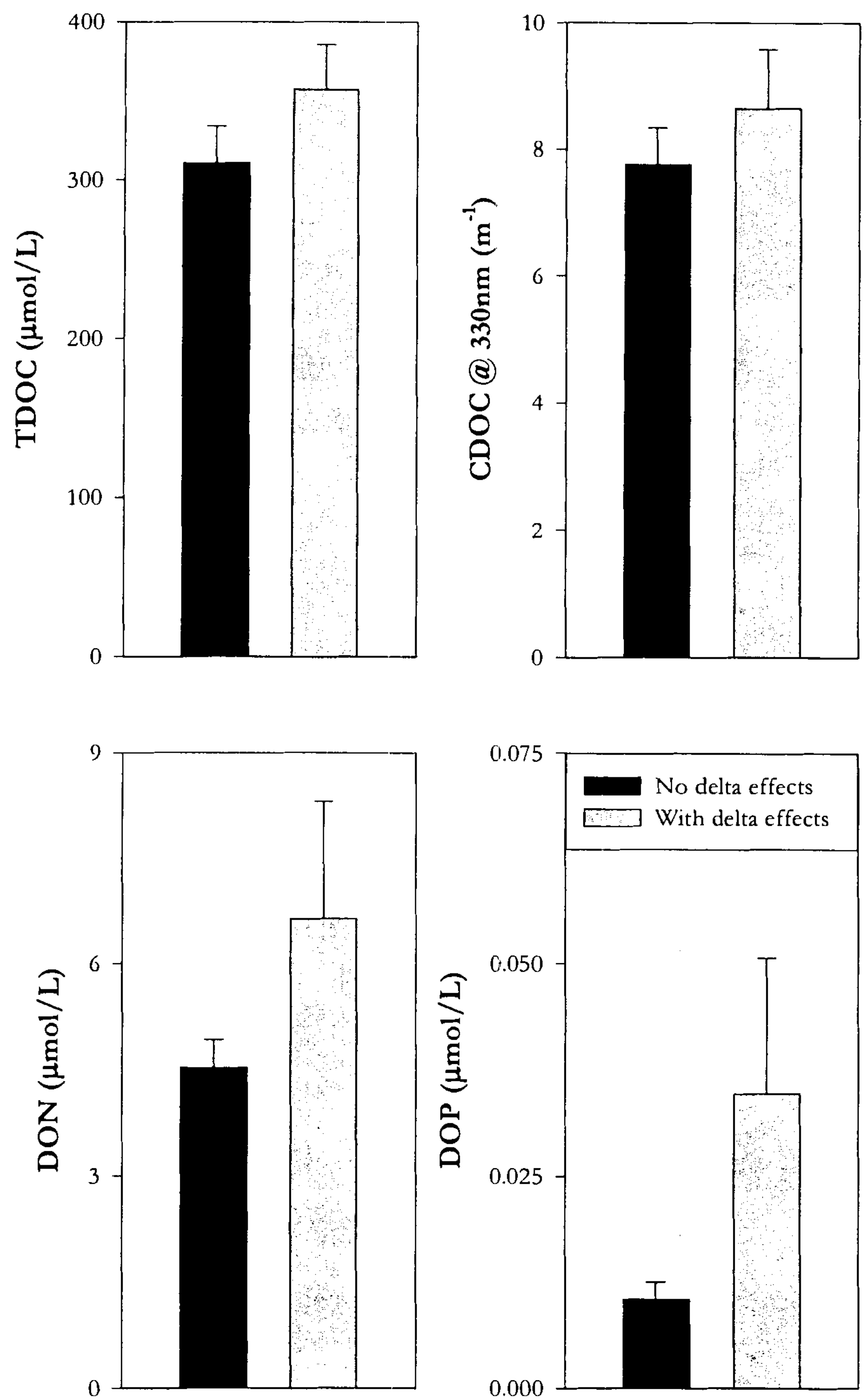

Figure 2.16 Delta effect model results for dissolved organic measures (TDOC, CDOC, DON, DOP). Volume-weighted means based on a 3-Jun. to 15-Aug., 2004 measurement period. Error bars indicate flow weighted error.

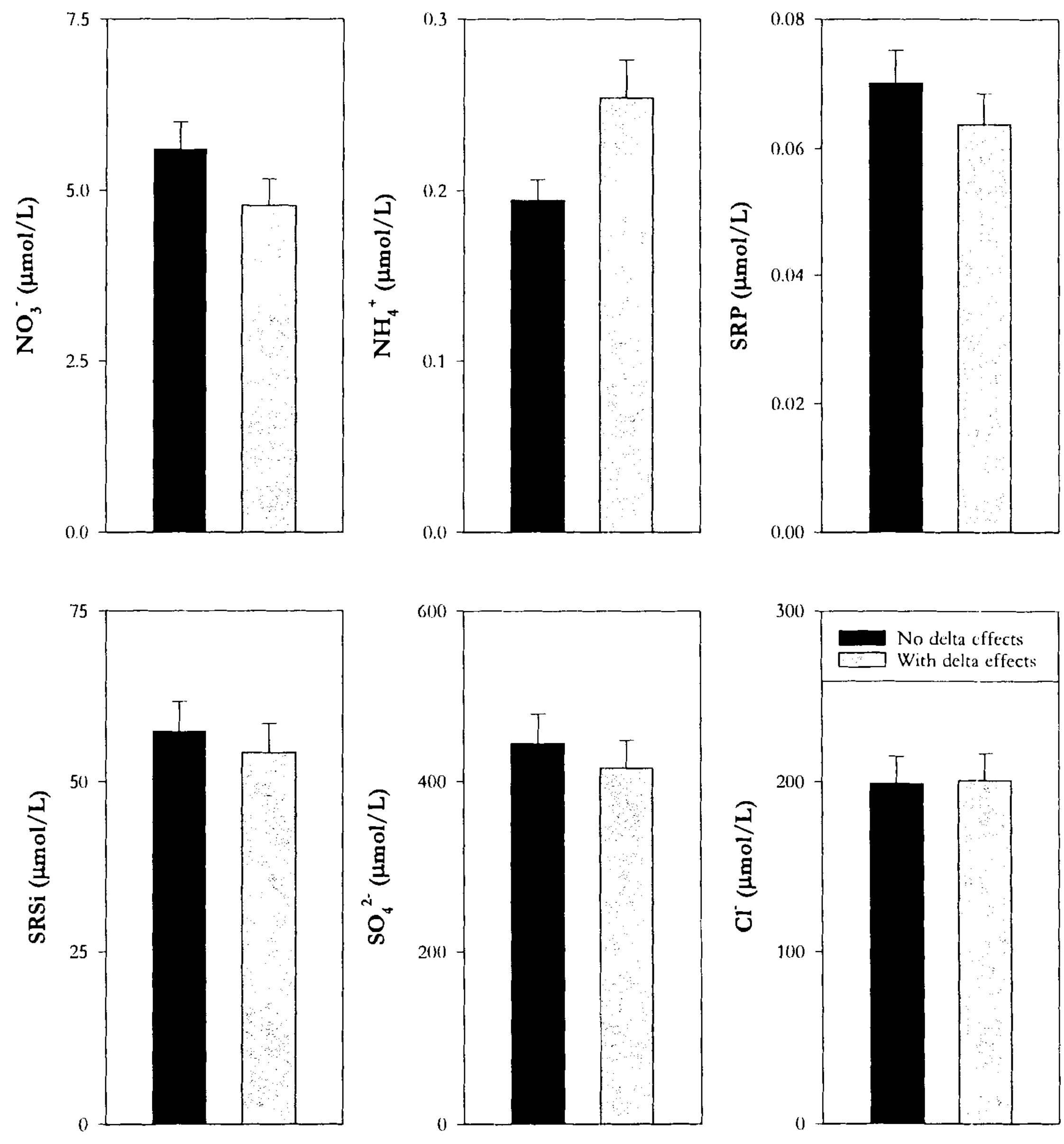

Figure 2.17 Delta effect model results for dissolved inorganic measures (nitrate, ammonium, SRP, SRSi, sulphate, chloride). Volume-weighted means based on a 3-Jun. to 15-Aug., 2004 measurement period. Error bars indicate flow weighted error.

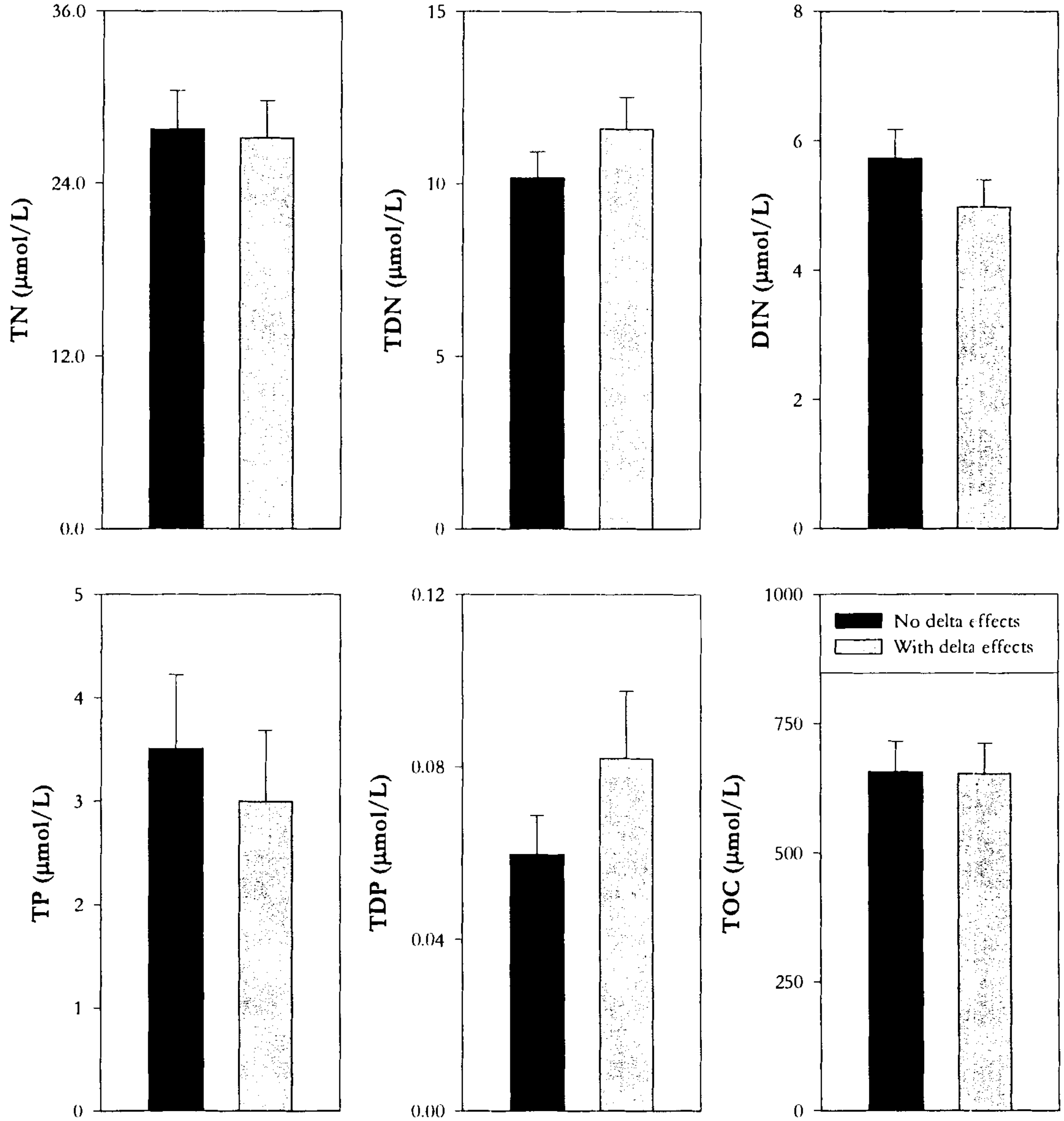

Figure 2.18 Delta effect model results for composite measures (TN, TDN, TP, TDP, DIN, TOC). Volume-weighted means based on a 3-Jun. to 15-Aug., 2004 measurement period. Error bars indicate flow weighted error.

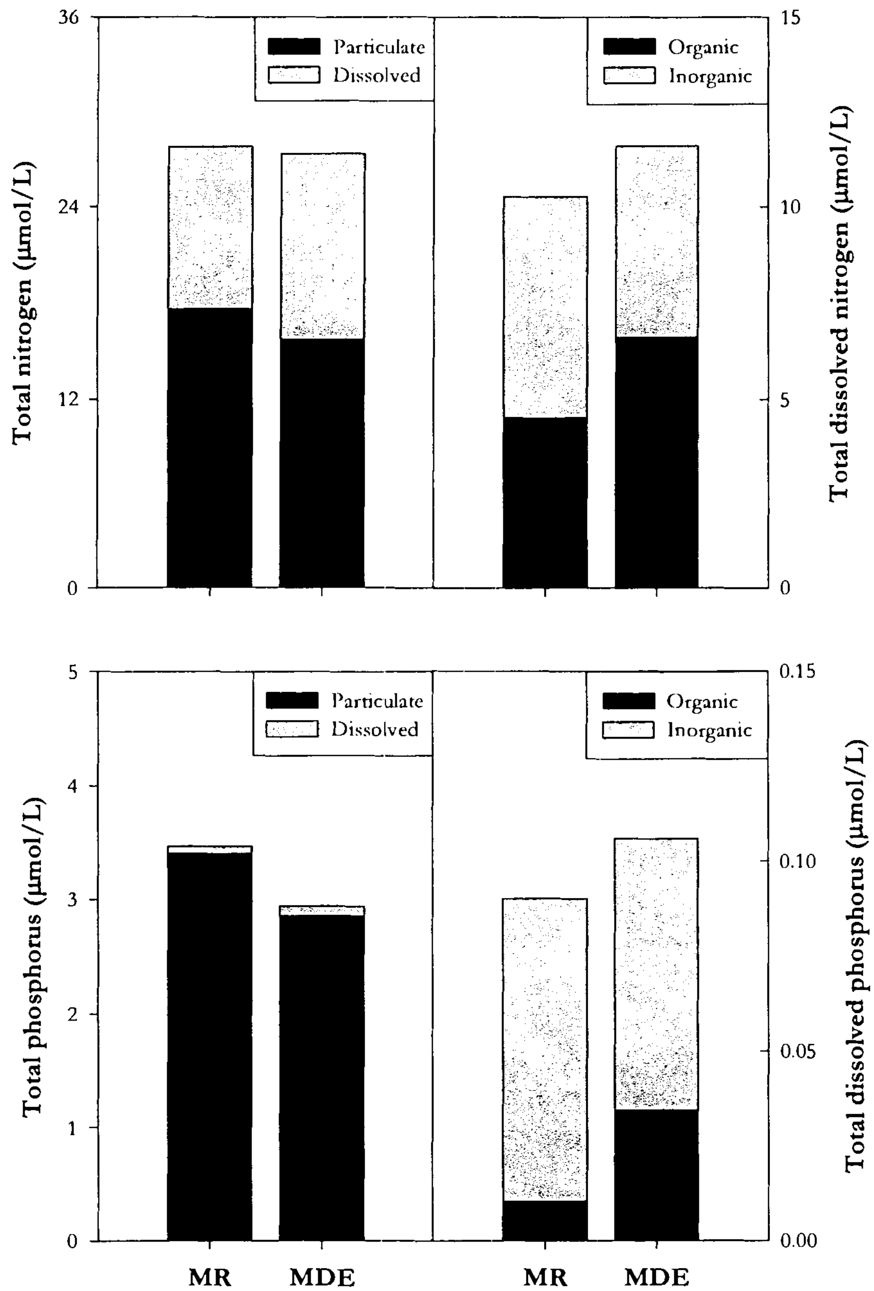

Figure 2.19 Delta effect model results for composite measures (TN, TDN, TP, TDP, DIN, TOC). Volume-weighted means based on a 3-Jun. to 15-Aug., 2004 measurement period. MR indicates 'no delta effects' scenario while MDE indicates 'with delta effects' scenario.

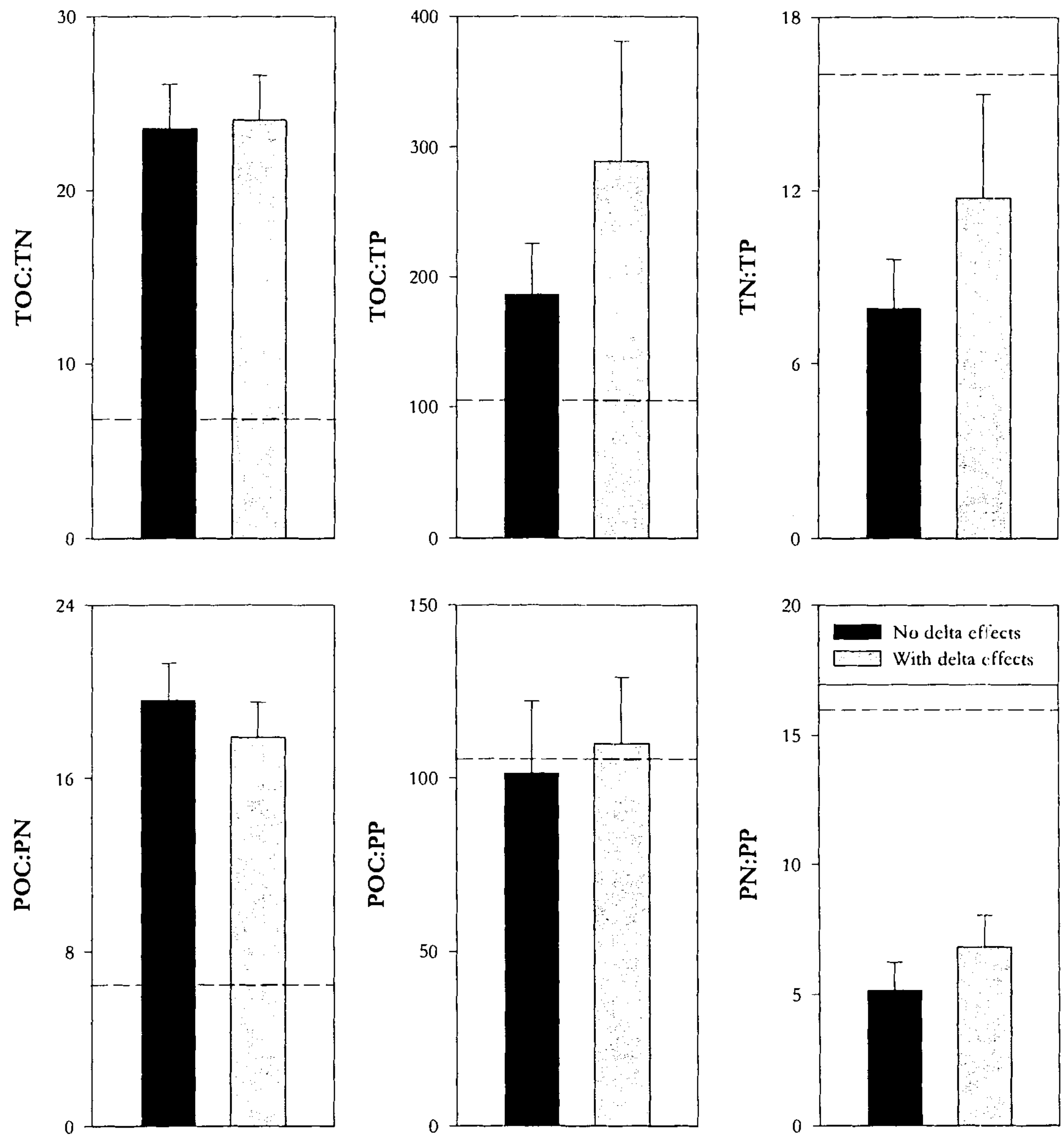

Figure 2.20 Delta effect model results for composite measures (TN, TDN, TP, TDP, DIN, TOC). Volume-weighted mean ratios based on a 3-Jun. to 15-Aug., 2004 measurement period. The dashed lines indicate the Redfield ratio while error bars indicate flow weighted error.

3 DOWNSTREAM NUTRIENT CHANGES AND VERTICAL STRUCTURE ACROSS THE FRESHWATER-SALTWATER TRANSTION ZONE OF THE MACKENZIE ESTUARY, WESTERN CANADIAN ARCTIC

3.1 Abstract

The nutrient composition of river water was tracked across the freshwater-saltwater transition zone (FSTZ) of the Mackenzie River East Channel into the adjacent Beaufort Shelf during an 8-day mid summer cruise during 2004. Particulates (TSS, POC, PN, PP) rapidly declined downstream across the estuarine region and generally declined in organic content seaward. Levels of dissolved inorganic constituents (nitrate, silica) also rapidly declined across the FSTZ. High levels of total dissolved organic carbon (TDOC) in river-water conservatively mixed with seawater containing much lower levels, while coloured-DOC behaved similarly with no obvious photobleaching effects. In contrast to behaviour in typical (i.e. non-arctic) estuaries, dissolved organic N and P each increased substantially across the FSTZ to relatively high levels on the Beaufort Shelf. On the seaward side of the FSTZ, the marine sites were stratified into 3 layers, consisting of a top layer (down to 5 m) actively mixing with river-water, a second layer (down to 20 m) possibly representing a remnant of Mackenzie water derived from the high flow period of ice breakup and full-salinity (nutrient-rich) deeper ocean water below that. The build up organic N and P levels in the estuary plus the layered structure offshore are generally consistent with slow coastal flushing rates likely related to the relatively short open-water period and the sea ice remaining close enough to the coast to inhibit wind driven circulation of the water.

KEYWORDS: arctic; estuary; nutrients; Mackenzie

3.2 Introduction

The Arctic Ocean is almost entirely landlocked by large river basins making it the most freshwater-influenced of the world's oceans (Opsahl et al. 1999; Lobbes et al. 2000). It is also heavily influenced by pack ice for most of the year with only coastal regions of open water during the summer. Each combine to create a strongly stratified open water environment that largely limits upwelling of nutrient-rich deep waters (Macdonald et al. 2004; Macdonald et al. 1987). Consequently, coastal autotrophic and heterotrophic communities are more dependent on riverine inputs of 'new' nutrients to sustain their productivity. Annual spring flooding of rivers provides the largest annual fluxes of nutrients, heat, freshwater, sediment and organic matter to the system. This initiates a short and intensive growing season in coastal regions (Carmack et al. 2004) that is further driven by nearly continuous irradiance. Such conditions provide an environment where biogeochemical change is intense across arctic estuaries, both downstream and vertically across the freshwater-saltwater transition zone (FSTZ).

Significant changes in nutrient content occur across the FSTZ in all estuaries, which are driven by abiotic, autotrophic and heterotrophic processes (Raymond and Bauer 2001; Lebo 1990; Fox et al. 1985). Sediment and particulate organic matter are efficiently stripped from the water column in estuaries due to losses in river velocity. Organic particulates are further affected by flocculation and coagulation processes associated with increased salinity (Dittmar and Kattner 2003; Droppo et al. 1998). The fate of much of this riverine material is burial in the coastal shelf system and the overall refractive character of much of the particulate matter shows strong resistance to microbial breakdown (Macdonald et al. 1998). Biological particulate organic matter may increase or decrease through an estuarine system depending on species and life cycle aspects (Barlow et al. 1963). Resuspension, wave turbulence, tides, coastal erosion and primary production all have the potential to increase turbidity in estuaries and add a further source to discharging waters.

Dissolved organic matter (DOM) content in estuaries is highly variable. Total dissolved organic carbon (TDOC) is a major portion of DOM imported to estuaries and concentrations can change due to salinity effects, bacterial uptake, photo-bleaching and export offshore (Raymond and Bauer 2001). Internal autochthonous recycling, production by phytoplankton and wetlands can be important sources of TDOC in estuaries (Aminot et al. 1990; Cole et al. 1982; Odum and Smith 1985). Consequently, TDOC shows both conservative (Cauwet and Sidorov 1996) and non-conservative behaviour (Raymond and Bauer 2001) through estuaries. Algal release of dissolved organic nitrogen (DON) and phosphorus (DOP) during production (Cook et al. 2004; Dittmar et al. 2001; Myclestad 1995), breakdown of algae by microorganisms, grazing and atmospheric sources can contribute to the dissolved organic nutrient pool in estuaries (Nagao and Miyazaki 2002; Eyre and Ferguson 2002; Paerl et al. 1990). DON and DOP are also heterotrophic substrates, thus many studies have shown no clear trends of either through estuaries (Sharp et al. 1982; Cauwet and Sidorov 1996; Kattner et al. 1999; Macdonald et al. 1998; Dittmar et al. 2001; Burdige and Zheng 1998; Lomstein et al. 1989; Tyler 2001). The proportion of DOP to total dissolved phosphorus (TDP) through estuaries in some studies was shown to increase and attributed to in situ biological production (Ormaza-Gonzalez and Statham 1991; Fang 2000).

Dissolved inorganic nutrients are not normally conservative across estuaries. Many studies have looked at the buffering dynamics of metal oxide particles and subsequent release of phosphate with increasing salinity (Fox et al. 1985; Conley et al. 1995; Jordan et al. 1991). Uptake of dissolved inorganic phosphorus (DIP) by algae during seasonal blooms can be an important loss pathway in estuaries (Conley et al. 1995; Sharp et al. 1982). Dissolved inorganic nitrogen (DIN) is generally in high demand by algae in estuarine systems and is normally lost across the FSTZ (Sharp et al. 1982; Jordan et al. 1991). Denitrification in estuarine sediments is also a possible removal mechanism for nitrate (NO_3^-), though its magnitude in different estuaries is highly variable (Fox et al. 1987; Seitzinger 1988). Anaerobic production of ammonium (NH_4^+), via decomposition in estuarine sediments, may produce increases in nitrate based on nitrification processes in oxic river waters (Cai et al. 2000). Ammonium levels may be significant in sediments of estuaries (Fox et al. 1987; Cai et al. 2000), however its high biological demand keeps recycling efficient and free ammonium low in unpolluted systems. If oxygen levels are low, ammonium may persist in the water column, but its existence in usually only considerable in sediment layers. Many studies have concluded that soluble reactive silica (SRSi) behaves both conservatively (Sharp et al. 1982; Fang 2000) and non-conservatively through estuaries (Nijampurkar et al. 1983 and references within). Growth of diatoms can reduce concentrations (Carmack et al. 2004; Peterson et al. 1985) and recycling and dissolution may be important in estuaries upon diatom death and senesce to sediments.

In arctic estuaries, studies of nutrient patterns have been mostly confined to the great Siberian rivers with few studies in the Mackenzie Estuary. Most studies have focused on organic matter content across estuaries and general nutrient behaviour is described in Table 3.1. Other studies were limited to specific areas in the estuary. Lara et al. (1998) measured several organic and inorganic nutrients from the Lena River into the beginning of its estuary, however still within heavy river influence. Lobbes et al. (2000) performed a wide survey of Siberian rivers for many organic and inorganic nutrients, however sampling from low salinity estuarine regions (<1.7 psu). Yunker et al. (1993, 1994) proceeded further into the Mackenzie river portion of the FSTZ, though measuring various forms of hydrocarbons. Primary production studies by Parsons et al. (1988, 1989) and Carmack et al. (2004) provided important analysis on primary producers inherent to nutrient concentration studies. Overall, studies investigating nutrient transitions across the entire FSTZ have been few in arctic estuaries, particularly across the Mackenzie River FSTZ. This despite the Mackenzie's high sediment flux and small coastal shelf area compared to other arctic estuaries.

Climate-induced changes in arctic watersheds are expected to modify river chemistry through estuaries. Therefore, the Mackenzie Estuary is a potentially important environment due to predicted environmental change in its region. Mean air temperature increases of 3-5°C (under 2 x CO_2 scenario) have been predicted in the Mackenzie Basin (Moritz et al. 2002; Rouse et al. 1997). Currently, warming (Bengtsson et al. 2004) and related environmental responses have progressed in regions of the arctic (Mueller et al. 2003; Vincent and Pienitz 1996; Comiso 2003; Smith et al. 2005) and are expected intensify in the Mackenzie Basin. One important response of the Mackenzie River to such changes may be a reduction in seasonal ice jams that facilitate widespread flooding of the ecologically sensitive delta area. This process partially determines the type and magnitude of nutrient fluxes delivered to the estuary via temporary storage within the delta floodplain and thousands of floodplain lakes (Chapter 2; Lesack et al. submitted; Emmerton et al. submitted). Gradual disconnection of river floodwaters with the delta plain and lakes is expected to alter nutrient content being delivered to the estuary (Chapter 2). Increased water storage in melted permafrost and evapotranspiration are also expected to be a consequence of climate warming in the basin, thus delivering reduced runoff and discharge to the Beaufort Sea. This may impact the chemical and biological processes through the estuary that depend on consistent freshwater and nutrient fluxes. Ice cover dynamics may be another large estuarine impact resulting from a warming climate. Algal communities at the bottoms and margins of land-fast sea ice are important habitats for production (Gradinger 1995) and play a critical role in early spring productivity in the estuary (Carmack and Macdonald 2002; Carmack et al. 2004). Regional warming may not only lengthen the open water season in the estuary, but may reduce the habitats for these algae. As another consequence, extensive loss of ice coverage past the shelf break may hasten upwelling of deep ocean water and provide a strong nutrient source to the surface waters (Carmack et al. 2004).

With climate-related changes in sea ice (Vinnikov et al. 1999) and river hydrology (Yang et al. 2004) occurring throughout much of the arctic, it is essential to study the current nutrient patterns in order to understand how arctic estuaries, specifically the Mackenzie Estuary, will respond in the future. The Arctic River-Delta Experiment (ARDEX) was developed to evaluate the properties of DOM and the photochemical, biological and geochemical processes regulating its dynamics across the Mackenzie FSTZ. Within this context, the downstream and vertical nutrient structure across the FSTZ was investigated to address the validity of two overarching hypotheses:

1. That nutrients across the FSTZ will change from typical river composition high in phosphorus and inorganic-rich suspended material, inorganic nutrients and CDOC to estuarine-coastal shelf composition lower in inorganic suspended material, inorganic nutrients and CDOC. Inorganics are expected to be taken up across as water transparency improves across the FSTZ. Organic nutrients are expected to increase as a consequence of enhanced primary and secondary production through the estuary. TDOC is expected to decline as it is diluted by seawater, reacts to increased salinity, photobleaches and is processed by coastal bacterioplankton.

2. That strong layering will occur in the Mackenzie Shelf because of the large amount of freshwater discharged from the Mackenzie River to the relatively reduced area of open ocean because of the local sea-ice patterns.

3.3 Methods

3.3.1 Study area

The Mackenzie Estuary (approx. 69°N, 133-137°W) is the freshwater-saltwater transition zone between the lower Mackenzie Delta and the Beaufort Sea in Canada's western Arctic. There are four main estuarine locations in the lower delta: West and Reindeer Channels via Shallow Bay, Middle Channel via Beluga Bay and East Channel via Kugmallit Bay, the focus location of this study (Fig. 3.1). Strong estuarine conditions extend offshore over the Mackenzie Shelf, with the Mackenzie plume generating an equivalent freshwater depth of 6.2 m (Macdonald et al. 1987). The delta plain surrounding the estuary channels is comprised of freshwater floodplain lakes and permafrost influenced silt and sand covered by tundra species (Mackay 1963). The high latitude of the estuary results in 7-8 months of annual ice cover and open water is mainly controlled by the seasonal break up and flooding of the delta in late spring (Prowse 1986; Lesack et al. 1998; Rouse 1997; Marsh and Hey 1989; Marsh et al. 1999). Near shore sea-ice melts in place and is mechanically retreated by the relatively warm river flood plume beginning mid to late June (Carmack et al. 2004). The front proceeds northward to the extent of permanent sea ice, around late August. Freeze up begins around mid September and the sea ice front proceeds southward to meet near-shore landfast ice by early November. Production in the estuary is mainly driven by diatoms and flagellates with minor contributions by ice and pelagic algae and near shore heterotrophic communities (Carmack et al. 2004 and references within). Nutrient-rich deeper waters of Pacific origin do not readily mix to drive production due to the significant stratification in the estuary and shelf, though some upwelling has been observed (Garneau et al. 2006; Carmack et al. 2004). Production rates in the estuary are typically low during the ice cover period and increase rapidly during the open water season. Annual production values typically range from 10-200 mg C m^{-2} d^{-1} in the estuary (Carmack et al. 2004), however some exceptional values have been found in the Siberian Lena River estuary of up to 720 mg C m^{-2} d^{-1} (Sorokin and Sorokin 1996). The highest levels of production in the estuarine region are expected off-shore due to the relatively high sediment load of the

Mackenzie River which attenuates light efficiently until sedimentation (Carmack et al. 2004).

3.3.2 ARDEX sampling program and field methods

ARDEX utilized the shallow-draft CCGS *Nahidik* research vessel and embarked from Inuvik, Northwest Territories 26-Jul. and returned 02-Aug., 2004. ARDEX was comprised of 12 sites (4 fresh, 4 estuarine, 4 marine) with selected sites having multiple sampling depths and times (Fig. 3.1; Table 3.2). Freshwater sampling was from the East Channel (R1, R4) and the Middle Channel (R2,R3) with East Channel sampling occurring on the initial leg while the Middle Channel was sampled on the return leg (Table 3.2). River sampling involved both surface and bottom samples collected via bucket and pump as well as a column-integrated sample. Estuarine and marine samples were collected at the surface and bottom with additional samples at the pycnocline and local chlorophyll-*a* maximum layers where applicable. Samples were collected by bucket, pump or kimmerer. All samples were transferred to clean 1L HDPE bottles and stored in cool and dark conditions until on-board filtration, splitting and preservation performed as soon as possible after collection.

3.3.3 Water sample analysis

Samples were passed through Whatman GF/C filters. GF/C filtration was chosen to comply with historical delta datasets at Fisheries and Oceans Canada's Freshwater Institute as well as to more efficiently deal with the relatively high sediment loads of the Mackenzie River. Samples were rigorously shaken per 100mL of filtrate to ensure suspension of settled sediments and an overall well-mixed sample. Sample filtrate was partitioned for separate analyses into either clean 60mL or 125mL HDPE bottles rinsed with filtrate. Samples were partitioned for: nitrate (NO_3^-); soluble reactive silica (SRSi); total dissolved organic carbon (TDOC); coloured DOC; total dissolved nitrogen and phosphorus (TDN/TDP); and soluble reactive phosphate and ammonium (SRP, NH_4^+). Coloured DOC was further passed through 0.22 m membrane filters before analysis. Total suspended solids (TSS) were measured using pre-combusted GF/C filters (16 hrs. @ 500°C) while oven-dried filters were used for particulate organic carbon, nitrogen and phosphorus analyses (POC, PN, PP). Table 3.3 describes nutrient preservation and analysis methods used.

3.3.4 Mixing and dilution models

To further resolve surface nutrient patterns across the FSTZ, mixing and dilution models were developed. Each model represents a theoretical scenario where representative river water (~0 psu) and representative seawater (maximum measured psu) mix perfectly across the salinity gradient. Therefore, depending on the measured salinity across the gradient, the mixing line will represent a fraction of river water mixed with a fraction of seawater:

$$C_{MIX} = C_{RIVER}*(1-x) + C_{MARINE}*x$$

Where C_{MIX} is the nutrient concentration of river and ocean water mixed together
C_{RIVER} is the nutrient concentration as an average of all river stations
C_{MARINE} is the nutrient concentration of the highest salinity station (R8)
x is the ratio of measured salinity to full salinity at the specific station

The dilution model was identical to the mixing model except that C_{MARINE} was zero indicating river water mixing with perfectly diluted (nutrient depleted) seawater.

3.4 Results

3.4.1 Environmental conditions

The ARDEX sampling period occurred after annual flooding in the Mackenzie Delta region during flows of roughly 40% of peak discharge (Fig. 3.2A). Compared to the entire open water period of 2004, the timing of the cruise represented average flow conditions in the Mackenzie system. Total discharge from the Mackenzie River during 2004 was 12% lower than the annual historical mean (284 km^3) and flows lower than this have occurred only 15% of the time based on historical records (Fig. 3.2B). Hydrological conditions in the East Channel pointed to a significant drainage of water toward the Middle Channel based on discharge measurements on 20-Jul., just before the measurement period (Chapter 2). This represented a reversal from flooding conditions where the Middle Channel is relatively higher than the rest of the delta distributary channels (Marsh et al. 1999). Water temperature through the transect gradually decreased from the warmer river environment to the marine sites (Fig. 3.2C). Salinity sharply increased across the estuary (Fig. 3.2C), though a dilute upper layer up to 5 m in thickness was apparent across all estuarine and marine stations, indicating the influence of the Mackenzie River (ARDEX Report). The open-water portion of the Beaufort Sea was more extensive than normal during the cruise period (Canadian Ice Service 2004) and the sea ice front at the time of R9 sampling was about 100 km to the north. Chlorophyll-*a* at surface sites was variable in the river and was highest at R1 (Fig. 3.2C). Through the estuary and marine sites, levels remained low. From 29-Jul. to 30-Jul. and 01-Aug. to 02-Aug., frontal storms from the north were observed, bringing strong winds, precipitation and changes in air temperature (Fig. 3.3A,B). These strong storms created storm surges toward the south and increased water levels throughout the near-shore and middle and lower delta areas (Fig. 3.3C). The first storm may have affected R8-R6 sites that were sampled after it passed while the second storm was during R3 and R2 sampling. Tides measured in Tuktoyaktuk, NT were between 0.3 and 0.7 m during the study period and during estuarine sampling, R5A was measured during low tide while the remaining samples were during higher tide.

3.4.2 Particulates

Surface - Particulates followed a predictable change from the riverine environment through to the marine sites (Fig. 3.4A-D). All particulate measures (TSS, POC, PN, PP) decreased roughly an order of magnitude in concentration from the particulate-rich Mackenzie toward the relatively depleted marine environment. Concentrations between river sites were highly variable, in agreement to other results within delta distributary channels during 2004 (Chapter 2). A weak increasing trend was observed across all measures through the river sites after R1. Largest changes occurred across the estuarine sites while the marine sites were generally stable and low, though slight increases were observed at R6. All particulates (Fig. 3.4E-H) showed exponential declines below the theoretical mixing line across the salinity gradient. Perfect dilution and mixing lines were similar reflecting the low marine levels. Based on the measurements, R8-R6 stations did not seem to be affected by the storm a day earlier though effects were not clear during R3-R2 sampling during the second storm. Particle composition decreased slightly from higher POC composition in the river to lower composition through the estuary (Fig. 3.5A). Particulate P composition of total suspended matter decreased steadily from the river to the marine environment while particulate N was steady at about 0.20% of all suspended matter through the FSTZ (Fig. 3.5B,C).

Vertical structure - Each site along the transect showed an increase with depth for all particulate parameters (Fig. 3.4A-D). The effect was largest in the river and marine sites while the estuarine sites showed smaller differences through the column. Column-integrated samples (R2-R4) were more characteristic of bottom layer concentrations rather than representing an average of surface and bottom layers. A high bottom measure at site R7 for all particulates was observed and chlorophyll-*a* maximum layers at sites R8 and R9 also showed elevated particulate contents. Compared to the surface, POC:TSS decreased at the pycnocline at all sites and was higher at bottom depths at most sites (Fig. 3.5A). The chlorophyll-*a* maximum layers had a higher POC fraction compared to the surface and the R9 site was similar to river POC fractions. Particulate P content followed a similar pattern across the estuary whereas particulate N was relatively steady throughout the water column, except at the chlorophyll-*a* maximum layer which spiked dramatically above river ratios (Fig. 3.5B,C).

3.4.3 Dissolved organic matter (DOM)

Surface - Total dissolved organic carbon (TDOC) at R1 was considerably higher in concentration (+40%) relative to other river stations (Fig. 3.6A). Concentrations declined progressively from the last river site towards a minimum at the outer marine site R9, decreasing almost an order of magnitude across the sites. The decrease was consistent between the R5D and R9 sites, losing about 40 μmol/L between each site. Observed TDOC values followed the mixing line well, though a minor increase at R7 was observed (Fig. 3.6E). Coloured dissolved organic carbon (CDOC) was low during mid summer and behaved similar to TDOC across the FSTZ, though a spike at station R5E was not observed (Fig. 3.6B,F).

Organic nitrogen concentration (Fig. 3.6C) increased threefold from river stations (mean 5.1 μmol/L) to marine stations (mean 17.2 μmol/L). Aside from the R1 station, DON concentrations in the river were steady. The largest changes occurred between the last two estuarine sites (R5B-R5A) where concentrations increased from 6 to 13 μmol/L. This increasing trend appeared to continue offshore to the R9 station. The mixing line for DON predicted observed concentrations quite well ($R^2 = 0.91$) (Fig. 3.6G).

Organic phosphorus concentrations in the Mackenzie Estuary were low, especially at the river stations (Fig. 3.6D). The river showed a stable pattern of DOP and, similar to DON, it showed considerable increases of about an order of magnitude through the estuary. At marine stations, concentrations increased and then stabilized at R8 and R9. A large measure was also observed at the R7 station. The mixing line supported observed increases across the estuary and generally represented a mixing of the low river and higher marine end member (Fig. 3.6H).

Vertical structure - TDOC (Fig. 3.6A) and CDOC (Fig. 3.6B) were well-mixed throughout the water column of the river sites. Stratification was apparent across the estuarine sites as a TDOC poor lower layer was overlain by higher concentration water. The lower layer was comparable in concentration to some offshore surface waters.

Offshore sites showed some differences between upper and lower layers with lower concentrations observed at depth.

DON was well distributed throughout the river sites while estuarine sites were stratified through the column with increased concentrations in the lower layers and lower levels in the upper layer (Fig. 3.6C). Highest DON concentration in the marine water column occurred at the chlorophyll-*a* maximum layer.

DOP vertical structure was similar to DON with well-mixed river sites and stratified estuarine stations with a relatively organic rich layer underneath a depleted upper layer (Fig. 3.6D). Offshore stations increased in DOP concentration with depth except for the R7 site which had a high surface measurement.

3.4.4 Dissolved inorganic nutrients (NO_3^-, NH_4^+, SRP, SRSi)

Surface - Nitrate concentrations reduced substantially across the FSTZ from 4-6 μmol/L in the river to levels below detection in marine sites (Fig. 3.7A). Concentrations within the river were in agreement with past work in the delta (Chapter 2; Millot et al. 2003) and some variability was observed across all sites with a low measure at R1. Largest changes in concentration occurred through the outer estuarine sites. Marine station concentrations were generally low and stable. The dilution and mixing lines were essentially identical due to very low offshore measures and observed values were below both, following an apparent exponential decline across the estuary (Fig. 3.7E).

Ammonium surface concentrations in the Mackenzie River and through the estuary were below the analytical detection limit (0.5 μmol/L) in most cases and below across all marine stations (Fig. 3.7B). Only one river (R3) and one estuarine (R5D) site had detectable surface levels.

SRP increased about by an order of magnitude from the river to offshore stations (Fig. 3.7C). Levels stayed steady near the method detection limit (0.035 μmol/L) through the river and estuarine sites and began to rise drastically above a salinity of 10 psu. Observed values across the estuary followed the dilution line and then followed the mixing curve across the marine sites (Fig. 3.7G).

SRSi decreased rapidly through the FSTZ, declining over an order of magnitude in concentration from river to offshore sites (Fig. 3.7D). The largest decreases in SRSi were observed between R5A and R6 stations and continued to decrease toward the R9 site. River concentrations were quite consistent between sites, though R1 again showed differences compared to the other river sites. Mixing diagrams showed SRSi concentrations followed conservative patterns across the FSTZ, though R7 did show levels above conservative mixing (Fig. 3.7H).

Vertical structure - Stratification of nitrate distinctly occurred in two regions of the transect (Fig. 3.7A). In the estuarine sites, strong layering was apparent at R5D through to R5A as undercutting nutrient poor water was overlain by a higher nutrient upper layer. Through the marine sites, the column became more homogenous, however a second stratification was observed in the deep layers of the R9 station.

Ammonium was high in concentration in the bottom and pycnocline layers of the R5D site, each well above the detection limit. The remaining sites at depth were below detection.

Little stratification of SRP was observed through the river and estuarine sites as low levels were observed in all sampling depths and locations. Upon progression to marine sites, SRP levels began to increase with depth, with large differences observed in the last offshore sites.

SRSi was similar to nitrate as vertical structure was observed both across the estuarine sites as well as in the marine stations (Fig. 3.7D). River waters were well-mixed and lower concentrations of SRSi were observed in the bottom layers in the estuary below a relatively high nutrient river layer. Offshore, pycnocline and bottom concentrations were lower than surface levels except for the R9 station which had relatively high concentrations at the chlorophyll-*a* maximum and bottom layers.

3.4.5 Composite measures (TDN, TN, TDP, TP)

Composite measures of TDN ($NO_3^- + NH_4^+$ + DON) (Fig. 3.8A,E) and TN (PN + TDN) (Fig. 3.8B,F) each changed depending on the dominant composition of their constituents. Average total dissolved nitrogen through the water column of all sites was mostly composed of organic nitrogen (~75%) (Fig. 3.9A). This proportion changed from 42% in river sites to approximately 90% through to the offshore region. Total nitrogen in river water was split evenly into the particulate and dissolved forms (Fig. 3.9B). This was consistent with similar measures in the Mackenzie River (Anema et al. 1990a,b). Across the estuary into the marine stations, this fraction decreased drastically to ~20% particulate nitrogen. TDN reflected DON patterns throughout the water column at all sites, though deep ocean water was elevated in DIN (Fig. 3.8A). TN increased in particulate fraction with depth in the river and marine sites but decreased through the estuary (Fig. 3.8A).

DOP made up about 50% of river TDP (SRP + DOP) and increased to 67% in the estuarine and marine regions (Fig. 3.8C,G; Fig. 3.9C). Through the water column across all sites, DOP decreased in composition to about 50% of TDP as compared to surface waters (64%). Deep ocean water was elevated in both organic and inorganic P compared to the surface layer. Particulate phosphorus composed a much higher fraction of TP (PP + TDP) when compared to nitrogen over the transect (Fig. 3.8D,H; Fig. 3.9D). Over 95% of all phosphorus in the Mackenzie River was in particulate form and dropped to 41% in the estuary and marine stations. Particulate P fell from 68% of TP in surface waters to 56% of TP with depth across all sites. Deep ocean waters were elevated in particles and dissolved P.

3.4.6 C:N:P ratios

Surface - TOC:TN:TP ratios can be indicators of terrestrial versus marine primary producer composition as well as providing insight into general nutrient limitation for local communities. Levels across the Mackenzie FSTZ changed considerably from the river to marine environment. TOC:TP in the river was highly variable with a mean of 282 (Fig. 3.10A). This remained fairly steady through the estuary and then decreased rapidly at marine stations with a mean of 98. Observed values showed a strong fit to the conservative mixing line ($R^2 = 0.91$). TOC:TN ratios (Fig. 3.10B) showed similar patterns across the FSTZ with variable but high levels in the river (mean 23). This was in good agreement with Telang et al. (1991) who measured 19.3. However, sharp decreases through the estuarine sites were observed towards the lower marine sites (mean 8), in agreement with Rutterberg and Goni (1997). Observed values were variable and mostly lower than the conservative mixing line and appeared to decline exponentially. TN:TP (Fig. 3.10C) was highly variable across the FSTZ with no clear pattern. The river decreased at a steady rate from R1 to R4 with a mean of 13. Through the estuary, levels increased while the marine sites showed a similar pattern with a mean of 18. The conservative mixing line did not strongly predict observed values as variability was high. POC:PP was generally steady across the FSTZ with a mean value of 86 (Fig. 3.10D). POC:PN showed a small R1 value compared to the rest of the river sites (7.3), but overall patterns changed from mean river and estuary values of 15 down to 9 in marine sites (Fig. 3.10E). PN:PP increased through the FSTZ ranging from mean river and estuary values of 6, to marine values of 10 (Fig. 3.10F).

Vertical structure - TOC:TN:TP ratios (Fig. 3.10A-C) were generally stable through the river sites with only minor decreases with depth for each variable. Through the estuary, both TOC:TN and TOC:TP showed sharp decreases with depth indicating the layering of differing water types through the column. TN:TP measures were stable through the column, though based on only one sample site. The marine stations also showed decreases in all ratios with depth with TN:TP showing the largest differences top to bottom. Particulate ratios (Fig. 3.10D-F) were generally stable through the water column in the river and estuarine sites. Marine stations were more variable with no clear patterns.

3.5 Discussion

3.5.1 Seasonal context of ARDEX

The open water structure of the Mackenzie Estuary differs substantially from the flooding period to low water conditions. During flooding conditions, winter Mackenzie River water stored in the ice-constrained Lake Mackenzie releases and flows over the coastal Beaufort Sea (Carmack et al. 2004). This dominates both the seaward and vertical structure of the estuary during this short flooding period. After annual flooding, 'new' water from the Mackenzie slowly mixes with both the old winter water and intruding seawater due to the weaker Mackenzie plume. A more classical vertical estuarine structure develops due to an undercutting of high density seawater underneath less dense river water. This relatively mixed plume is effectively constrained by permanent pack ice offshore resulting in the stagnation and recirculation of the plume back with inflowing river water. Salinity results from the ARDEX cruise indicated that the timing of the cruise was during this more mixed, relatively layered period, representative of average open water conditions across estuaries in the arctic.

Nutrient patterns during the ARDEX cruise period would also be quite different relative to the flooding period. Although the short flooding period delivers the highest fluxes of particles and nutrients to the ocean, downstream and vertical nutrient patterns would be dominated by a strong river signature which would only occur for a short time during the entire open water season. Biogeochemical changes across the estuary during this flooding period would likely be tempered as salinity-induced changes would be reduced and the sediment-laden signature of the Mackenzie would largely inhibit bioactivity. Results from ARDEX indicated a more structured downstream and vertical nutrient pattern through the estuary where biogeochemical changes were sharp due to salinity, sedimentation and biological effects.

3.5.2 Riverine environments: downstream changes, composition and vertical patterns

Particulates - The Mackenzie River delivers more than twice the suspended material load to the Arctic Ocean than all other rivers combined (Holmes et al. 2002). Relatively high sediment concentrations were observed even during the cruise. Since East Channel samples (R1,R4) were both above and below Middle Channel samples (R2/R3), high variability across river sites was not adequately explained by channel differences or the time lag between sampling. Local resuspension or deposition may have played a role in the differences. The windstorm during Middle Channel sampling may have resuspended particles from the river bottom or shores at R3 while flow backups caused by the storm surge may have initiated sediment deposition at R2. General increases across all sites towards the estuary may also reflect general shallowing of channels and resuspension of bottom sediments. River particles were dominantly inorganic in composition (approx. 96%), likely representing sand and silt from heavily terraced environments within the Liard and Arctic Red rivers which contribute most of the Mackenzie's sediment load (Carson et al. 1998). Also, during lower flow conditions, watershed inputs of organic material are much lower compared to the flooding period. Organics that were available were low in N and P. This likely reflected summer storm runoff from the organic carbon-rich soils and vegetation from the substantial taiga environments within the basin.

Increases vertically through the water column showed minor bedload transport previously defined by Carson et al. (1998). The bottom layer of R3 was considerably higher in particle concentrations than other river stations and may have been due to channel conditions as sampling was within a localized scour cavity where bedload may have accumulated and local turbulence may have been important.

Dissolved organic material (DOM) - Relatively high concentrations of all DOM types at the R1 station were apparent compared to the other river stations. This was also observed throughout most of the 2004 summer season based on wide scale surveys (Chapter 2). Reasons for the higher DOM concentrations at this site are not currently understood. One possible explanation could be the drainage of DOM-rich upstream rivers into the East Channel such as the Rengleng River. Rivers draining from the east of the delta may receive water draining through organic rich wetlands and tundra environments. The Campbell River may also have increased DOM to the East Channel as it receives water from Campbell Lake which passes through a large 'reverse' delta at its outlet. An anthropogenic effect may also have played a role in the anomalous R1 site as sampling was performed at the townsite, though upstream of the marina and waste management lagoon. As the East Channel mixed with other channels downstream, this effect would have been reduced and other stations along the transect would not show the anomaly (i.e. R4). CDOC also followed this pattern reflecting its watershed derived source. Another influence may include the considerable drainage of the East Channel to the Middle Channel observed just prior to the sampling period (Chapter 2). This may have promoted increased inputs of organic-rich water from draining active layers bordering the river. Through the remaining river sites, DOM increased slightly downstream which was likely due to floodplain lake additions of both watershed derived and biologically produced DOM during that time of year (Chapter 2). CDOC also increased, therefore suggesting that some of the TDOC was still floodplain derived rather than biologically derived. Further, CDOC increases through the stations may suggest that photo-bleaching losses both in the river and from floodplain lakes were not particularly strong during that time period.

Through the water column, concentrations of DOM were relatively stable compared to particulate measures and reflected the well-mixed nature of river water.

Inorganic nutrients - Dissolved inorganic nutrients were generally lower at the R1 site compared to relative stability among the rest of the river. This may be a dilution effect from both the Rengleng and Campbell rivers which drain into the East Channel. Each drain a watershed not connected to the delta and the nutrient inputs from the Mackenzie during the flooding. Therefore, these rivers likely input inorganic poor water to the East Channel and diluted concentrations at the R1 station. Most inorganics were stable downstream past R1 though decreases in nitrate were evident and may have been due to inputs of dilute floodplain lake waters or denitrification (Chapter 2). Vertically through the water column, inorganic nutrient patterns were similar to DOM showing a well-mixed water column.

C:N:P - Ratios through the river sites were highly variable with no clear patterns. Total ratios indicated that carbon was in excess in the river system compared to N and P, reflecting the high terrestrial carbon inputs from the Mackenzie Basin. TN:TP ratios in the river were at or below the Redfield ratio, though not low enough to suggest nitrogen limitation. Sediments at R1 seemed to be enriched in nitrogen which may reflect inputs from the eastern rivers or an anthropogenic effect from Inuvik. POC:PN in the sediments were higher than the Redfield ratio indicating a largely terrestrial source of particulates. Particulate phosphorus was high in the river, thus POC:PP was close to the Redfield ratio and PN:PP was much lower than the Redfield ratio.

3.5.3 Estuarine and marine environments: stratification

Salinity (ARDEX Report) and chemistry measures indicated strong vertical stratification through the estuarine stations. This confirmed the classic salt wedge structure through the estuarine sites, which was a product of both time of year as well as local ice conditions in the western Arctic. During the flooding period, the estuary is inundated with freshwater and vertical structure would be well-mixed until deeper stations. Post flood, the river's momentum decreases and slides above the seawater rather than pushing it seaward. This dilute surface layer was observed across all estuarine and marine sites, up to 5 m deep in some offshore stations. Local shelf and ice conditions also contribute the strongly stratified patterns. The Mackenzie Shelf is relatively small compared to the large freshwater influence of the Mackenzie and thus creates a much more stratified shelf compared to other arctic rivers. Local ice patterns also restrict the export of freshwater off of the shelf, thus sustaining the freshwater signature in the upper layer.

Besides the well-defined pycnocline across all of the estuarine/marine sites, a deep chlorophyll-*a* maximum layer was also observed at the two furthest offshore sites (R8, R9) at depths of 12m and 21m respectively. This has been also observed in other studies (Martin and Tremblay 2005). The development of this layer is a function of light and nutrient availability. During the early open water season, the offshore surface waters receive inorganic nutrients from the river. However, as the season progresses, nutrients are quickly removed from the surface waters, creating nutrient limited conditions in surface waters for the duration of the season. Particle and CDOC contents also reduce during the summer, creating light conditions in surface waters often too intense for most phytoplankton species. These conditions force phytoplankton communities deep into the water column where light and nutrient availability balance, thus creating a deep chlorophyll-*a* maximum layer.

In sufficiently deep waters on the Mackenzie shelf, evidence of nutrient-rich deep waters was observed, likely water from the Pacific Ocean bending eastward from the Bering Strait. The Arctic Ocean limits vertical replenishment of nutrients to the upper layers from deep waters due to its strong freshwater signature in its waters. This further contributes to nutrient limitation in surface layers during the open water season. This stratification of the Mackenzie shelf apparently restricts deep waters to below 20m during low flow conditions. Though some nutrient upwelling has been observed (Carmack et al. 2004), these nutrients are not a strong source to surface waters.

3.5.4 Estuarine environment: downstream changes, composition and vertical patterns

Particulates - The general surface water trend of particle settling was apparent across the FSTZ as levels decreased exponentially seaward due to river energy losses. Discharge from the Mackenzie was relatively low in later July so intense turbulent resuspension of particles through the estuary would not be expected and was not observed based on the mixing line. Estuarine sampling also occurred between the two frontal storms, so storm-related resuspension was not observed. Slight increases across all measures at R6 may have been related to surface Mackenzie plume currents that emerge from the estuary and bend eastward, south of other marine stations. Despite stagnation and recirculation of the Mackenzie plume back with the estuary, resultant conservative mixing between plume waters and river waters was not observed due to intense losses of river sediment from particle settling.

Particles did not increase in organic composition across the surface waters of the estuary and was likely a function of increasing salinity, intense phytoplankton grazing across the estuary and phytoplankton communities gathering in deeper locations offshore. Salinity hastens the settling of organic particles through estuaries due to salinity-induced flocculation while phytoplankton were heavily grazed by zooplankton through the estuary and gathered at deeper offshore sites where production conditions were more ideal. Another possibility to explain the lack of biogenic signature in particulates across the FSTZ surface waters was a possible redistribution of communities due to the storm surge. There was some evidence of POC:TSS increase at R7 which may have indicated that a stronger primary producer community was present or storm-related terrestrial inputs were captured. POC:PN and POC:PP ratios across the FSTZ surface showed some evidence of a switch to more marine based particles as ratios fell from river levels towards the traditional Redfield ratio of 6.6 and 16 respectively. Particulate P also decreased in relation to TSS across the estuary showing that the Mackenzie was a source of phosphorus-bound particles compared to the estuary and marine environments.

Reduced concentration differences between the surface and bottom waters across the estuarine sites suggest that particles were either being re-suspended in the bottom layers of the salt wedge or were settling from the river layer. The elevated R8-R6 bottom samples may be associated with the storm surge increases in water level and related turbulence. Bedload transport would likely not be important in the deeper offshore sites, however turbulent movement of waters onshore during the storm may have mixed the water near the bottom sediments enough to increase particle concentrations, especially in the 5m deep R7 site. Chlorophyll-*a* maximum layers also showed elevated particulate content and POC:TSS values at R9-R7 stations, related to dense communities of phytoplankton.

Dissolved organic matter (DOM) - Evidence from the mixing line across the FSTZ showed conservative behaviour of TDOC, similar to other arctic estuaries (Amon and Meon 2004; Cauwet and Sidorov 1996). Mixing of end members resulted in strong linear dilution ($R^2 = 0.90$). This was likely a product of recirculation of the Mackenzie plume into the estuary. Since offshore water is normally depleted in organic carbon due to salinity effects, a recirculation of this water would mix with inflow Mackenzie water, generating conservative patterns along the salinity gradient. This conservative pattern further suggests that additions or losses (including heterotrophic activities) through the estuary were largely absent, unlike particulates. TDOC losses associated with near shore biological activity (Parsons et al. 1989) were likely small compared to total inputs from the Mackenzie as it primarily carries allochthonous watershed forms (Goni et al. 2005) that are less labile and resistant to uptake. Local changes in TDOC were also not apparent due to local freeze/melt processes that can change salinity and affect organic solute behaviour (Dittmar and Kattner 2003).

Photo-bleaching of CDOC across the estuary during the sampling period was not expected to be significant for two reasons. First, irradiance is lower in both duration and intensity during the later summer period in the arctic. Sun angles are decreased compared to the flooding period and daylight duration falls below 24hrs, contrary to the continuous light situation during flooding. Each reduces the power to photo-bleach the coloured portion of DOC. Second, the coloured portion of DOC is relatively low during the mid summer period when compared to the flooding portion. During the freshet period, runoff is largely derived by snowmelt that contacts more terrestrial material (CDOC source) than the post flood period. Therefore, more carbon is available to be photo-bleached during the spring flooding period when compared to mid summer. Overall, as expected, CDOC declined from higher levels in the river to lower levels in the marine environment, following rather conservative behaviour similar to TDOC (R^2 = 0.94).

Based on past studies in arctic rivers (Cauwet and Sidorov 1996; Kattner et al. 1999; Macdonald et al. 1998; Dittmar et al. 2001), dissolved organic nitrogen was expected to dilute upon mixing with depleted ocean waters. However, across the FSTZ a sharp increase of DON was apparent and was well explained by the mixing line (R^2 = 0.91). Conservative mixing across the estuary suggested that addition and loss processes of DON were largely minimized during the study period as concentrations were best explained by mixing of river water with offshore plume water. High concentrations of DON offshore were likely remnants of the earlier higher production period through the estuary when surface nutrient concentrations were in higher supply. Production (Myklestad 1995; Tyler et al. 2001) and decomposition (Cook et al. 2004) related releases of DON through the estuary were then likely transported offshore where the slow flushing plume would recirculate back toward the estuary during the remainder of the open water season. Similar processes for DOP may have also been the source of the high DOP levels offshore and subsequent conservative mixing patterns.

Inorganic nutrients - Since ammonium levels in the Mackenzie were quite low, nitrate was expected to be the primary nitrogen source for estuarine phytoplankton communities. Therefore, it was expected that nitrate would decrease below the dilution line where communities existed. This did occur through the estuarine sites, though chlorophyll-*a* levels remained low. This was likely due to intense grazing by the dense zooplankton communities through the estuary (ARDEX report) that overturned phytoplankton communities quickly. Denitrification in sediment layers may have also played a role in the loss of nitrate through the estuary as observed elsewhere (Seitzinger 1988). The lower than average water levels throughout the delta may have magnified this loss, especially during portions of East Channel near Kugmallit Bay. Continuing offshore, nitrate levels fell close to detection and reflected the nutrient depleted nature of much of the surface waters of the Arctic Ocean during later summer. Zooplankton and chlorophyll-*a* levels were subsequently low in this layer suggesting that uptake of nitrate by phytoplankton communities was not strong. Since nitrate losses occurred across the estuary similar to particulates, remixing of nitrate-depleted water would not create a conservative gradient across the estuary. High concentrations of nitrate were observed at both the chlorophyll-*a* maximum and bottom layers at the R9 stations. This was likely from nutrient-rich deep ocean waters which provided much of the nutrient supply for the phytoplankton layer. At the R8 site, there was not strong evidence of nutrient-rich deep ocean waters, thus the chlorophyll-*a* maximum layer was likely sustained by nutrients at the sediment bottom 2m below.

Ammonium is preferentially sequestered in the terrestrial environment and is in high demand in aquatic ecosystems. Therefore, levels were expected to be low and what was present was predicted to be below the dilution line, indicating uptake and stripping from the water. Though most sites showed levels below detection, concentrations observed at the R5D site were high throughout the water column. Since several estuarine communities were present at this site (ARDEX Report), die-off and ammonification of organic matter may have created a source of ammonium to the water column, as observed in other estuaries (Fox et al. 1987). Stable nitrate levels between sites R5E and R5D may suggest that ammonium was competing with nitrate as the primary nitrogen source for primary production.

Low SRP levels in unpolluted freshwater is expected (Schindler 1974) and was observed in the Mackenzie River. Low levels observed at all sampling depths and locations in the river and estuary suggested that recycling of 'old' phosphorus was efficient in the water column, thus little free SRP was available. SRP that was available was below the mixing line possibly due to primary and secondary production uptake across the estuary. Toward the offshore sites, levels were closer to the mixing line, possibly showing the switch from P limitation in freshwater to N limitation commonly observed in marine environments. However, this was not strongly supported by N:P ratios across the estuary which had relatively no pattern. Calcium levels in the Mackenzie are commonly high and may have played a role in the increased P concentrations in the offshore regions due to SRP desorption from particles, commonly observed in other world rivers. Recirculation of the offshore plume did not produce conservative patterns through the estuary due to loss processes through the estuary. Deep ocean waters rich in SRP were observed and likely followed a similar pattern to nitrate with respect to sustaining the phytoplankton layers at R8 and R9.

SRSi is primarily diluted upon is progression from riverine to marine environments. This was observed across the Mackenzie FSTZ and suggested conservative mixing behaviour between the river and marine end-members. Recycling of SRSi through the estuary was likely efficient for estuarine organisms. Further offshore where diatom communities are expected to be more prevalent (Carmack et al. 2004; Parsons et al. 1988), production-related losses were not apparent, likely due to nutrient depletion in the upper layers during that time of year. A high R7 measure may have been storm surge related or variability within the Mackenzie plume. High concentrations were observed at the chlorophyll-*a* and bottom layers, again showing the influence of deep ocean waters in sustaining the phytoplankton layer.

3.5.5 ARDEX nutrient content and water structure across the Mackenzie FSTZ: an overview

Four well-defined water masses were observed across the Mackenzie FSTZ during the study period including river, estuary, offshore upper (including the dilute river-influenced surface layer) and offshore deep waters (Fig. 3.11). Mean nutrient concentrations from all samples within each water type are shown in Table 3.4.

Seasonal averages of river water (Chapter 2) were generally higher in all nutrients compared to the ARDEX sampling period, with DOP, ammonium and SRSi being notable exceptions. This was largely due to flooding period effects where particulates, organic matter and most inorganic nutrients were at peak concentrations. Total C:N:P ratios were higher in later summer river water compared to open water averages likely reflecting the nutrient poor waters later in the summer compared to the flooding period. Particulate C:N:P ratios were generally the same between the ARDEX survey and seasonal river averages. Delta outflow waters were different from inflowing waters due to lake effects through the delta (Chapter 2). Through the estuary, particulates, TDOC and inorganic nutrients decreased compared to river waters due to settling, mixing, biological uptake, salinity and other processes. Ammonium increased at some estuarine sites, possibly a signature of considerable decomposition of organic matter in the sediment layer. Dissolved organic nitrogen and phosphorus increased likely due to production and decomposition through the estuary and subsequent concentration in waters through the estuary due to high river plume residence times. Total C:N:P ratios generally changed towards the Redfield ratio, however a large terrestrial signal was still apparent. Particulate C:N:P ratios were generally similar to river levels. The offshore upper layer water was a mix of nutrient poor offshore waters and diluted river water. Therefore particulates and most inorganic nutrients were low throughout the layer. SRP increased considerably towards the offshore sites which may be driven by desorption from river particles and mixing with high P plume waters. High P levels with little evidence of high productivity may indicate N limitation in these upper waters as available N was quite low. DON and DOP were relatively high in this layer possibly a remnant of production and decomposition releases in the estuary and a relatively stagnant and confined Mackenzie plume. All C:N:P ratios were closer to the Redfield ratio in this layer compared to the more river-influenced waters, suggesting more favourable conditions for marine primary production. Relatively nutrient-rich deep water was observed below 20 m. Nitrate, SRP and SRSi were all relatively high in this water and sustained a dense phytoplankton layer at 21 m. DON and DOP were also relatively high, likely from production-related releases. C:N:P ratios indicated that carbon was relatively low in these waters, indicating adequate N and P supplies for growth. This deep water layer was likely of Pacific origin from the Bering Strait as considerable Pacific influence has been observed in the coastal waters of this region (Carmack et al. 2004).

3.6 Conclusions

During the 2004 open water period following flooding of the Mackenzie River, the Mackenzie FSTZ was characterized by strong downstream biogeochemical changes, similar to other arctic estuaries. Water changed rapidly from typical river composition to more estuarine and ocean in composition. This was likely strongly driven by primary production, decomposition and physical processes through the estuary before and during the sampling period. Particulates settled rapidly, inorganic nutrients were removed from the water column and TDOC conservatively mixed with dilute offshore waters. However, unlike other arctic estuaries, the Mackenzie appeared to have a strong DON and DOP signatures within its estuarine and offshore upper waters. This was likely a consequence of high productivity through the estuary and local offshore ice patterns. The 29-Jul. storm surge may have also played a role in the persistence of the river plume offshore.

The Mackenzie FSTZ was also strongly stratified, with both the classic salt-wedge structure through the estuary and the intrusion of nutrient-rich deep waters below 20 m. The large discharge of the Mackenzie over the relatively small shelf area created a diluted layer over the shelf which restricted vertical mixing and maintained the stratification.

3.7 References

Aminot, A., M.A. Elsayed and R. Kerouel. 1990. Fate of natural and anthropogenic dissolved organic-carbon in the macrotidal Elorn Estuary (France). *Marine Chemistry* 29(2-3): 255-275.

Amon, R.M.W. and B. Meon. 2004. The biogeochemistry of dissolved organic matter and nutrients in two large arctic estuaries and potential implications for our understanding of the Arctic Ocean system. *Marine Chemistry* 92(1-4): 311-330.

Anema, C., R.E. Hecky, E.J. Fee, D. Nernberg and S.J. Guildford. 1990a. Water chemistry of some lakes and channels in the Mackenzie Delta and on the Tuktoyaktuk Peninsula, N.W.T., 1985. *Canadian Data Report of Fisheries and Aquatic Sciences* 726: 1-73.

Anema, C., R.E. Hecky,S. Himmer and S.J. Guildford. 1990b. Water chemistry of some lakes and channels in the Mackenzie Delta and on the Tuktoyaktuk Peninsula, N.W.T., 1986. *Canadian Data Report of Fisheries and Aquatic Sciences* 729: 1-63.

ARDEX Report. ARDEX: The Arctic River Delta Experiment, Cruise Report 5 Aug. 2004 and Workshop Report 3-4 Mar. 2005.

Barlow, J.P., C.J. Lorenzen and R.T. Myren. 1963. Eutrophication of a tidal estuary. *Limnology and Oceanography* 8(2): 251-262.

Bengtsson, L., V.A. Semenov and O.M. Johannessen. 2004. The early twentieth-century warming in the arctic - A possible mechanism. *Journal of Climate* 17(20): 4045-4057.

Brunskill, G.J., D.M. Rosenberg, N.B. Snow, G.L. Vascotto, and R. Wageman. 1973. Ecological studies of aquatic systems in the Mackenzie-Porcupine drainages in relation to proposed pipeline and highway developments. Canada Task Force, North. Oil Develop. Envir. Comm., II. Report 73-41. 345 pp.

Burdige, D.J. and S.L. Zheng. 1998. The biogeochemical cycling of dissolved organic nitrogen in estuarine sediments. *Limnology and Oceanography* 43(8): 1796-1813.

Cai, W.J., W.J. Wiebe, Y.C. Wang and J.E. Sheldon. 2000. Intertidal marsh as a source of dissolved inorganic carbon and a sink of nitrate in the Satilla River-estuarine complex in the southeastern US. *Limnology and Oceanography* 45(8): 1743-1752.

Canadian Ice Service (Environment Canada). 2004. Seasonal summary for the Canadian Arctic Summer 2004. Available: http://ice-glaces.ec.gc.ca.

Carmack, E.C. and R.W. Macdonald. 2002. Oceanography of the Canadian shelf of the Beaufort Sea: A setting for marine life. *Arctic* 55: 29-45.

Carmack, E.C., R.W. Macdonald and S. Jasper. 2004. Phytoplankton productivity on the Canadian Shelf of the Beaufort Sea. *Marine Ecology-Progress Series* 277: 37-50.

Carson, M.A., J.N. Jasper and F.M. Conly. 1998. Magnitude and sources of sediment input to the Mackenzie Delta, northwest territories, 1974-94. *Arctic* 51(2): 116-124.

Cauwet, G. and I. Sidorov. 1996. The biogeochemistry of Lena River: Organic carbon and nutrients distribution. *Marine Chemistry* 53(3-4): 211-227.

Cole, J.J., G.E. Likens and D.L. Strayer. 1982. Photosynthetically produced dissolved organic-carbon - an important carbon source for planktonic bacteria. *Limnology and Oceanography* 27(6): 1080-1090.

Comiso, J.C. 2003. Warming trends in the Arctic from clear sky satellite observations. *Journal of Climate* 16: 3498-3510.

Conley, D.J., W.M. Smith, J. C. Cornwell and T. R. Fisher. 1995. Transformation of particle-bound phosphorus at the land sea interface. *Estuarine Coastal and Shelf Science* 40(2): 161-176.

Cook, P.L.M., A.T. Revill, E.C.V. Butler and B. D. Eyre. 2004. Carbon and nitrogen cycling on intertidal mudflats of a temperate Australian estuary. II. Nitrogen cycling. *Marine Ecology-Progress Series* 280: 39-54.

Dionex Corporation. 1991. Dionex DX-300 gradient chromatography systems user's manual release 01. Dionex Corportation, Sunnyvale California.

Dittmar, T., H.P. Fitznar and G. Kattner. 2001. Origin and biogeochemical cycling of organic nitrogen in the eastern Arctic Ocean as evident from D- and L-amino acids. *Geochimica Et Cosmochimica Acta* 65(22): 4103-4114.

Dittmar, T. and G. Kattner. 2003. The biogeochemistry of the river and shelf ecosystem of the Arctic Ocean: a review. *Marine Chemistry* 83(3-4): 103-120.

Droppo, I.G., D. Jeffries, C. Jaskot and S. Backus. 1998. The prevalence of freshwater flocculation in cold regions: A case study from the Mackenzie River Delta, northwest territories, Canada. *Arctic* 51(2): 155-164.

Emmerton, C.A., L.F.W. Lesack and P. Marsh. 2005. Aquatic habitat composition, lake abundance, and potential water storage in the Mackenzie River Delta, western Canadian Arctic. Submitted: *Water Resources Research.*

Environment Canada. Environment Canada (Env. Canada). 2005 [Online]. Past weather data. Available: http://www.weatheroffice.ec.gc.ca.

Eyre, B.D. and A.J.P. Ferguson. 2002. Comparison of carbon production and decomposition, benthic nutrient fluxes and denitrification in seagrass, phytoplankton, benthic microalgae- and macroalgae-dominated warm-temperate Australian lagoons. *Marine Ecology-Progress Series* 229: 43-59.

Fang, T.H. 2000. Partitioning and behaviour of different forms of phosphorus in the Tanshui Estuary and one of its tributaries, northern Taiwan. *Estuarine Coastal and Shelf Science* 50(5): 689-701.

Fox, L.E., S.L. Sager and S.C. Wofsy. 1985. Factors controlling the concentrations of soluble phosphorus in the Mississippi Estuary. *Limnology and Oceanography* 30(4): 826-832.

Fox, L.E., F. Lipschultz, L. Kerkhof and S.C. Wofsy. 1987. A chemical survey of the Mississippi Estuary. *Estuaries* 10(1): 1-12.

Garneau, M.-E., W.F. Vincent, L. Alonso-Saez, Y. Gratton and C. Lovejoy. 2006. Prokaryotic community structure and heterotrophic production in a river influenced coastal arctic ecosystem. *Aquatic Microbial Ecology* 42: 27-40.

Gebhardt, A.C., F. Schoster, B. Gaye-Haake, B. Beeskow, V. Rachold, D. Unger and V. Ittekkot. 2005. The turbidity maximum zone of the Yenisei River (Siberia) and its impact on organic and inorganic proxies. *Estuarine Coastal and Shelf Science* 65(1-2): 61-73.

Goni, M.A., M.B. Yunker, R.W. Macdonald and T.I. Eglinton. 2005. The supply and preservation of ancient and modem components of organic carbon in the Canadian Beaufort Shelf of the Arctic Ocean. *Marine Chemistry* 93(1): 53-73.

Gradinger, R. 1995. Climate-Change and Biological Oceanography of the Arctic-Ocean. *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences* 352(1699): 277-286.

Holmes, R.M., J.W. McClelland, B.J. Peterson, I.A. Shiklomanov, A.I. Shiklomanov, A.V. Zhulidov, V.V. Gordeev and N.N. Bobrovitskaya. 2002. A circumpolar perspective on fluvial sediment flux to the Arctic Ocean. *Global Biogeochemical Cycles* 16(4).

Jordan, T.E., D.L. Correll, J. Miklas and D.E. Weller. 1991. Nutrients and chlorophyll at the interface of a watershed and an estuary. *Limnology and Oceanography* 36(2): 251-267.

Kattner, G., J.M. Lobbes, H.P. Fitznar, R. Engbrodt, E.M. Nothig and R.J. Lara. 1999. Tracing dissolved organic substances and nutrients from the Lena River through Laptev Sea (Arctic). *Marine Chemistry* 65(1-2): 25-39.

Kohler, H., B. Meon, V.V. Gordeev, A. Spitzy, and R.M.W. Amon. 2003. Dissolved organic matter (DOM) in the estuaries of Ob and Yenisei and the adjacent Kara-Sea, Russia. In: Stein, R., K. Fahl, D.K. Futterer, E.M. Galimov, and O.V. Stepanets. (Eds.), Siberian river run-off in the Kara Sea. Proc. Mar. Sci. 6, 281–308.

Krishnamurthy, R.V., M. Machavaram, M. Baskaran, J.M. Brooks and M.A. Champ. 2001. Organic carbon flow in the Ob, Yenisey Rivers and Kara Sea of the arctic region. *Marine Pollution Bulletin* 42(9): 726-732.

Lara, R.J., V. Rachold, G. Kattner, H.W. Hubberten, G. Guggenberger, A. Skoog and D.N. Thomas. 1998. Dissolved organic matter and nutrients in the Lena River, Siberian Arctic: Characteristics and distribution. *Marine Chemistry* 59(3-4): 301-309.

Lebo, M.E. 1990. Phosphate-uptake along a coastal-plain estuary. *Limnology and Oceanography* 35(6): 1279-1289.

Lesack, L.F.W., M.M. Squires, P. Marsh, C.A. Emmerton, C.M. Febria, J.A.L. Gareis, A.J. Riedel, B.M. Spears, C.J. Teichreb, and M.L. Bothwell. Ecology of lakes in the Mackenzie River Delta: Potential responses to global change. Submitted: *Ecological Monographs.*

Lesack, L.F.W., P. Marsh and R.E. Hecky. 1998. Spatial and temporal dynamics of major solute chemistry among Mackenzie Delta lakes. *Limnology and Oceanography* 43(7): 1530-1543.

Lobbes, J.M., H.P. Fitznar and G. Kattner. 2000. Biogeochemical characteristics of dissolved and particulate organic matter in Russian rivers entering the Arctic Ocean. *Geochimica Et Cosmochimica Acta* 64(17): 2973-2983.

Lomstein, B.A., T.H. Blackburn and K. Henriksen. 1989. Aspects of nitrogen and carbon cycling in the northern Bering Shelf sediment .1. The significance of urea turnover in the mineralization of Nh4+. *Marine Ecology-Progress Series* 57(3): 237-247.

Lukashin, V.N., S.V. Lyutsarev, A.D. Krasnyuk, V.P. Shevchenko and V.Y. Rusakov. 2000. Suspended matter in estuaries of the Ob' and Yenisei rivers: Data from the 28th cruise of R/V Akademik Boris Petrov. *Geochemistry International* 38(12): 1221-1236.

Macdonald, R.W. and C.S. Wong. 1987. The distribution of nutrients in the southeastern Beaufort Sea - Implications for water circulation and primary production. *Journal of Geophysical Research-Oceans* 92(C3): 2939-2952.

Macdonald, R.W., S.M. Solomon, R.E. Cranston, H.E. Welch, M.B. Yunker and C. Gobeil. 1998. A sediment and organic carbon budget for the Canadian Beaufort shelf. *Marine Geology* 144(4): 255-273.

Macdonald, R.W., A.S. Naidu, M.B. Yunker and C. Gobeil. 2004. The Beaufort Sea: distribution, sources, variability and burial of carbon. Stein, R. and Macdonald, R. W. The Arctic Ocean organic carbon cycle present and past. (7.2):177-193. Berlin - New York, Springer Publishing Company.

Marsh, P. and M. Hey. 1989. The Flooding Hydrology of Mackenzie Delta Lakes near Inuvik, Nwt, Canada. *Arctic* 42(1): 41-49.

Marsh, P., L.F.W. Lesack and A. Roberts. 1999. Lake sedimentation in the Mackenzie Delta, NWT. *Hydrological Processes* 13(16): 2519-2536.

Martin, J. and J-E Tremblay. 2005. Structure and dynamics of deep chlorophyll maxima in the Canadian Arctic. [poster] ArcticNet annual science meeting. Banff, Alberta, Canada. Dec. 13-16, 2005.

Millot, R., J. Gaillardet, B. Dupre and C.J. Allegre. 2003. Northern latitude chemical weathering rates: Clues from the Mackenzie River Basin, Canada. *Geochimica Et Cosmochimica Acta* 67(7): 1305-1329.

Moritz, R.E., C.M. Bitz and E.J. Steig. 2002. Dynamics of recent climate change in the Arctic. *Science* 297(5586): 1497-1502.

Mueller, D.R., W.F. Vincent and M.O. Jeffries. 2003. Break-up of the largest Arctic ice shelf and associated loss of an epishelf lake. *Geophysical Research Letters* 30(20): 2031.

Myklestad, S.M. 1995. Release of extracellular products by phytoplankton with special emphasis on polysaccharides. *Science of the Total Environment* 165(1-3): 155-164.

Nagao, F. and T. Miyazaki. 2002. Release of dissolved organic nitrogen from Scenedesmus quadricauda (Chlorophyta) and Microcystis novacekii (Cyanobacteria). *Aquatic Microbial Ecology* 27(3): 275-284.

Nijampurkar, V.N., J.M. Martin and M. Maybeck. 1983. Si-32 as a tool for studying silicon behavior in estuaries. *Limnology and Oceanography* 28(6): 1237-1242.

Odum, W.E. and D. Smith. 1985. DOC flux from tidal fresh-water and salt marshes as estimated with replicate flumes. *Estuaries* 8(2B): A74-A74.

Opsahl, S., R. Benner and R.M.W. Amon. 1999. Major flux of terrigenous dissolved organic matter through the Arctic Ocean. *Limnology and Oceanography* 44(8): 2017-2023.

Ormaza-Gonzalez, F.I. and P.J. Statham. 1991. Determination of dissolved inorganic phosphorus in natural waters at nanomolar concentrations using a long capillary cell detector. *Analytica Chimica Acta* 244(1): 63-70.

Paerl, H.W., J. Rudek and M.A. Mallin. 1990. Stimulation of phytoplankton production in coastal waters by natural rainfall inputs - nutritional and trophic implications. *Marine Biology* 107(2): 247-254.

Parsons, T.R., D.G. Webb, H. Dovey, R. Haigh, M. Lawrence and G.E. Hopky. 1988. Production studies in the Mackenzie River Beaufort Sea Estuary. *Polar Biology* 8(3): 235-239.

Parsons, T.R., D.G. Webb, B.E. Rokeby, M. Lawrence, G.E. Hopky and D.B. Chiperzak. 1989. Autotrophic and heterotrophic production in the Mackenzie River Beaufort Sea Estuary. *Polar Biology* 9(4): 261-266.

Peterson, B.J. and R.W. Howarth. 1985. Sulfur, carbon and nitrogen isotopes as tracers of organic-matter flow in Georgia Estuaries. *Estuaries* 8(2B): A88-A88.

Prowse, T.D. 1986. Ice jam characteristics, Liard-Mackenzie rivers confluence. *Canadian Journal of Civil Engineering* 13(6): 653-665.

Raymond, P.A. and J.E. Bauer. 2001. DOC cycling in a temperate estuary: A mass balance approach using natural C-14 and C-13 isotopes. *Limnology and Oceanography* 46(3): 655-667.

Rouse, W.R., M.S.V. Douglas, R.E. Hecky, A.E. Hershey, G.W. Kling, L. Lesack, P. Marsh, M. McDonald, B.J. Nicholson, N.T. Roulet and J.P. Smol. 1997. Effects of climate change on the freshwaters of arctic and subarctic North America. *Hydrological Processes* 11(8): 873-902.

Ruttenberg, K.C. and M.A. Goni. 1997. Phosphorus distribution, C:N:P ratios, and delta C-13(oc) in arctic, temperate, and tropical coastal sediments: Tools for characterizing bulk sedimentary organic matter. *Marine Geology* 139(1-4): 123-145.

Schindler, D.W. 1974. Eutrophication and recovery in experimental lakes: Implications for lake management. *Science* 184, 897–899.

Seitzinger, S.P. 1988. Denitrification in fresh-water and coastal marine ecosystems - ecological and geochemical significance. *Limnology and Oceanography* 33(4): 702-724.

Sharp, J.H., C.H. Culberson and T.M. Church. 1982. The chemistry of the Delaware Estuary – general considerations. *Limnology and Oceanography* 27(6): 1015-1028.

Shimadzu Corporation. 2004. TOC-V CPH/CPN total organic carbon analyzer user's manual. Shimadzu Corporation, Kyoto, Japan.

Sorokin, Y.I. and P.Y. Sorokin. 1996. Plankton and primary production in the Lena River estuary and in the south-eastern Laptev sea. *Estuarine Coastal and Shelf Science* 43(4): 399-418.

Smith, L.C., Y. Sheng, G.M. MacDonald and L.D. Hinzman. 2005. Disappearing arctic lakes. *Science* 308: 1429.

Stainton, M.P., M.J. Capel and F.A.J. Armstrong. 1977. The chemical analysis of freshwater, 2nd edition. *Canada Fisheries and Mariane Services Miscellaneous Special Publication* 25.

Strickland, J.D., and T.R. Parsons. 1972. A practical handbook of seawater analysis. Bull. Fish. Res. Board Can. 167: 310.

Telang, S.A., R. Pocklington, A.S. Naidu, E.A. Romankevich, I.I. Gitelson and M.I. Gladyshev. 1991. Carbon and mineral transport in major North American, Russian Arctic, and Siberian rivers; the St. Lawrence, the Mackenzie, the Yukon, the Arctic Alaskan rivers, the Arctic Basin rivers in the Soviet Union, and the Yenisei. Biogeochemistry of major world rivers SCOPE (Chichester) 42: 75-104.

Tyler, A.C., K.J. McGlathery and I.C. Anderson. 2001. Macroalgae mediation of dissolved organic nitrogen fluxes in a temperate coastal lagoon. *Estuarine Coastal and Shelf Science* 53(2): 155-168.

Vincent, W.F. and R. Pienitz. 1996. Sensitivity of high-latitude freshwater ecosystems to global change: Temperature and solar ultraviolet radiation. *Geoscience Canada* 23(4): 231-236.

Vinnikov, K.Y., A. Robock, R.J. Stouffer, J.E. Walsh, C.L. Parkinson, D.J. Cavalieri, J.F.B. Mitchell, D. Garrett and V.F. Zakharov. 1999. Global warming and Northern Hemisphere sea ice extent. *Science* 286(5446): 1934-1937.

Water Survey of Canada (WSC). 2005. [Online]. Data products and services. Available: http://scitech.pyr.ec.gc.ca/waterweb/formnav.asp?lang=0.

Whitehouse, B.G., R.W. Macdonald, K. Iseki, M.B. Yunker and F.A. McLaughlin. 1989. Organic-carbon and colloids in the Mackenzie River and Beaufort Sea. *Marine Chemistry* 26(4): 371-378.

Yang, D., B. Ye and D.L. Kane. 2004. Streamflow changes over Siberian Yenisei River Basin. *Journal of Hydrology* 296: 59-80.

Yunker, M. B., R.W. Macdonald, W.J. Cretney, B.R. Fowler and F.A. McLaughlin. 1993. Alkane, terpene, and polycyclic aromatic hydrocarbon geochemistry of the Mackenzie River and Mackenzie Shelf - Riverine contributions to Beaufort Sea coastal sediment. *Geochimica Et Cosmochimica Acta* 57(13): 3041-3061.

Yunker, M.B., R.W. Macdonald and B.G. Whitehouse. 1994. Phase associations and lipid distributions in the seasonally ice-covered arctic estuary of the Mackenzie Shelf. *Organic Geochemistry* 22(3-5): 651-669.

3.8 Tables

Table 3.1 Biogeochemical studies and general results within the freshwater-saltwater transition zone of large arctic rivers.

RIVER ESTUARY	NUTRIENT	MIXING BEHAVIOUR	GRADIENT FROM RIVER TO OFFSHORE	AUTHOR
THIS STUDY				
Mackenzie	Particulates, NO_3^-, TP, POC:PN, POC:PP, PN:PP	Below mixing line	Declining	-
	SRP		Increasing	
	TDOC, CDOC, SRSi, TOC:TN	Follows mixing line	Declining	
	TN, TN:TP		No change	
	DON, DOP, TDN, TDP		Increasing	
	TOC:TP	Above mixing line	Declining	
OTHER STUDIES				
Lena	NO_3^-, TDN	Below mixing line	Declining	[A]
	TDOC, SRSi	Follows mixing line	Declining	
	DIC, SRP, TDP		Increasing	
	POC	N/A	Declining	

Table 3.1 (continued) Biogeochemical studies and general results within the freshwater-saltwater transition zone of large arctic rivers.

RIVER ESTUARY	NUTRIENT	MIXING BEHAVIOUR	GRADIENT FROM RIVER TO OFFSHORE	AUTHOR
Yenesei, Ob	TSS, POC, PN, TDOC, DOM, C:N, DON	Follows mixing line	Declining	[B][E][D][G]
	TSS	N/A	Declining	[C]
	Biogenic:abiogenic TSS		Increasing	
Russian rivers	DIN, NH_4^+, SRP	Below mixing line	Declining	[F]
	DOC, DON, SRSi, TSS, POC, PON	Follows mixing line	Declining	
Mackenzie	Particulates, POC:PN	N/A	Declining	[H]
	Cl^-, SO_4^{2-}, HCO_3^-, cations		Increasing	
	TDN, TDP, SRSi		No change	
Mackenzie	PO4 SRSi Nitrate	Conservative mixing Conservative mixing Decreased	Declining	[I]
	TDOC	Follows mixing line	Declining	[J]
	TOC:TN TOC:TP TN:TP	No change Slightly decreased Slightly decreased	No change Declining Declining	[K]
	TSS, TDOC, Chl-a	N/A	Declining	[L]

[A] Cauwet and Sidorov 1996 [B] Amon and Meon 2004 [C] Lukashin et al. 2000
[D] Gebhardt et al. 2005 [E] Kohler et al. 2003 [F] Dittmar et al. 2001
[G] Krishnamurthy et al. 2001 [H] Brunskill et al. 1973 [I] Macdonald et al. 1987
[J] Whitehouse et al. 1989 [K] Rutterberg and Goni 1997 [L] Garneau et al. 2006

Table 3.2 Locations and sampling information of each site along the ARDEX transect.

SITE	NORTH	WEST	SAMPLING DATE, COLUMN LOCATION AND DEPTH (m)*
R1 (EC-river)	68° 21.36′	133° 44.22′	26-Jul. → Sx2
R2 (MC-river)	68° 37.56′	134° 11.28′	01-Aug. → S,I,B (20m) 02-Aug. → Sx2, I, Bx2 (15,16m)
R3 (MC-river)	68° 50.52′	134° 37.80′	01-Aug. → S,I,B (28m)
R4 (EC-river)	69° 13.62′	134° 13.62′	27-Jul. → S,I,B (6m)
R5E (estuary)	69° 16.86′	133° 58.20′	31-Jul. → S
R5D (estuary)	69° 21.72′	133° 44.40′	31-Jul. → S,P (2m), B (3.4m)
R5B (estuary)	69° 24.96′	133° 31.26′	31-Jul. → S
R5A (estuary)	69° 27.36′	133° 08.82′	31-Jul. → S,P (1.5m),B (2.5m)
R6 (marine)	69° 33.06′	133° 25.20′	30-Jul. → S
R7 (marine)	69° 43.08′	133° 25.02	30-Jul. → S,P (5m),B (6.5m)
R8 (marine)	69° 52.92′	133° 25.20′	30-Jul. → S,P (7m),C (12m),B (14m)
R9 (marine)	70° 03.00′	133° 25.02′	28-Jul. → S,P (5m),C (21m),B (30m) 29-Jul. → Sx2

*S - surface I - integrated B - bottom P - pycnocline C - chlorophyll-*a* max
EC - East Channel MC - Middle Channel

Table 3.3 Nutrient measures and analytical methods for collected water samples from ARDEX stations.

ANALYSIS	PRESERVATION	ANALYSIS METHOD
NO_3^-	Frozen	Dionex DX-300 ion chromatography (Dionex Corporation 1991)
SRSi	Refrigerated	Acid molybdate spectroscopy (Strickland and Parsons 1972)
SRP	Refrigerated (<24hrs)	Molybdate blue spectroscopy (Strickland and Parsons 1972)
NH_4^+	Refrigerated (<24hrs)	Indophenol blue spectroscopy (Strickland and Parsons 1972)
TDOC	Frozen	Shimadzu TOC-V_{CPH} (Shimadzu Corporation)*
CDOC	Refrigerated	Spectrophotometry at 330nm. A=2.303 d/r where: A-absorbance coefficient; d-absorption @ 330nm; r-cell path length (cm)
TDN; TDP	Refrigerated	Acid photo-oxidation (Stainton et al. 1977)*
TSS	None	Gravimetric (Stainton et al. 1977)
POC; PN	Oven dried/sealed	Rapid Analysis Elemental CHN analyser (Stainton et al. 1977)*
PP	Oven dried/sealed	Filter digestion/molybdate blue spectroscopy (Stainton et al. 1977)*
Chlorophyll-*a*	In situ	CTD

*samples analysed by the Freshwater Institute, Fisheries and Oceans Canada (DFO)

Table 3.4 Mean nutrient concentrations from all samples within each water type across the ARDEX stations and 2004 reference river data before and after the Mackenzie Delta. All units are in μmol/L except for TSS (mg/L) and CDOC (m^{-1}).

NUTRIENT	2004 RIVERFLOW DURING HYDROGRAPH RECESSION		RIVER DURING ARDEX	ESTUARY	OFFSHORE UPPER WATERS[b]	OFFSHORE DEEP WATERS[b]
	NO DELTA EFFECT[a]	WITH DELTA EFFECT[a]				
PARTICULATES						
TSS	126	104	66	47	24	15
POC	347	296	170	101	34	27
PN	17.6	15.8	10.3	6.5	3.1	4.0
PP	3.4	2.9	1.8	1.2	0.5	0.37
DOM						
TDOC	311	357	305	240	98	49
CDOC	7.9	8.8	5.4	4.3	1.4	0.9
DON	4.5	6.6	4.2	10.2	18.9	20.0
DOP	0.01	0.03	0.04	0.20	0.50	0.78
INORGANICS						
NO_3^-	5.8	4.9	5.3	2.0	0.9	7.3
NH_4^+	0.2	0.2	0.4	0.5	0.1	0.0
SRP	0.08	0.07	0.03	0.04	0.69	1.20
SRSi	57.4	54.3	58.6	43.7	11.5	23

Table 3.4 (continued) Mean nutrient concentrations from all samples within each water type across the ARDEX stations and 2004 reference river data before and after the Mackenzie Delta. All units are in µmol/L except for TSS (mg/L) and CDOC (m^{-1}).

NUTRIENT	2004 RIVERFLOW DURING HYDROGRAPH RECESSION		RIVER DURING ARDEX	ESTUARY	OFFSHORE UPPER WATERS[b]	OFFSHORE DEEP WATERS[b]
	NO DELTA EFFECT[a]	WITH DELTA EFFECT[a]				
COMPOSITE MEASURES						
TN	27.8	26.2	20.2	19.1	23.0	31.3
TDN	10.2	11.6	9.9	12.7	19.8	27.3
TP	3.5	3.0	1.9	1.6	1.7	2.4
TDP	0.06	0.08	0.06	0.23	1.26	2.0
TOC	658	653	476	341	133	76
DIN	5.7	5.0	5.6	2.5	1.0	7.3
C:N:P RATIOS (Redfield)						
TOC:TP (106)	207.4	346.1	261.8	258.2	74.0	32.3
TOC:TN (6.6)	22.9	23.2	24.0	18.3	5.9	2.4
TN:TP (16)	9.6	15.0	11.1	12.9	15.0	13.3
POC:PP (106)	104.0	115.3	94.3	83.3	85.6	69.4
POC:PN (6.6)	19.4	17.7	17.1	14.8	9.1	7.0
PN:PP (16)	5.5	7.5	5.7	5.8	9.8	10.1

[a]Delta inflow river data were based on 2004 volume-weighted mean concentrations from the open water season while delta outflow data were based on river inflows and delta lake water additions during the same period (Chapter 2).

[b]Offshore upper waters were defined as all samples from R6-R8 plus surface and pycnocline layers of R9. Offshore deep waters were defined as R9 chlorophyll-*a* maximum and bottom layers.

3.9 Figures

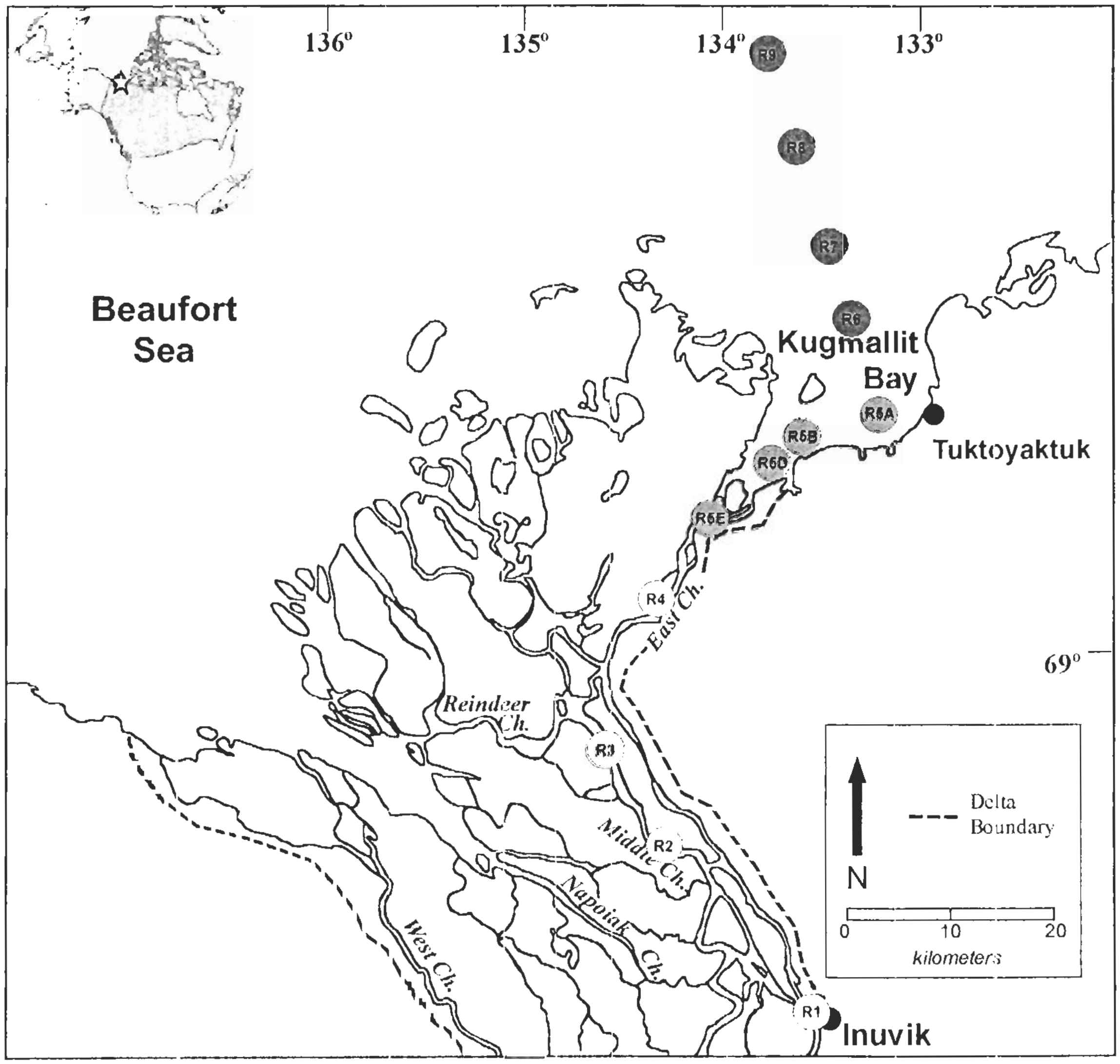

Figure 3.1 Study area and sampling stations during the Arctic River-Delta Experiment cruise, 26-Jul. to 02-Aug. 2004. R1-R4 were river sites, R5x were estuarine sites while R6-R9 were marine sites.

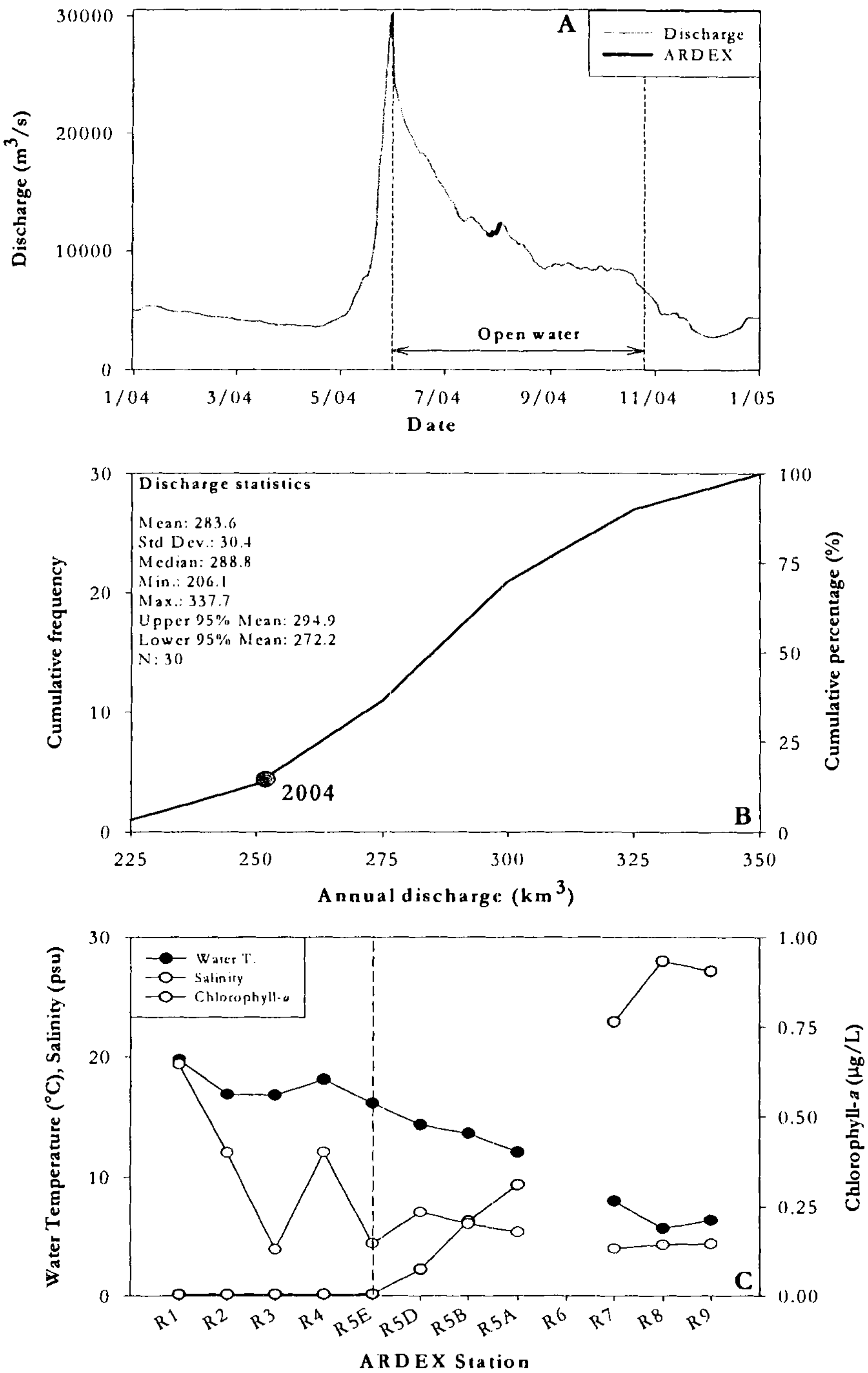

Figure 3.2 (A) Daily 2004 discharge of the Mackenzie River above Arctic Red River with the ARDEX sampling period indicated. (B) 30-year cumulative frequency and percentage of discharge at the Mackenzie River at Arctic Red River discharge station (WSC 2005). (C) Selected parameters across the ARDEX transect. The dashed line indicates the beginning of the estuary.

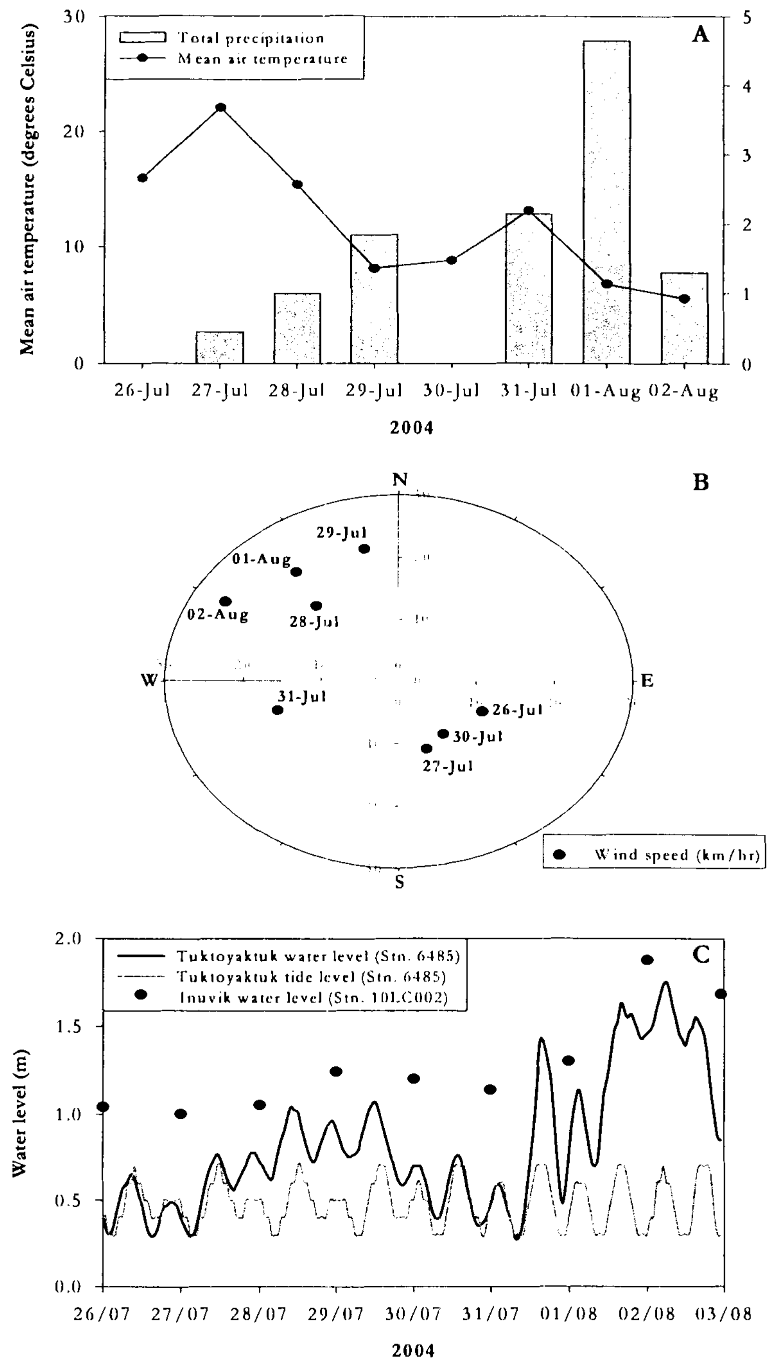

Figure 3.3 Evidence of frontal storms and related sea surges toward the coast during the ARDEX sampling period. (A) Air temperature and precipitation during the sampling period as a mean of Invuik and Tuktoyaktuk, NT weather station data (Env. Canada 2005). (B) Wind speed and direction as a mean of Inuvik and Tuktoyaktuk weather station data (Env. Canada 2005). (C) Water level data at Tuktoyaktuk and Inuvik (Env. Canada 2005).

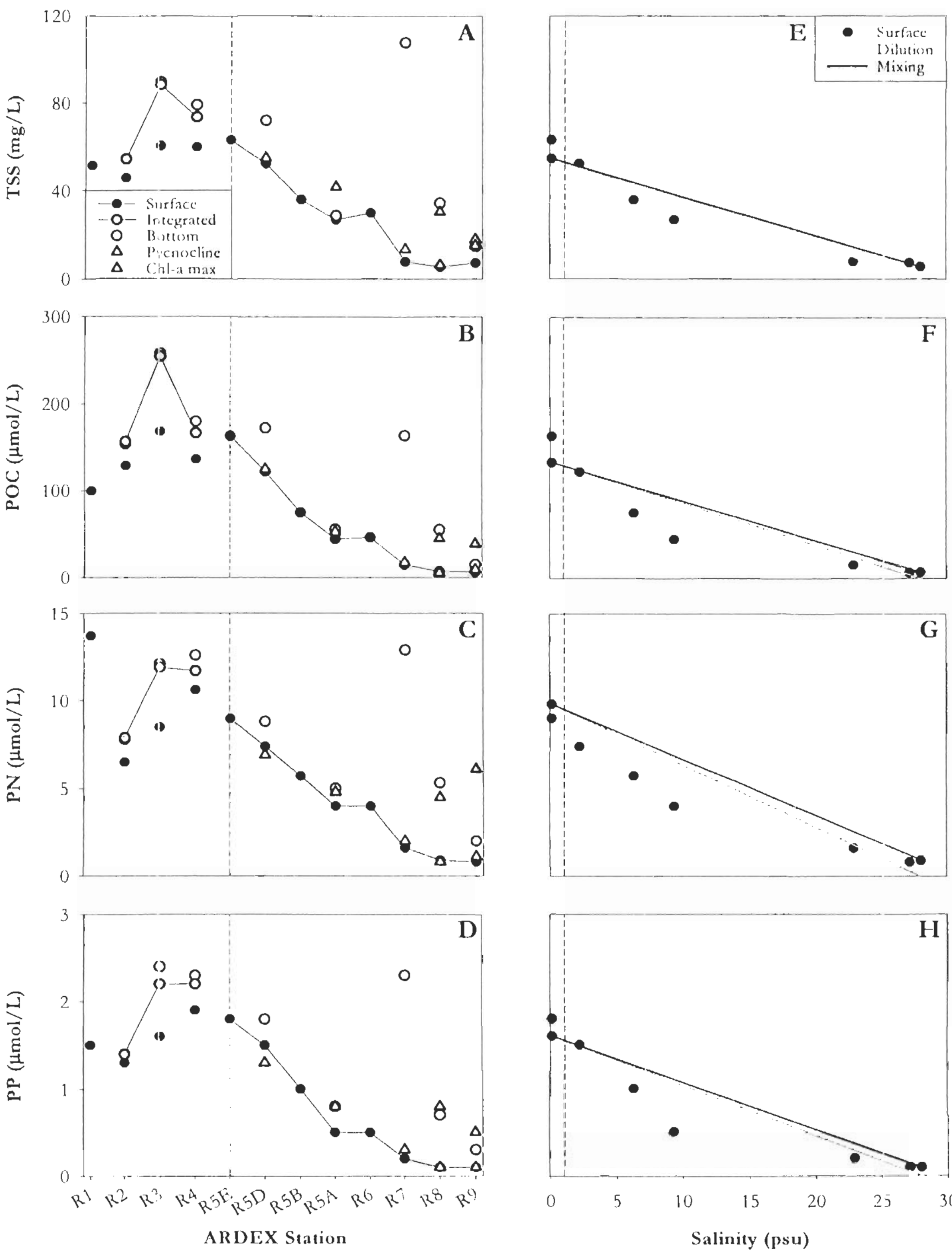

Figure 3.4 Downstream and vertical structure of particulates across the Mackenzie FSTZ (A-D) and associated mixing lines and observed data (E-H). Dashed lines indicate beginning of estuary.

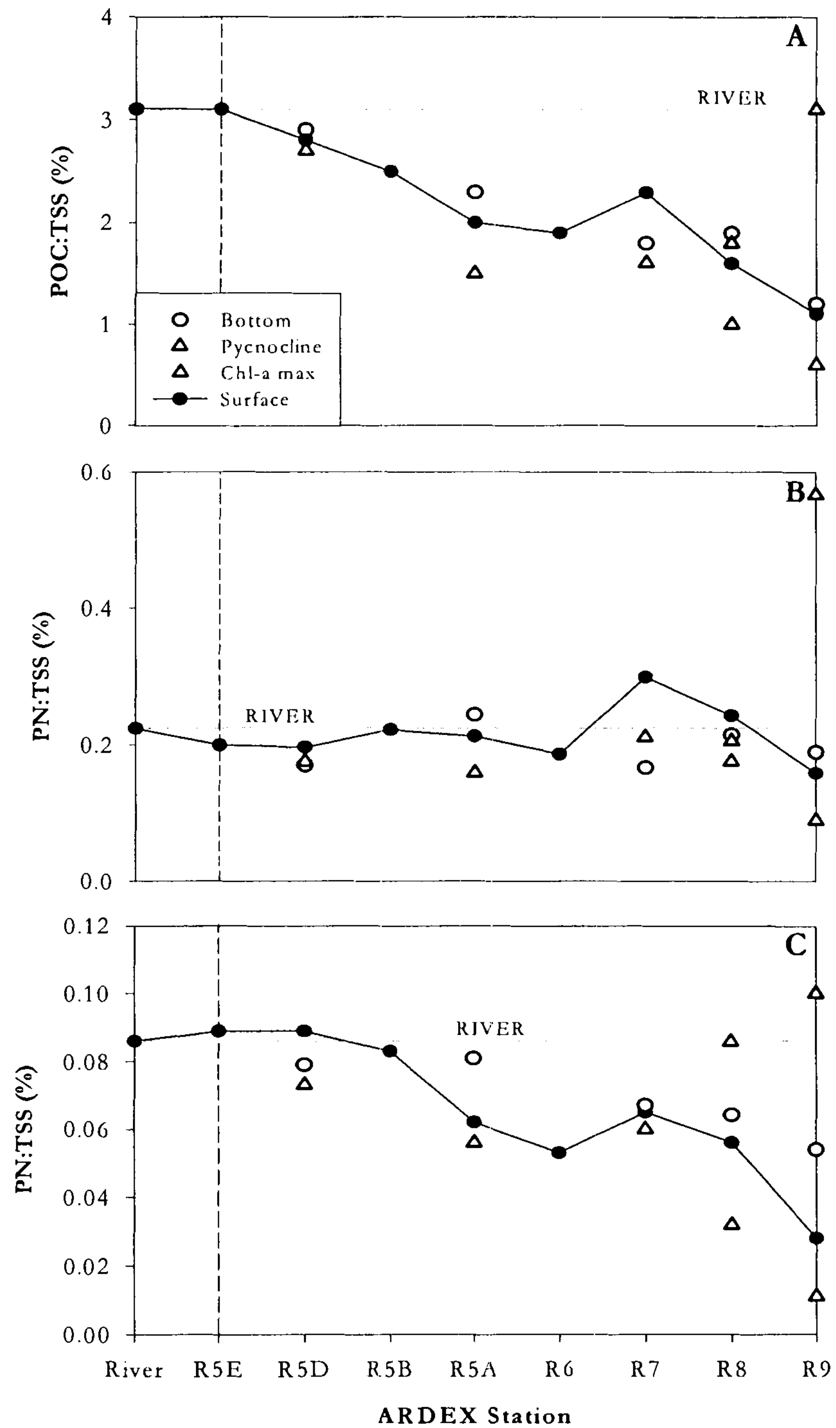

Figure 3.5 Particulate organic carbon (A), particulate phosphorus (B) and particulate nitrogen (C) as a percentage of total suspended sediment. The vertical dashed line indicates the beginning of the estuary and the dashed horizontal line indicates the average ratios observed in rivers.

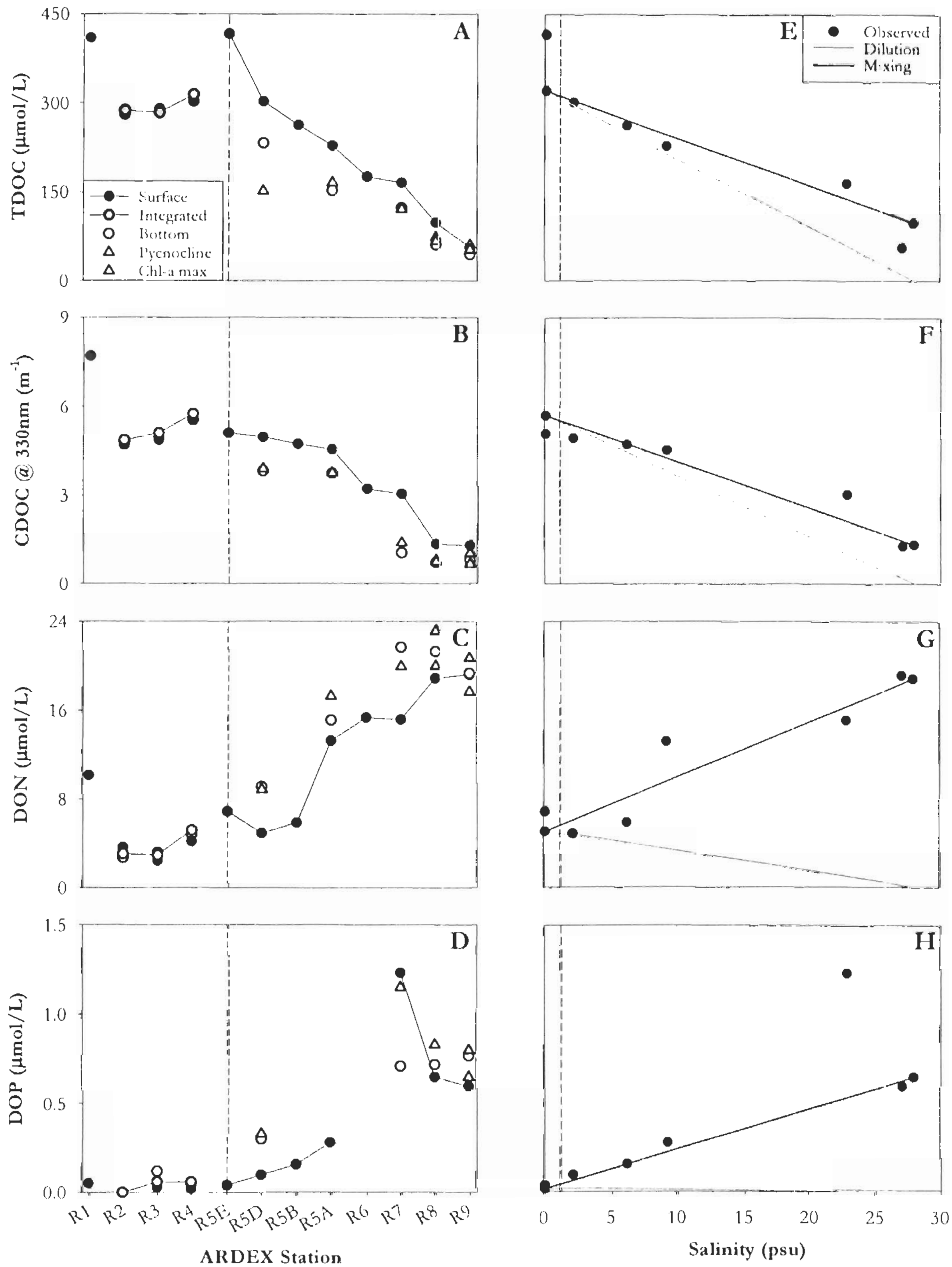

Figure 3.6 Downstream and vertical structure of dissolved organic matter across the Mackenzie FSTZ (A-D) and associated mixing lines and observed data (E-H). Dashed lines indicate beginning of estuary.

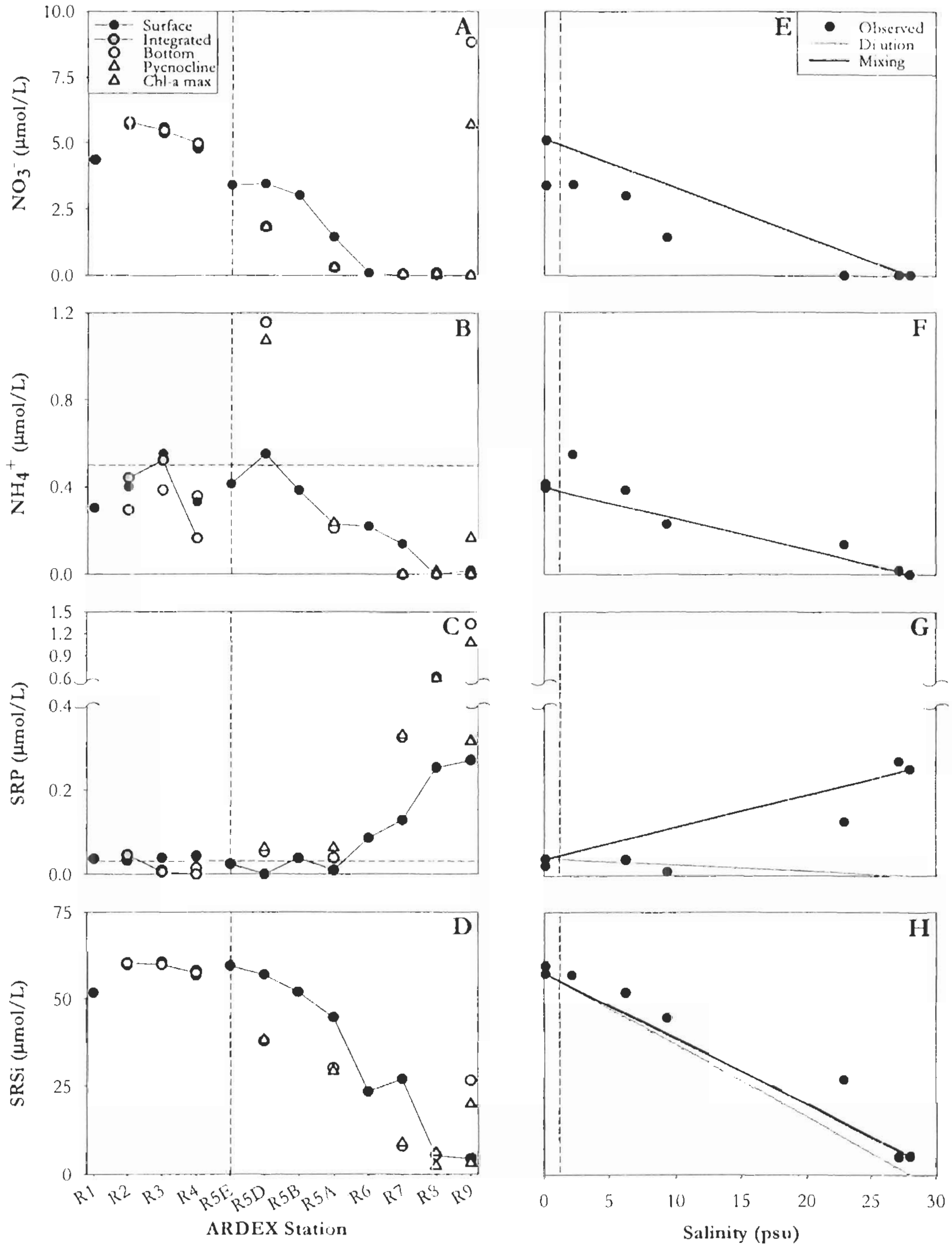

Figure 3.7 Downstream and vertical structure of inorganic nutrients across the Mackenzie FSTZ (A-D) and associated mixing lines and observed data (E-H). Vertical dashed lines indicate beginning of estuary; horizontal dashed lines indicate the analytical detection limit.

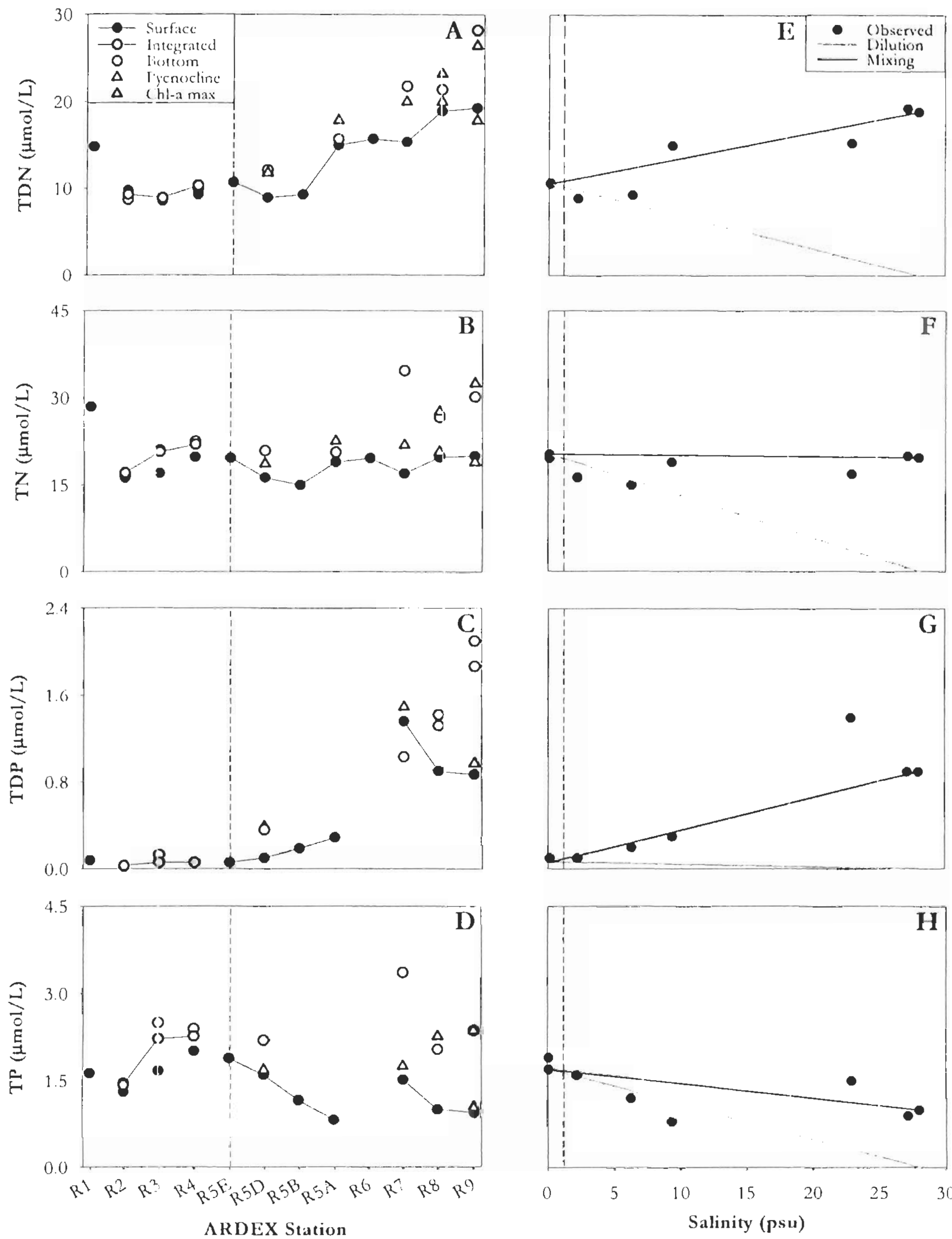

Figure 3.8 Downstream and vertical structure of composite N and P measures across the Mackenzie FSTZ (A-D) and associated mixing lines and observed data (E-H). Dashed lines indicate beginning of estuary.

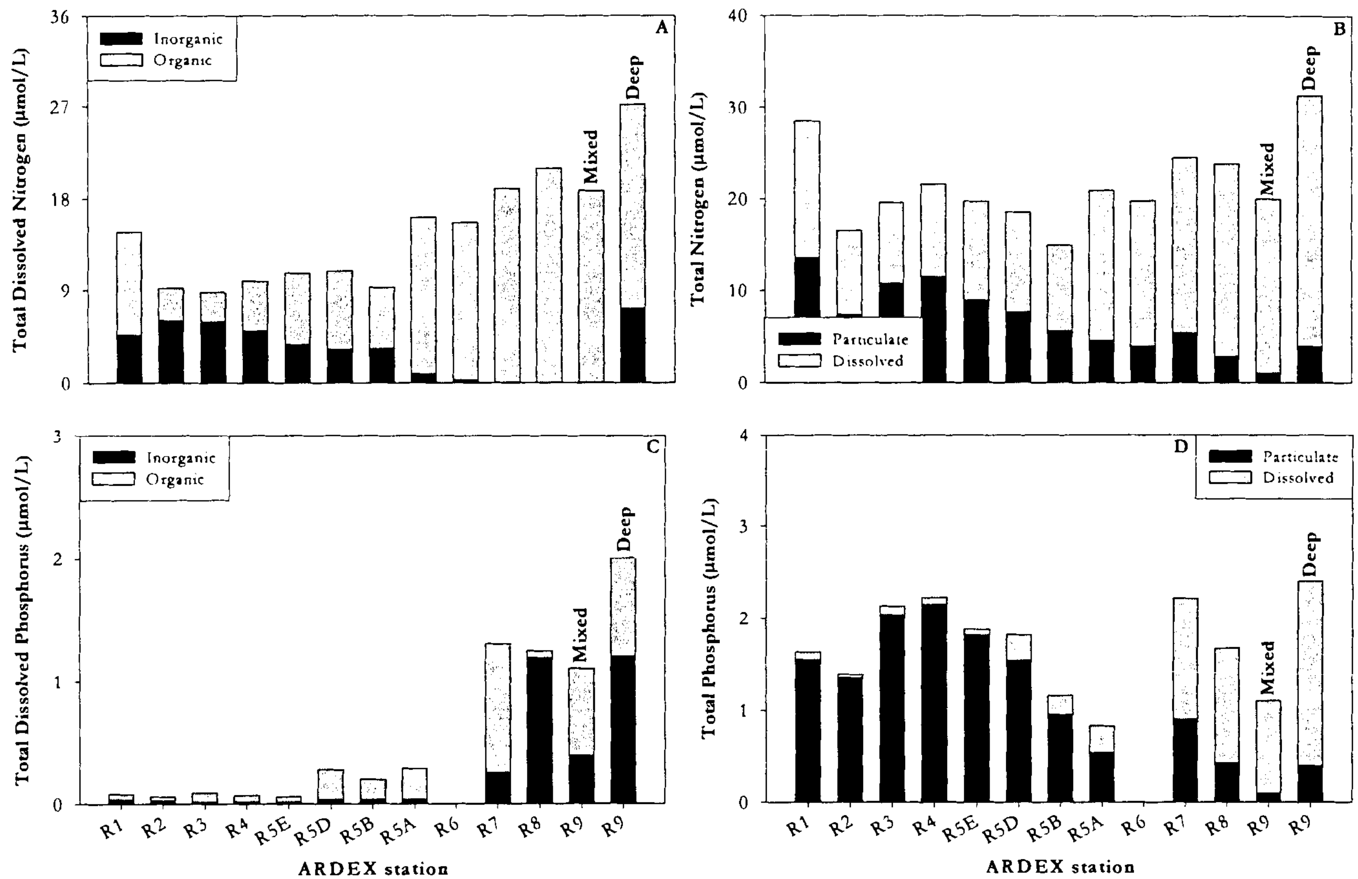

Figure 3.9 Inorganic and organic composition of total dissolved nitrogen (A) and total dissolved phosphorus (C) and particulate and dissolved composition of total nitrogen (B) and total phosphorus (D) across the ARDEX stations. 'Mixed' indicates the upper mixed waters of the Beaufort Sea; 'Deep' indicates deep ocean waters.

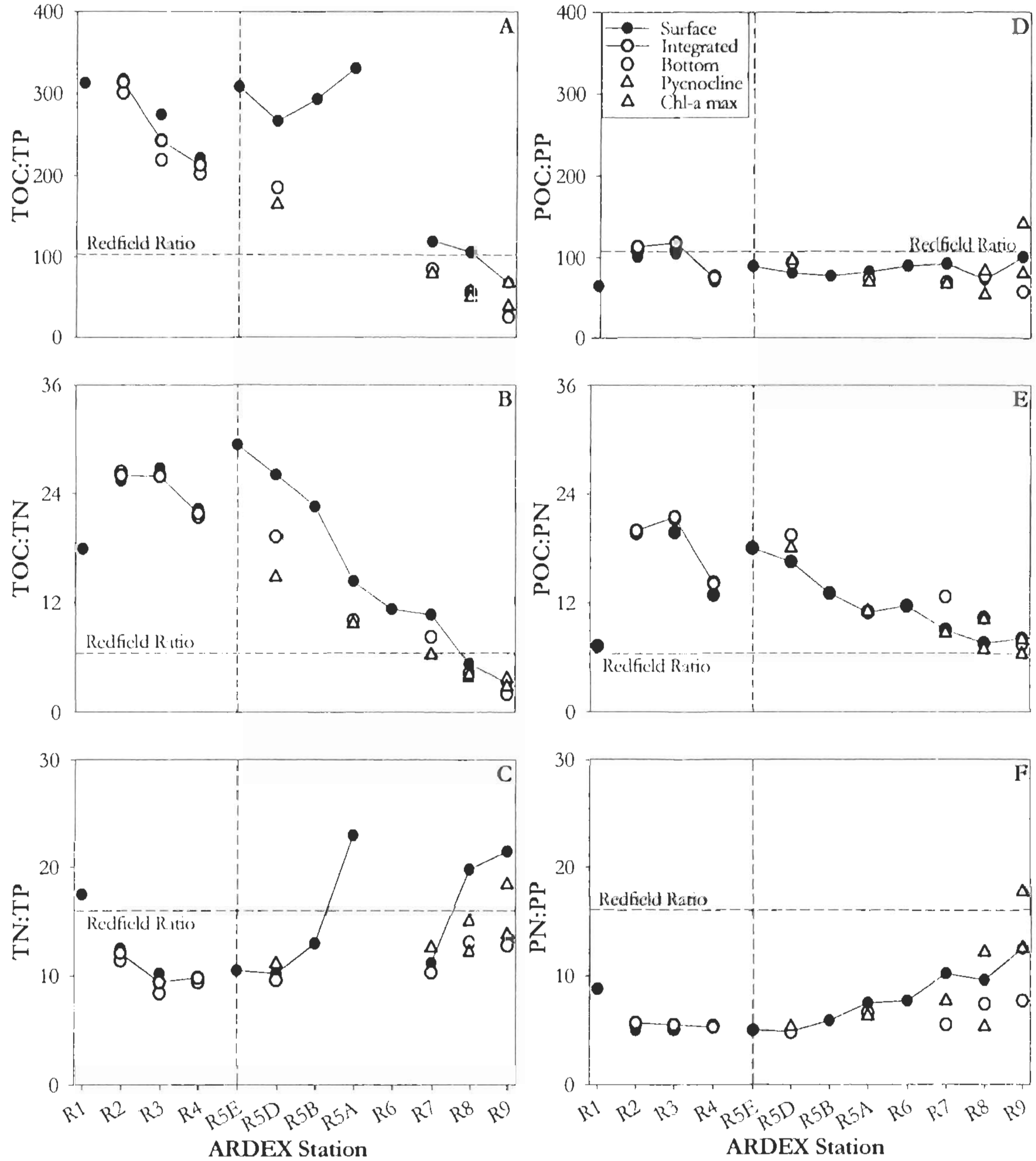

Figure 3.10 Total (A-C) and particulate (D-F) C:N:P ratios across the Mackenzie FSTZ. The vertical dashed line indicates the beginning of the estuary.

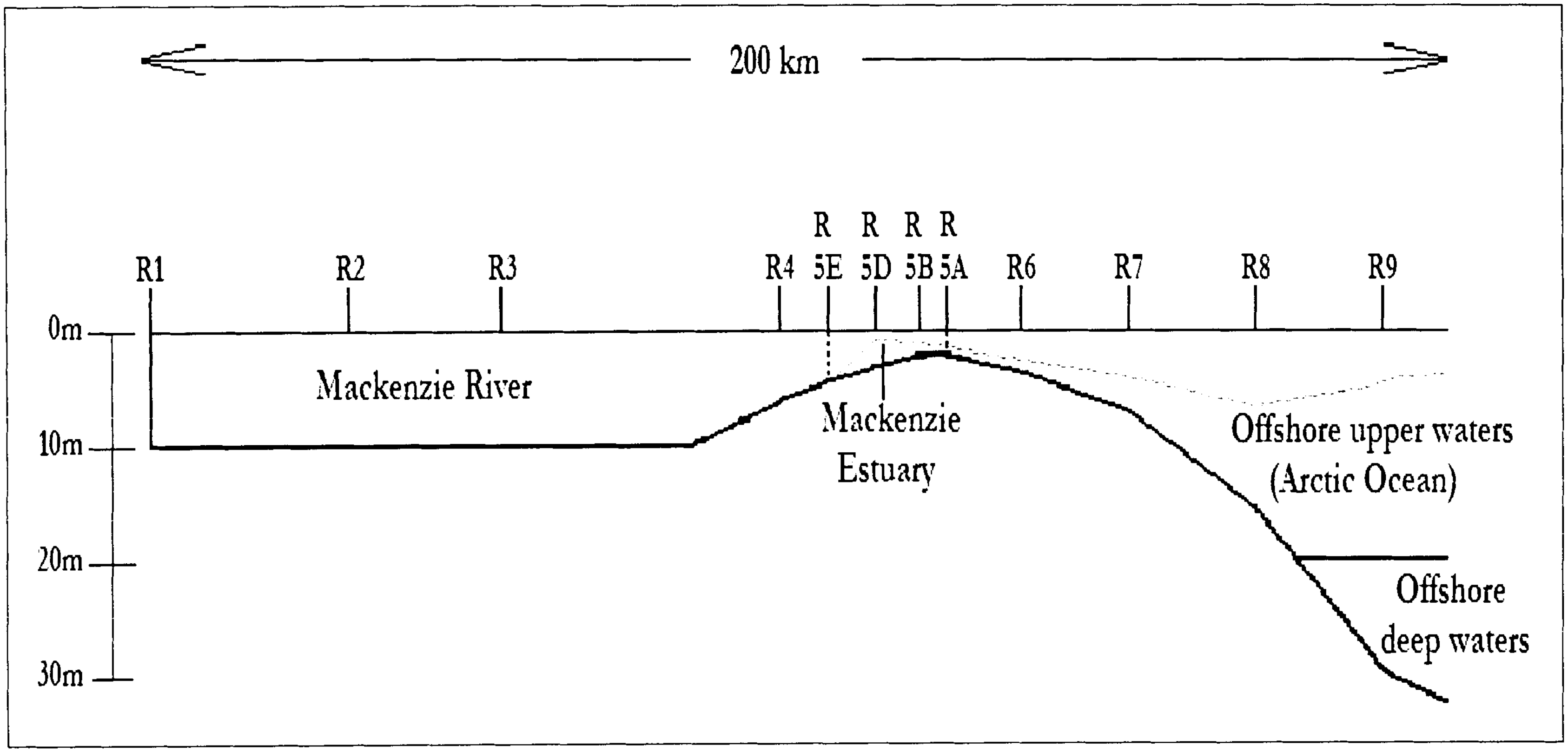

Figure 3.11 Water masses observed across the ARDEX stations. River depth is an approximate average across all river sites. The dashed horizontal line from the estuary to offshore indicates approximate location of the pycnocline. Vertical dashed lines delineate estuarine stations. Figure approximately to scale with vertical exaggeration factor of 2115 relative to the horizontal axis.

APPENDICES

Appendix A: Raw data

ARDEX RAW DATA (all data in µmol/L unless stated otherwise)

PARTICULATES	Total Suspended Solids (mg/L)					Particulate Organic Carbon					Particulate Nitrogen					Particulate Phosphorus				
Depth	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*
R1	52	-	-	-	-	100	-	-	-	-	13.7	-	-	-	-	1.5	-	-	-	-
R2	46	53	55	-	-	129	154	157	-	-	6.5	7.8	7.9	-	-	1.3	1.4	1.4	-	-
R3	61	90	88	-	-	168	258	254	-	-	8.5	12.1	11.9	-	-	1.6	2.4	2.2	-	-
R4	60	79	74	-	-	137	180	167	-	-	10.6	12.6	11.7	-	-	1.9	2.3	2.2	-	-
R5E	63	-	-	-	-	163	-	-	-	-	9.0	-	-	-	-	1.8	-	-	-	-
R5D	52	72	-	55	-	122	172	-	125	-	7.4	8.8	-	6.9	-	1.5	1.8	-	1.3	-
R5B	36	-	-	-	-	75	-	-	-	-	5.7	-	-	-	-	1.0	-	-	-	-
R5A	27	29	-	42	-	44	56	-	53	-	4.0	5.0	-	4.8	-	0.5	0.8	-	0.8	-
R6	30	-	-	-	-	47	-	-	-	-	4.0	-	-	-	-	0.5	-	-	-	-
R7	8	108	-	13	-	15	163	-	17	-	1.6	12.9	-	2.0	-	0.2	2.3	-	0.3	-
R8	5	34	-	6	30	7	55	-	5	46	0.9	5.3	-	0.8	4.5	0.1	0.7	-	0.1	0.8
R9	7	15	-	18	15	7	15	-	9	39	0.8	2.0	-	1.1	6.1	0.1	0.3	-	0.1	0.5

DOM	Total Dissolved Organic Carbon					Coloured Dissolved Organic Matter (m^{-1})					Dissolved Organic Nitrogen					Dissolved Organic Phosphorus				
Depth	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*
R1	418	-	-	-	-	7.7	-	-	-	-	10.2	-	-	-	-	0.05	-	-	-	-
R2	283	282	288	-	-	4.7	4.8	4.9	-	-	3.6	2.7	3.1	-	-	B/D	B/D	B/D	-	-
R3	290	290	284	-	-	4.9	5.0	5.1	-	-	2.4	3.2	2.9	-	-	B/D	0.12	0.06	-	-
R4	307	303	315	-	-	5.6	5.6	5.8	-	-	4.2	4.8	5.2	-	-	B/D	0.05	0.06	-	-
R5E	417	-	-	-	-	5.1	-	-	-	-	6.9	-	-	-	-	0.04	-	-	-	-
R5D	303	233	-	152	-	5.0	3.8	-	3.9	-	4.9	9.1	-	8.9	-	0.10	B/D	-	0.33	-
R5B	264	-	-	-	-	4.7	-	-	-	-	5.9	-	-	-	-	0.16	-	-	-	-
R5A	229	153	-	166	-	4.6	3.8	-	3.8	-	13.3	15.2	-	17.3	-	0.28	-	-	-	-
R6	176	-	-	-	-	3.2	-	-	-	-	15.4	-	-	-	-	-	-	-	-	-
R7	166	124	-	121	-	3.1	1.1	-	1.4	-	15.2	21.7	-	19.9	-	1.23	0.71	-	1.15	-
R8	99	61	-	74	67	1.4	0.7	-	0.8	0.8	18.9	21.3	-	20.0	23.1	0.65	0.72	-	B/D	0.83
R9	57	45	-	61	53	1.3	0.8	-	0.7	1.0	19.2	19.4	-	17.7	20.7	0.60	0.77	-	0.65	0.80

COMPOSITE MEASURES	Total Nitrogen					Total Dissolved Nitrogen					Total Phosphorus					Total Dissolved Phosphorus				
Depth	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	P	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*
R1	28.5	-	-	-	-	14.8	-	-	-	-	1.6	-	-	-	-	0.08				
R2	16.2	16.5	17.1	-	-	9.8	8.7	9.3	-	-	1.3	1.4	1.4	-	-	B/D	B/D	B/D		
R3	17.1	21.1	20.8	-	-	8.6	8.9	8.9	-	-	1.7	2.5	2.2	-	-	0.06	0.13	0.06		
R4	19.8	22.6	22.1	-	-	9.3	10.0	10.4	-	-	2.0	2.4	2.3	-	-	0.06	0.06	0.06		
R5E	19.7	-	-	-	-	10.7	-	-	-	-	1.9	-	-	-	-	0.06				
R5D	16.3	20.9	-	18.7	-	8.9	12.1	-	11.8	-	1.6	2.2	-	1.7	-	0.10	0.36		0.39	
R5B	15.0	-	-		-	9.3	-	-	-	-	1.2	-	-	-	-	0.19				
R5A	19.0	20.7	-	22.6	-	15.0	15.7	-	17.8	-	0.8	-	-	-	-	0.29				
R6	19.7	-	-	-	-	15.7	-	-	-	-	-	-	-	-	-					
R7	17.0	34.6	-	22.0	-	15.3	21.8	-	20.0	-	1.5	3.4	-	1.7	-	1.36	1.03		1.49	
R8	19.8	26.7	-	20.8	27.7	18.9	21.4	-	20.0	23.2	1.0	2.0	-	1.4	2.3	0.90	1.32		1.32	1.42
R9	20.1	30.2	-	19.0	32.5	19.3	28.2	-	17.8	26.4	0.9	2.4	-	1.0	2.4	0.87	2.10		0.97	1.87

DISSOLVED INORGANICS	Nitrate					Ammonium					Phosphate					Silica				
Depth	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*
R1	4.4	-	-	-	-	B/D	-	-	-	-	0.04	-	-	-	-	52	-	-	-	-
R2	5.7	5.7	5.8	-	-	B/D	B/D	B/D	-	-	B/D	B/D	0.05	-	-	60	60	60	-	-
R3	5.6	5.4	5.5	-	-	0.55	B/D	0.52	-	-	0.04	B/D	B/D	-	-	61	61	60	-	-
R4	4.8	4.8	5.0	-	-	B/D	B/D	B/D	-	-	0.04	B/D	B/D	-	-	57	58	58	-	-
R5E	3.4	-	-	-	-	B/D	-	-	-	-	B/D	-	-	-	-	60	-	-	-	-
R5D	3.5	1.8	-	1.8	-	0.55	1.16	-	1.07	-	B/D	0.05	-	0.06	-	57	38	-	38	-
R5B	3.0	-	-	-	-	B/D	-	-	-	-	0.04	-	-	-	-	52	-	-	-	-
R5A	1.5	0.3	-	0.3	-	B/D	B/D	-	B/D	-	B/D	0.04	-	0.06	-	45	30	-	29	-
R6	0.1	-	-	-	-	B/D	-	-	-	-	0.09	-	-	-	-	24	-	-	-	-
R7	B/D	0.1	-	0.1	-	B/D	B/D	-	B/D	-	0.13	0.33	-	0.33	-	27	8	-	9	-
R8	B/D	0.1	-	B/D	0.1	B/D	B/D	-	B/D	B/D	0.25	0.61	-	3.30	0.59	5	5	-	2	6
R9	B/D	8.8	-	B/D	5.7	B/D	B/D	-	B/D	B/D	0.27	1.33	-	0.32	1.08	5	27	-	3	20

TOC:TN:TP	TOC:TN					TOC:TP					TN:TP					Salinity
Depth	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*
R1	17.9	-	-	-	-	312.7	-	-	-	-	17.5	-	-	-	-	0.1253
R2	25.4	26.4	26.0	-	-	316.9	300.8	313.8	-	-	12.5	11.4	12.1	-	-	0.1321
R3	26.8	26.0	25.9	-	-	274.7	219.5	242.9	-	-	10.2	8.4	9.4	-	-	0.1316
R4	22.3	21.4	21.8	-	-	221.6	202.1	213.1	-	-	9.9	9.4	9.8	-	-	0.1307
R5E	29.4	-	-	-	-	308.3	-	-	-	-	10.5	-	-	-	-	0.1289
R5D	26.1	19.3	-	14.8	-	266.8	185.4	-	164.9	-	10.2	9.6	-	11.1	-	2.1991
R5B	22.6	-	-	-	-	293.2	-	-	-	-	13.0	-	-	-	-	6.2700
R5A	14.4	10.1	-	9.7	-	330.6	-	-	-	-	23.0	-	-	-	-	9.3415
R6	11.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
R7	10.7	8.3	-	6.3	-	119.3	85.5	-	79.4	-	11.2	10.3	-	12.6	-	22.9353
R8	5.3	4.3	-	3.8	4.1	106.0	57.0	-	57.2	49.8	19.8	13.1	-	15.0	12.2	28.0214
R9	3.2	2.0	-	3.7	2.8	68.2	25.5	-	67.9	39.1	21.5	12.8	-	18.4	13.8	27.1678

POC:TN:TP	POC:PN					POC:PP					PN:PP					Chlorophyll-*a*
Depth	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*	*B*	*I*	*P*	*CM*	*S*
R1	7.3	-	-	-	-	64.5	-	-	-	-	8.8	-	-	-	-	0.647
R2	20.0	19.7	20.0	-	-	101.2	108.8	113.2	-	-	5.0	5.5	5.7	-	-	0.402
R3	19.8	21.3	21.5	-	-	104.9	109.0	118.2	-	-	5.3	5.1	5.5	-	-	0.131
R4	12.9	14.3	14.2	-	-	70.5	77.4	75.8	-	-	5.5	5.4	5.3	-	-	0.403
R5E	18.1	-	-	-	-	89.8	-	-	-	-	5.0	-	-	-	-	-
R5D	16.6	19.5	-	18.1	-	81.6	94.0	-	96.7	-	4.9	4.8	-	5.3	-	0.178
R5B	13.1	-	-	-	-	77.9	-	-	-	-	5.9	-	-	-	-	0.234
R5A	11.0	11.1	-	11.1	-	82.8	73.7	-	70.0	-	7.5	6.6	-	6.3	-	0.147
R6	11.7	-	-	-	-	90.3	-	-	-	-	7.7	-	-	-	-	-
R7	9.1	12.7	-	8.7	-	92.8	70.2	-	67.7	-	10.2	5.5	-	7.7	-	0.133
R8	7.6	10.4	-	6.9	10.2	73.1	77.4	-	83.8	54.2	9.6	7.4	-	12.2	5.3	0.144
R9	8.1	7.5	-	8.0	6.4	101.0	58.0	-	141.8	80.8	12.5	7.7	-	17.7	12.5	0.146

DELTA SURVEYS RAW DATA (all data in µmol/L unless stated otherwise)

PARTICULATES	Total Suspended Solids (mg/L)					Particulate Organic Carbon					Particulate Nitrogen					Particulate Phosphorus				
*Date**	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*
Inflow Transect																				
Mac@PS	124	90	125	61	119	366	251	264	301	159	16.2	11.2	19.3	15.5	9.1	4.5	2.3	4.4	2.7	1.5
Mac@ARR	152	113	166	73	66	454	291	362	293	171	18.2	13.3	25.0	13.9	8.2	4.0	2.7	3.9	2.9	1.6
Arctic Red River	77	11	86	49	158	-	40	261	220	1846	-	2.4	12.4	9.9	62.2	2.4	0.4	2.8	2.4	13.8
Peel River	121	42	113	41	77	322	102	233	110	154	16.7	7.1	19.8	6.8	10.5	5.9	1.4	3.9	1.5	2.3
Middle Transect																				
Peel Channel	104	26	34	47	74	605	70	72	155	259	35.7	6.0	6.2	10.9	21.4	4.5	1.1	1.4	2.4	4.6
Aklavik Channel	107	32	61	32	51	712	90	144	186	109	44.3	5.4	9.3	10.4	8.6	3.6	1.0	1.8	2.0	1.6
Middle Channel	129	106	65	68	69	525	289	161	233	177	24.3	13.7	9.3	11.6	8.6	4.0	2.6	1.6	2.3	1.7
Kalinek Channel	51	18	49	41	24	511	70	111	157	109	25.2	4.1	9.0	10.0	6.2	1.8	0.6	1.4	1.7	1.1
East Channel@IN	70	21	59	50	19	355	67	136	180	75	21.7	3.9	10.0	9.8	5.1	2.0	0.7	1.8	1.8	0.1
Mouth Transect																				
Middle@Reindeer	176	52	83	79	40	749	175	200	433	167	36.8	6.8	11.9	19.4	8.9	4.8	1.5	2.5	4.1	1.5
East Channel	54	40	97	61	50	147	117	222	339	135	9.8	5.4	14.0	15.9	7.4	2.3	1.1	2.8	3.3	1.4
Middle@Langley	173	53	110	118	53	433	152	261	355	138	20.0	6.4	15.5	15.7	7.0	4.4	1.3	3.6	3.5	1.5
Reindeer Channel	175	39	83	60	55	462	112	180	342	134	21.4	5.9	12.6	16.1	7.1	4.2	1.3	2.6	3.4	1.3
Kipnik Channel	74	26	116	49	29	196	77	266	172	96	11.8	5.0	16.5	10.2	6.1	2.3	0.8	3.4	1.9	1.0
Crooked Channel	62	28	108	57	33	319	90	246	192	72	19.8	5.3	15.7	11.6	5.0	1.9	0.9	3.7	2.0	0.7
Napoiak Channel	99	29	58	67	28	554	83	133	235	106	30.0	4.6	9.5	11.9	6.8	2.6	1.0	1.9	2.4	1.0
Jamieson Channel	69	17	50	38	77	316	52	117	116	149	18.9	5.6	9.3	8.3	14.2	2.4	0.6	1.6	1.4	2.7
Hvatum Channel	129	26	56	53	214	753	62	125	152	361	48.2	6.9	9.8	10.3	32.3	3.7	1.0	1.7	1.9	6.4
West Channel	156	31	52	65	218	741	80	112	186	370	41.4	7.6	9.1	12.0	33.0	4.7	1.1	1.7	2.6	6.8

**Dates:* *04.1: 14-Jun-04* *04.2: 17-Jul-04* *04.3: 15-Aug-04* *03.1: 01-Aug-03* *03.2: 18-Aug-03*

DOM	Total Dissolved Organic Carbon					Coloured Dissolved Organic Matter (m^{-1})					Dissolved Organic Nitrogen					Dissolved Organic Phosphorus				
*Date**	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*
Inflow Transect																				
Mac@PS	443	274	256	382	395	14.5	5.1	6.5	-	-	9.3	3.8	1.5	13.1	10.3	B/D	0.01	B/D	0.10	B/D
Mac@ARR	425	273	267	380	386	12.9	4.7	6.3	-	-	8.5	3.5	3.3	10.5	9.4	B/D	B/D	B/D	0.08	B/D
Arctic Red River	269	99	111	152	201	6.6	1.3	3.4	-	-	2.9	B/D	B/D	4.1	5.4	B/D	B/D	0.07	B/D	B/D
Peel River	111	85	87	156	193	2.4	1.5	2.6	-	-	B/D	B/D	B/D	4.2	3.6	B/D	B/D	B/D	0.04	B/D
Middle Transect																				
Peel Channel	409	189	143	272	347	12.4	3.3	4.2	-	-	7.6	1.1	B/D	8.3	7.4	0.08	B/D	B/D	B/D	B/D
Aklavik Channel	367	249	242	370	370	12.7	4.6	5.6	-	-	7.4	3.9	2.8	10.7	9.5	0.05	B/D	B/D	0.04	B/D
Middle Channel	429	258	256	366	371	13.4	4.5	5.8	-	-	8.3	3.1	2.3	10.0	9.4	B/D	B/D	B/D	B/D	0.04
Kalinek Channel	510	297	277	411	391	17.7	4.7	6.1	-	-	11.1	4.6	4.6	11.5	9.5	B/D	B/D	B/D	0.10	0.14
East Channel@IN	561	310	339	419	437	21.5	5.6	8.0	-	-	12.8	5.5	5.5	11.0	10.6	0.09	B/D	B/D	0.06	0.05
Mouth Transect																				
Middle@Reindeer	462	271	258	384	400	16.3	4.6	6.2	-	-	7.2	4.7	4.0	10.5	9.6	B/D	B/D	B/D	B/D	B/D
East Channel	565	268	271	376	395	18.5	4.5	-	-	-	13.3	4.5	3.1	10.5	9.4	0.09	B/D	B/D	B/D	0.07
Middle@Langley	464	279	261	390	390	15.6	4.5	6.4	-	-	9.1	3.5	2.8	10.4	9.1	B/D	B/D	B/D	B/D	0.04
Reindeer Channel	467	324	260	378	388	15.3	4.4	6.4	-	-	8.6	5.0	3.3	11.1	9.2	B/D	B/D	B/D	B/D	B/D
Kipnik Channel	456	270	259	413	396	15.3	4.7	6.1	-	-	9.8	5.6	4.7	12.6	10.3	0.05	B/D	B/D	0.04	B/D
Crooked Channel	453	286	207	399	417	15.7	4.7	6.2	-	-	9.0	6.4	4.4	11.9	10.7	B/D	B/D	B/D	0.06	B/D
Napoiak Channel	467	270	262	392	390	14.5	4.8	6.1	-	-	9.3	5.0	4.0	11.2	11.1	0.09	B/D	B/D	0.07	B/D
Jamieson Channel	431	255	190	415	387	15.1	4.1	5.4	-	-	8.4	6.5	5.0	12.1	9.8	0.06	0.05	0.06	0.08	B/D
Hvatum Channel	436	217	219	348	365	13.2	3.6	6.1	-	-	8.2	2.5	3.6	10.4	7.8	B/D	B/D	B/D	B/D	B/D
West Channel	431	221	210	342	371	12.7	3.7	5.8	-	-	6.9	4.5	3.4	8.5	7.5	0.18	B/D	B/D	B/D	B/D

**Dates: 04.1: 14-Jun-04 04.2: 17-Jul-04 04.3: 15-Aug-04 03.1: 01-Aug-03 03.2: 18-Aug-03*

DISSOLVED INORGANICS	Nitrate					Ammonium					Phosphate					Silica				
*Date**	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*
Inflow Transect																				
Mac@PS	4.9	5.5	5.2	3.0	3.1	B/D	B/D	B/D	1.71	0.57	0.09	0.05	0.06	0.06	0.10	58	55	56	58	60
Mac@ARR	5.0	5.5	4.2	3.1	3.2	B/D	B/D	B/D	0.64	B/D	0.06	0.04	0.05	0.11	0.14	48	57	58	57	60
Arctic Red River	7.9	7.1	5.5	7.0	5.8	B/D	B/D	B/D	B/D	B/D	0.10	0.07	B/D	0.15	0.18	47	47	50	47	48
Peel River	8.1	7.1	7.3	5.6	4.7	B/D	B/D	B/D	B/D	B/D	0.10	0.10	0.10	0.16	0.20	52	50	52	55	52
Middle Transect																				
Peel Channel	5.4	7.7	6.9	5.4	4.9	0.50	1.03	B/D	0.64	0.57	0.18	0.06	0.08	0.14	0.36	43	47	54	53	52
Aklavik Channel	5.7	5.9	4.4	3.4	3.1	0.65	0.85	1.07	0.50	0.57	0.11	0.06	0.06	0.16	0.18	47	53	57	57	56
Middle Channel	5.1	5.7	5.1	3.0	2.8	B/D	B/D	B/D	0.93	B/D	0.08	0.09	0.06	0.15	0.12	57	55	58	58	60
Kalinek Channel	4.6	5.1	5.2	3.0	2.4	0.59	B/D	0.67	0.50	B/D	0.09	B/D	0.06	0.13	0.05	51	52	58	57	57
East Channel@IN	4.6	5.4	5.1	2.8	1.9	0.53	0.57	0.95	0.50	B/D	0.07	B/D	0.08	0.10	0.08	50	55	56	56	57
Mouth Transect																				
Middle@Reindeer	5.6	4.3	4.1	3.0	2.3	1.03	B/D	B/D	0.79	B/D	0.13	0.07	0.07	0.16	0.11	56	56	60	57	59
East Channel	4.8	4.3	4.5	3.0	2.9	B/D	B/D	B/D	1.14	0.57	0.07	0.08	0.08	0.22	0.12	50	56	60	58	58
Middle@Langley	5.6	4.2	4.4	3.1	2.8	1.18	B/D	B/D	1.14	B/D	0.14	0.08	0.09	0.16	0.12	55	58	60	57	59
Reindeer Channel	5.7	4.1	4.4	3.1	3.0	1.09	B/D	B/D	0.79	B/D	0.12	0.08	0.12	0.18	0.14	55	57	62	57	59
Kipnik Channel	5.1	4.4	3.9	2.6	2.3	1.06	0.75	0.76	0.50	B/D	0.11	0.04	0.06	0.12	0.13	51	54	61	54	54
Crooked Channel	4.4	4.2	4.0	2.6	1.9	0.65	0.66	1.34	0.50	B/D	0.14	0.05	0.06	0.13	0.12	49	55	58	54	55
Napoiak Channel	5.4	4.4	5.3	2.8	1.9	0.65	B/D	B/D	B/D	B/D	0.14	0.05	0.08	0.12	0.10	54	55	62	57	57
Jamieson Channel	5.6	3.7	4.8	3.3	2.5	1.09	B/D	B/D	B/D	0.57	0.17	0.04	B/D	0.14	0.18	42	51	53	53	48
Hvatum Channel	5.7	5.0	6.0	4.1	4.5	0.80	B/D	B/D	0.50	0.93	0.23	0.08	0.05	0.19	0.42	40	50	57	53	50
West Channel	5.7	4.9	6.4	4.4	4.5	0.68	0.54	B/D	0.64	1.21	0.18	0.06	0.06	0.25	0.39	38	48	59	54	52

**Dates: 04.1: 14-Jun-04 04.2: 17-Jul-04 04.3: 15-Aug-04 03.1: 01-Aug-03 03.2: 18-Aug-03*

COMPOSITE MEASURES	Total Nitrogen					Total Dissolved Nitrogen					Total Phosphorus					Total Dissolved Phosphorus				
*Date**	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*
Inflow Transect																				
Mac@PS	30.9	20.7	26.1	33.3	23.1	14.7	9.4	6.9	17.8	13.9	4.6	2.3	4.4	2.9	1.7	0.10	0.06	0.03	0.16	0.13
Mac@ARR	32.0	22.5	32.7	28.2	21.1	13.8	9.1	7.7	14.3	12.9	4.1	2.7	4.0	3.1	1.7	0.10	0.03	0.03	0.19	0.13
Arctic Red River	11.1	5.9	16.2	20.9	73.6	11.1	3.5	3.9	11.1	11.4	2.5	0.5	2.9	2.6	13.9	0.10	0.10	0.06	0.16	0.10
Peel River	23.4	11.3	22.3	16.8	19.1	6.7	4.1	2.6	10.0	8.6	6.0	1.4	3.9	1.7	2.4	0.03	0.06	0.06	0.19	0.13
Middle Transect																				
Peel Channel	49.3	15.8	13.0	25.2	34.3	13.6	9.8	6.9	14.3	12.9	4.8	1.1	1.4	2.5	4.9	0.26	0.03	0.03	0.16	0.26
Aklavik Channel	58.0	16.1	17.6	25.0	21.8	13.8	10.7	8.3	14.6	13.2	3.7	1.1	1.9	2.2	1.7	0.16	0.06	0.03	0.19	0.16
Middle Channel	38.1	22.9	17.0	25.5	21.1	13.8	9.1	7.7	13.9	12.5	4.0	2.7	1.6	2.4	1.8	0.06	0.10	0.03	0.16	0.16
Kalinek Channel	41.5	14.2	19.5	25.0	18.3	16.3	10.1	10.4	15.0	12.1	1.9	0.7	1.5	1.9	1.3	0.10	0.03	0.06	0.23	0.19
East Channel@IN	39.6	15.4	21.6	24.1	17.9	17.9	11.5	11.6	14.3	12.9	2.2	0.8	1.8	2.0	0.3	0.16	0.06	0.06	0.16	0.13
Mouth Transect																				
Middle@Reindeer	50.7	16.2	20.4	33.7	21.1	13.9	9.4	8.5	14.3	12.1	4.9	1.5	2.5	4.3	1.6	0.10	0.06	0.06	0.19	0.13
East Channel	28.3	14.5	21.9	30.6	20.2	18.6	9.1	7.9	14.6	12.9	2.4	1.2	2.8	3.5	1.6	0.16	0.06	0.06	0.19	0.19
Middle@Langley	35.8	14.4	23.2	30.3	19.1	15.8	8.0	7.7	14.6	12.1	4.5	1.4	3.6	3.7	1.6	0.13	0.06	0.03	0.19	0.16
Reindeer Channel	36.8	15.3	20.8	31.1	19.6	15.3	9.4	8.1	15.0	12.5	4.3	1.4	2.6	3.6	1.4	0.13	0.10	0.06	0.16	0.13
Kipnik Channel	27.8	15.7	25.9	25.9	18.9	16.0	10.7	9.4	15.7	12.9	2.4	0.9	3.4	2.0	1.1	0.16	0.06	0.06	0.16	0.13
Crooked Channel	33.8	16.5	25.4	26.6	17.8	14.1	11.2	9.7	15.0	12.9	2.1	1.0	3.7	2.2	0.8	0.13	0.06	0.03	0.19	0.13
Napoiak Channel	45.3	14.3	19.4	26.2	20.0	15.3	9.8	9.9	14.3	13.2	2.8	1.1	2.0	2.6	1.2	0.23	0.06	0.10	0.19	0.13
Jamieson Channel	34.0	16.1	19.6	24.0	27.1	15.1	10.6	10.3	15.7	12.9	2.6	0.7	1.7	1.6	2.8	0.23	0.10	0.10	0.23	0.13
Hvatum Channel	62.9	14.8	19.8	25.3	45.5	14.7	8.0	10.0	15.0	13.2	4.0	1.0	1.8	2.1	6.7	0.26	0.03	0.06	0.19	0.32
West Channel	54.7	17.5	19.2	25.6	46.2	13.3	9.9	10.1	13.6	13.2	5.0	1.2	1.8	2.9	7.2	0.36	0.06	0.06	0.23	0.36

**Dates: 04.1: 14-Jun-04 04.2: 17-Jul-04 04.3: 15-Aug-04 03.1: 01-Aug-03 03.2: 18-Aug-03*

OTHER MEASURES	Sulphate					Chloride					Total Organic Carbon					Dissolved Inorganic Carbon				
*Date**	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*	*04.1*	*04.2*	*04.3*	*03.1*	*03.2*
Inflow Transect																				
Mac@PS	352	451	515	378	368	179	242	279	195	213	810	526	519	683	554	-	-	-	1831	1928
Mac@ARR	353	433	527	374	368	182	238	288	205	214	878	564	629	673	557	-	-	-	1803	1928
Arctic Red	1144	1739	1246	1147	1088	20	22	16	16	17	-	139	372	372	2047	-	-	-	2412	2432
Peel River	676	930	955	694	722	41	71	72	56	55	433	186	320	266	347	-	-	-	2611	2514
Middle Transect																				
Peel Ch.	508	898	1004	684	735	35	69	62	53	49	1014	259	215	427	606	-	-	-	2283	1958
Aklavik Ch.	439	519	581	443	497	89	215	266	176	157	1079	339	386	556	479	-	-	-	1961	1946
Middle Ch.	369	437	477	373	368	166	236	274	189	204	953	547	417	599	548	-	-	-	1834	1940
Kalinek Ch.	313	414	476	356	392	182	214	268	191	221	1021	367	388	568	500	-	-	-	1856	1910
East Ch.@IN	294	430	431	351	350	185	240	259	197	192	916	376	475	599	512	-	-	-	1750	1875
Mouth Transect																				
Middle@RC	343	446	525	370	379	167	234	277	195	212	1211	446	458	817	567	-	-	-	1772	1907
East Ch.	291	448	522	363	365	227	223	274	186	218	712	385	493	715	530	-	-	-	1818	1919
Middle@LGY	343	445	517	384	378	170	228	274	187	224	897	431	522	745	528	-	-	-	1796	1919
Reindeer Ch.	342	443	518	364	404	170	229	275	195	228	929	437	441	720	522	-	-	-	1828	1916
Kipnik Ch.	310	437	532	372	378	185	229	292	204	243	652	347	525	585	492	-	-	-	1890	1872
Crooked Ch.	296	433	532	376	377	221	229	284	199	244	772	376	453	591	489	-	-	-	1809	1931
Napoiak Ch.	331	452	490	377	376	169	234	267	199	214	1020	353	395	627	496	-	-	-	1806	1830
Jamieson Ch.	363	538	732	445	525	119	174	182	152	151	747	306	307	531	536	-	-	-	1961	1910
Hvatum Ch.	431	738	822	560	646	53	121	127	103	90	1189	279	344	500	726	-	-	-	2192	1833
West Ch.	424	733	825	584	605	50	119	122	93	77	1172	301	322	528	741	-	-	-	2020	1901

**Dates: 04.1: 14-Jun-04 04.2: 17-Jul-04 04.3: 15-Aug-04 03.1: 01-Aug-03 03.2: 18-Aug-03*

WEEKLY RIVER AND LAKE RAW DATA (all data in µmol/L unless stated otherwise)

PARTICULATES	Total Suspended Solids (mg/L)			Particulate Organic Carbon			Particulate Nitrogen			Particulate Organic Phosphorus		
Rivers	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*
19-May-04	14	-	-	70	-	-	5.3	-	-	0.7	-	-
27-May-04	858	-	-	1624	-	-	97.1	-	-	10.7	-	-
02-Jun-04	228	-	-	598	-	-	31.1	-	-	6.1	-	-
10-Jun-04	172	180	123	448	562	358	22.3	25.0	17.4	4.8	6.3	4.3
17-Jun-04	112	123	56	522	713	403	26.4	32.4	20.4	2.7	3.5	2.4
24-Jun-04	128	42	45	351	137	117	15.1	6.0	6.7	3.2	1.2	1.4
29-Jun-04	125	28	30	341	110	83	14.4	4.3	5.1	3.1	0.9	1.1
07-Jul-04	120	248	94	346	866	225	12.9	34.3	13.3	3.0	4.0	3.0
14-Jul-04	64	46	26	193	173	68	8.6	7.9	5.3	1.7	1.5	1.0
22-Jul-04	128	15	27	306	62	80	19.2	4.9	6.6	4.2	0.6	1.0
26-Jul-04	41	12	41	11	58	94	6.2	4.3	7.6	1.1	0.5	1.3
09-Aug-04	149	72	50	328	210	115	22.8	11.5	8.4	4.8	2.3	1.5
Lakes	No Closure	Low Closure	High Closure	No Closure	Low Closure	High Closure	No Closure	Low Closure	High Closure	No Closure	Low Closure	High Closure
03-Jun-04	47	36	35	122	137	164	10.3	10.6	13.8	1.4	1.5	1.5
08-Jun-04	17	15	12	113	93	53	11.4	7.3	5.9	0.6	0.9	0.6
16-Jun-04	11	6	5	127	142	104	12.5	15.0	12.0	0.5	0.6	0.3
22-Jun-04	9	5	5	145	60	88	14.0	5.8	9.8	0.5	0.7	0.4
01-Jul-04	5	6	3	67	52	44	6.7	5.5	4.5	0.4	0.3	0.2
06-Jul-04	12	8	6	72	73	63	5.6	7.0	5.8	0.5	0.5	0.4
12-Jul-04	8	7	3	57	47	44	5.6	4.6	3.9	0.4	0.4	0.3
19-Jul-04	13	4	9	65	57	59	5.4	6.2	5.9	0.5	0.3	0.4
07-Jul-04	6	2	2	43	33	30	4.9	4.0	3.4	0.3	0.2	0.2

DOM	Total Dissolved Organic Carbon			Coloured Dissolved Organic Matter (m^{-1})			Dissolved Organic Nitrogen			Dissolved Organic Phosphorus		
Rivers	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*
19-May-04	324	-	-	4.1	-	-	11.9	-	-	B/D	-	-
27-May-04	535	-	-	14.7	-	-	10.9	-	-	0.06	-	-
02-Jun-04	555	-	-	17.9	-	-	11.0	-	-	0.08	-	-
10-Jun-04	478	108	359	17.2	8.2	11.4	8.6	3.4	8.7	B/D	-	0.20
17-Jun-04	370	215	202	10.2	3.4	4.2	5.2	B/D	10.1	B/D	-	-
24-Jun-04	292	131	128	7.1	1.8	2.2	3.3	B/D	11.0	B/D	B/D	B/D
29-Jun-04	272	116	149	4.4	1.7	2.0	3.3	B/D	7.7	B/D	-	-
07-Jul-04	253	370	102	5.4	4.9	3.1	3.1	9.0	7.3	B/D	B/D	B/D
14-Jul-04	276	92	143	5.4	1.5	2.4	4.7	B/D	7.5	B/D	B/D	B/D
22-Jul-04	240	93	106	4.2	1.2	1.3	2.4	B/D	5.7	B/D	B/D	B/D
26-Jul-04	238	97	76	3.3	1.3	0.9	2.6	B/D	7.2	B/D	B/D	B/D
09-Aug-04	277	201	127	6.4	6.5	3.7	3.5	B/D	4.5	B/D	B/D	B/D
Lakes	*No Closure*	*Low Closure*	*High Closure*	*No Closure*	*Low Closure*	*High Closure*	*No Closure*	*Low Closure*	*High Closure*	*No Closure*	*Low Closure*	*High Closure*
03-Jun-04	511	544	514	-	-	-	12.5	12.8	14.5	0.13	0.09	0.10
08-Jun-04	514	537	626	16.2	-	-	-	-	-	-	-	-
16-Jun-04	557	580	727	-	-	-	-	-	-	-	-	-
22-Jun-04	572	599	806	14.3	13.8	10.5	-	-	-	-	-	-
01-Jul-04	529	642	877	13.5	12.7	11.3	16.5	21.5	34.4	0.18	0.20	0.24
06-Jul-04	559	637	920	12.1	11.3	10.9	-	-	-	-	-	-
12-Jul-04	545	654	913	11.6	10.5	10.5	-	-	-	-	-	-
19-Jul-04	542	658	926	12.2	11.6	11.7	-	-	-	-	-	-
07-Jul-04	420	655	959	8.6	10.6	11.9	13.2	24.5	38.2	0.08	0.13	0.18

DISSOLVED INORGANICS	Nitrate			Ammonium			Phosphate			Silica		
Rivers	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*
19-May-04	7.3	-	-	1.02	-	-	0.06	-	-	59	-	-
27-May-04	5.0	-	-	0.84	-	-	0.29	-	-	47	-	-
02-Jun-04	5.2	-	-	B/D	-	-	0.11	-	-	52	-	-
10-Jun-04	4.9	7.0	4.8	B/D	B/D	-	0.08	0.04	B/D	55	40	43
17-Jun-04	5.2	8.3	7.5	B/D	B/D	B/D	B/D	B/D	0.09	58	43	50
24-Jun-04	5.7	7.7	6.8	B/D	B/D	B/D	0.04	0.05	0.08	59	47	49
29-Jun-04	5.7	7.7	6.6	B/D	B/D	B/D	0.08	0.10	0.08	58	49	52
07-Jul-04	5.6	7.5	6.9	B/D	0.76	B/D	0.08	0.07	0.08	62	49	50
14-Jul-04	4.8	7.3	6.9	B/D	B/D	B/D	0.06	0.06	0.12	58	47	52
22-Jul-04	6.8	7.5	8.8	B/D	B/D	B/D	0.10	0.04	0.06	61	44	53
26-Jul-04	6.7	4.1	7.4	B/D	B/D	B/D	0.04	B/D	0.07	62	43	53
09-Aug-04	5.6	7.9	7.5	0.12	B/D	B/D	0.07	0.04	0.07	60	49	56
Lakes	No Closure	Low Closure	High Closure	No Closure	Low Closure	High Closure	No Closure	Low Closure	High Closure	No Closure	Low Closure	High Closure
03-Jun-04	4.8	4.5	2.2	1.51	1.17	2.01	0.09	0.10	0.05	44	38	27
08-Jun-04	4.3	3.8	1.7	0.95	1.60	3.04	0.08	0.06	B/D	42	40	40
16-Jun-04	3.8	B/D	B/D	B/D	B/D	0.70	0.06	0.04	B/D	50	44	38
22-Jun-04	B/D	B/D	B/D	0.71	B/D	0.75	0.05	B/D	B/D	51	40	26
01-Jul-04	B/D	B/D	B/D	B/D	B/D	0.90	B/D	B/D	B/D	50	31	21
06-Jul-04	B/D	B/D	B/D	B/D	B/D	1.38	B/D	B/D	B/D	48	23	20
12-Jul-04	B/D	B/D	B/D	B/D	B/D	0.73	B/D	B/D	B/D	46	14	21
19-Jul-04	B/D	B/D	B/D	0.72	B/D	1.42	B/D	B/D	B/D	40	8	19
07-Jul-04	B/D	B/D	B/D	B/D	B/D	1.00	B/D	B/D	B/D	37	5	26

OTHER MEASURES	Sulphate			Chloride			Total Organic Carbon			Dissolved Inorganic Nitrogen		
Rivers	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*	*MAC@ARR*	*ARR*	*PR*
19-May-04	432	-	-	355	-	-	294	-	-	8.3	-	-
27-May-04	307	-	-	190	-	-	2158	-	-	5.8	-	-
02-Jun-04	315	-	-	177	-	-	1153	-	-	5.4	-	-
10-Jun-04	329	861	309	161	23	21	925	670	717	5.1	7.3	-
17-Jun-04	367	1284	659	172	20	42	891	928	605	5.4	8.3	7.5
24-Jun-04	367	1388	726	151	16	46	643	268	245	6.0	7.9	7.1
29-Jun-04	385	1508	785	166	18	51	614	226	232	6.0	8.0	6.8
07-Jul-04	382	1384	830	186	55	65	598	1236	326	5.8	8.2	7.2
14-Jul-04	439	1649	869	235	18	65	469	265	211	4.8	7.5	7.2
22-Jul-04	453	1714	899	240	26	75	545	155	186	6.9	7.5	8.8
26-Jul-04	453	1743	811	264	28	67	349	156	171	6.7	4.1	7.4
09-Aug-04	505	1315	948	286	19	61	605	411	243	5.7	8.2	7.5
Lakes	No Closure	Low Closure	High Closure	No Closure	Low Closure	High Closure	No Closure	Low Closure	High Closure	No Closure	Low Closure	High Closure
03-Jun-04	310	258	135	212	174	106	633	681	678	6.3	5.6	4.2
08-Jun-04	288	239	111	189	169	155	641	639	749	5.3	5.4	4.7
16-Jun-04	301	237	107	197	181	191	684	722	831	4.1	0.1	0.7
22-Jun-04	299	224	95	203	205	202	717	659	894	0.7	0.2	0.8
01-Jul-04	324	213	77	211	213	201	596	694	921	0.2	0.0	0.9
06-Jul-04	313	198	74	207	222	215	631	710	983	0.1	0.3	1.4
12-Jul-04	320	204	70	214	223	223	602	700	957	0.1	0.2	0.7
19-Jul-04	310	193	62	213	213	212	607	715	985	0.7	B/D	1.4
07-Jul-04	379	206	55	237	219	229	463	688	989	B/D	0.1	1.0

MASS BALANCE SURVEY RAW DATA all data in µmol/L unless stated otherwise)

	PARTICULATES				DISSOLVED ORGANICS				DISSOLVED INORGANICS			
	TSS (mg/L)	POC	PN	PP	TDOC	CDOC (m^{-1})	DON	DOP	Nitrate	Ammonium	Phosphate	Silica
UPSTREAM												
INT-1	65	144	8.3	1.7	259	4.7	5.3	B/D	4.9	B/D	0.04	57
INT-2	67	161	9.0	1.8	283	4.9	5.3	B/D	5.1	B/D	0.05	57
INT-3	75	180	10.2	1.7	280	5.0	5.3	B/D	4.9	B/D	0.04	59
GRAB-1	53	119	7.1	1.6	293	4.6	5.5	B/D	4.9	B/D	B/D	57
GRAB-2	56	128	7.6	1.5	280	4.8	5.8	B/D	4.9	B/D	B/D	58
GRAB-3	66	153	9.0	1.6	286	4.3	4.8	B/D	5.0	B/D	0.04	55
INUVIK												
INT-1	36	97	6.2	1.0	311	6.0	7.5	B/D	4.6	B/D	0.04	54
INT-2	34	94	5.9	1.0	307	6.1	7.6	0.05	4.5	B/D	0.04	54
INT-3	34	94	6.4	1.0	295	6.3	7.8	0.05	4.4	B/D	0.05	51
GRAB-1	33	89	5.9	1.0	311	6.3	7.3	B/D	4.2	B/D	0.06	53
GRAB-2	29	80	5.5	0.9	296	5.5	6.8	B/D	4.6	B/D	0.06	51
GRAB-3	28	78	5.2	0.9	313	6.2	7.5	0.04	4.3	B/D	0.05	53
DOWNSTREAM												
INT-1	36	103	6.9	1.0	305	5.6	7.4	B/D	4.7	B/D	0.04	54
INT-2	38	105	6.9	1.0	318	5.0	6.9	B/D	4.6	B/D	0.04	55
INT-3	33	94	6.4	1.0	312	5.5	7.1	B/D	4.5	B/D	0.05	55
GRAB-1	37	100	6.7	1.0	296	5.2	6.2	B/D	4.8	B/D	0.05	55
GRAB-2	29	83	5.7	1.0	303	6.5	7.6	B/D	4.5	B/D	0.05	55
GRAB-3	31	86	5.7	0.9	288	5.7	6.7	B/D	4.7	B/D	0.04	55

20-Jul-04	COMPOSITE MEASURES				OTHER MEASURES			
	TN	TDN	TP	TDP	Sulphate	Chloride	TOC	DIN
UPSTREAM								
INT-1	18.6	10.3	1.8	B/D	433	220	403	5.0
INT-2	19.6	10.6	1.9	B/D	450	230	444	5.2
INT-3	20.5	10.3	1.8	B/D	437	224	460	4.9
GRAB-1	17.6	10.4	1.6	B/D	438	228	412	4.9
GRAB-2	18.3	10.7	1.5	B/D	431	223	408	4.9
GRAB-3	18.8	9.8	1.6	B/D	443	224	439	5.0
INUVIK								
INT-1	18.3	12.1	1.0	0.06	410	241	409	4.6
INT-2	18.1	12.1	1.1	0.10	402	243	402	4.5
INT-3	18.6	12.1	1.1	0.10	412	258	390	4.4
GRAB-1	17.4	11.5	1.0	B/D	377	220	399	4.2
GRAB-2	16.8	11.4	0.9	0.06	413	252	377	4.6
GRAB-3	17.1	11.9	1.0	0.10	407	250	390	4.3
DOWNSTREAM								
INT-1	19.0	12.1	1.0	B/D	422	244	407	4.7
INT-2	18.4	11.5	1.0	0.06	417	257	424	4.6
INT-3	18.1	11.6	1.0	B/D	407	253	407	4.5
GRAB-1	17.7	11.0	1.0	B/D	429	247	396	4.8
GRAB-2	17.8	12.1	1.0	0.06	416	253	386	4.5
GRAB-3	17.1	11.4	0.9	0.06	419	245	374	4.7

SURVEY STATISTICS			
Statistic	Upstream	Inuvik	Downstream
Channel Width (m)	213.5	139.9	129.5
Cross-sectional Area (m^2)	977.6	584.2	614.4
Mean Velocity (m/s)	0.267	0.276	0.198
Discharge (m^3/s)	260	161	122
Water Temperature (°C)	17.3	17.5	17.9
Maximum Velocity (m/s)	0.619	1.240	0.598
Maximum Depth (m)	6.9	7.9	11.7
Mean Depth (m)	4.58	4.18	4.75

Appendix B: Daily discharge from delta inflow rivers 2003-2004

MACKENZIE RIVER ABOVE ARCTIC RED RIVER-STATION [10LC014] (FROM WATER SURVEY OF CANADA)

Jan 2003	m^3/s	Feb 2003	m^3/s	Mar 2003	m^3/s	Apr 2003	m^3/s	May 2003	m^3/s	Jun 2003	m^3/s
1	4090	1	3580	1	3400	1	3470	1	4400	1	26800
2	4080	2	3570	2	3400	2	3470	2	5260	2	26500
3	4060	3	3570	3	3400	3	3480	3	6850	3	25800
4	4040	4	3560	4	3400	4	3480	4	8330	4	24500
5	4030	5	3560	5	3400	5	3480	5	9440	5	23300
6	4020	6	3550	6	3400	6	3490	6	10100	6	22900
7	4000	7	3540	7	3400	7	3490	7	10400	7	21700
8	3980	8	3530	8	3400	8	3500	8	10500	8	22100
9	3960	9	3520	9	3400	9	3500	9	10600	9	22800
10	3950	10	3510	10	3400	10	3500	10	10800	10	23200
11	3930	11	3500	11	3400	11	3510	11	10900	11	22800
12	3910	12	3490	12	3400	12	3520	12	11000	12	22200
13	3900	13	3480	13	3400	13	3530	13	11000	13	21500
14	3880	14	3470	14	3400	14	3540	14	11500	14	20800
15	3850	15	3460	15	3400	15	3550	15	12100	15	20100
16	3830	16	3450	16	3410	16	3570	16	12600	16	19800
17	3800	17	3450	17	3410	17	3580	17	13300	17	19600
18	3780	18	3440	18	3410	18	3600	18	14300	18	19500
19	3760	19	3430	19	3410	19	3620	19	15200	19	19600
20	3740	20	3420	20	3420	20	3630	20	15900	20	19600
21	3720	21	3410	21	3420	21	3650	21	17100	21	19500
22	3700	22	3410	22	3420	22	3680	22	18000	22	19400
23	3690	23	3410	23	3430	23	3710	23	19000	23	19300
24	3670	24	3410	24	3430	24	3730	24	20000	24	19300
25	3650	25	3400	25	3430	25	3760	25	21000	25	19200
26	3630	26	3400	26	3440	26	3810	26	22000	26	19200
27	3620	27	3400	27	3440	27	3870	27	24000	27	19200
28	3610	28	3400	28	3450	28	3960	28	25000	28	19100
29	3600			29	3450	29	4090	29	25500	29	19100
30	3590			30	3450	30	4200	30	26000	30	19100
31	3580			31	3460			31	26300		

Jul 2003	m^3/s	Aug 2003	m^3/s	Sep 2003	m^3/s	Oct 2003	m^3/s	Nov 2003	m^3/s	Dec 2003	m^3/s
1	19000	1	15500	1	12200	1	10100	1	8500	1	3150
2	18600	2	15300	2	11800	2	10000	2	8350	2	3050
3	18100	3	15000	3	11500	3	10000	3	8250	3	2980
4	17800	4	14900	4	11300	4	10100	4	8150	4	2850
5	17200	5	14600	5	11200	5	10400	5	8000	5	2800
6	16900	6	14500	6	11100	6	10600	6	7800	6	2750
7	17200	7	14600	7	11000	7	10500	7	7650	7	2700
8	17200	8	15800	8	11000	8	10500	8	7500	8	2650
9	17500	9	14900	9	10700	9	10700	9	7350	9	2630
10	18200	10	14500	10	10500	10	10700	10	7150	10	2600
11	19100	11	14000	11	10500	11	10700	11	7000	11	2630
12	19800	12	13600	12	10600	12	10700	12	6800	12	2700
13	20100	13	13400	13	10900	13	10600	13	6600	13	2800
14	20100	14	13100	14	11200	14	10600	14	6400	14	2900
15	19900	15	12800	15	11100	15	10500	15	6200	15	3020
16	19600	16	12800	16	11300	16	10400	16	6000	16	3380
17	19200	17	12500	17	11900	17	10200	17	5850	17	3700
18	19300	18	12400	18	11800	18	10100	18	5650	18	3950
19	19200	19	12400	19	11500	19	9900	19	5450	19	4150
20	19200	20	12400	20	11400	20	9740	20	5300	20	4330
21	19100	21	12400	21	11400	21	9660	21	5100	21	4490
22	18800	22	12400	22	11400	22	9560	22	4870	22	4640
23	18300	23	12500	23	11100	23	9480	23	4740	23	4790
24	18000	24	12400	24	10900	24	9290	24	4570	24	4930
25	17600	25	12600	25	10800	25	9190	25	4370	25	5070
26	17400	26	12600	26	10600	26	9150	26	4140	26	5170
27	17100	27	12800	27	10500	27	8970	27	3900	27	5220
28	16800	28	12700	28	10400	28	8900	28	3650	28	5230
29	16500	29	12600	29	10200	29	8820	29	3320	29	5200
30	16300	30	12500	30	10100	30	8750	30	3250	30	5130
31	15900	31	12300			31	8670			31	5060

Jan 2004	m^3/s	Feb 2004	m^3/s	Mar 2004	m^3/s	Apr 2004	m^3/s	May 2004	m^3/s	Jun 2004	m^3/s
1	5010	1	4860	1	4220	1	3780	1	4420	1	24900
2	4990	2	4840	2	4190	2	3770	2	4480	2	23700
3	5000	3	4820	3	4170	3	3760	3	4550	3	23000
4	5040	4	4800	4	4160	4	3750	4	4660	4	22500
5	5100	5	4780	5	4140	5	3720	5	4840	5	22000
6	5200	6	4760	6	4120	6	3700	6	5080	6	21500
7	5280	7	4720	7	4110	7	3680	7	5400	7	21000
8	5340	8	4700	8	4090	8	3660	8	5770	8	20600
9	5360	9	4660	9	4080	9	3680	9	6160	9	20300
10	5370	10	4600	10	4080	10	3690	10	6340	10	20000
11	5380	11	4560	11	4080	11	3680	11	6590	11	19800
12	5380	12	4530	12	4080	12	3660	12	6940	12	19600
13	5370	13	4510	13	4090	13	3640	13	7320	13	19300
14	5350	14	4480	14	4070	14	3620	14	7640	14	18900
15	5330	15	4470	15	4050	15	3600	15	7820	15	18600
16	5270	16	4460	16	4010	16	3600	16	7860	16	18300
17	5220	17	4450	17	3970	17	3640	17	7960	17	18300
18	5170	18	4440	18	3930	18	3650	18	8570	18	18300
19	5110	19	4430	19	3890	19	3660	19	9280	19	18100
20	5070	20	4420	20	3840	20	3670	20	10100	20	17900
21	5020	21	4400	21	3810	21	3710	21	11100	21	17700
22	4970	22	4390	22	3800	22	3780	22	13000	22	17400
23	4930	23	4370	23	3800	23	3860	23	16400	23	17200
24	4910	24	4350	24	3780	24	3940	24	18000	24	16900
25	4900	25	4320	25	3770	25	4010	25	19300	25	16700
26	4880	26	4300	26	3760	26	4080	26	22000	26	16300
27	4870	27	4290	27	3750	27	4130	27	24000	27	16000
28	4870	28	4260	28	3750	28	4200	28	26000	28	15800
29	4870			29	3750	29	4260	29	28000	29	15600
30	4870			30	3770	30	4330	30	30000	30	15400
31	4870			31	3790			31	29000		

Jul 2004	m^3/s	Aug 2004	m^3/s	Sep 2004	m^3/s	Oct 2004	m^3/s	Nov 2004	m^3/s	Dec 2004	m^3/s
1	15200	1	11900	1	8660	1	8680	1	5700	1	2830
2	14900	2	12300	2	8820	2	8520	2	5500	2	2800
3	14700	3	12500	3	8920	3	8370	3	5150	3	2780
4	14300	4	12400	4	8880	4	8260	4	4740	4	2750
5	14300	5	12100	5	8870	5	8370	5	4650	5	2730
6	14100	6	11700	6	8790	6	8520	6	4730	6	2750
7	13700	7	11400	7	8720	7	8540	7	4730	7	2800
8	13400	8	11200	8	8770	8	8440	8	4660	8	2830
9	12900	9	11100	9	8850	9	8380	9	4650	9	2850
10	12800	10	11000	10	8930	10	8400	10	4690	10	2900
11	12600	11	10900	11	8970	11	8430	11	4760	11	2930
12	12500	12	10800	12	8940	12	8360	12	4780	12	2960
13	12500	13	10500	13	8830	13	8370	13	4780	13	3000
14	12700	14	10600	14	8740	14	8290	14	4800	14	3070
15	12800	15	10600	15	8600	15	8300	15	4400	15	3140
16	12900	16	10500	16	8560	16	8220	16	4410	16	3210
17	12900	17	10200	17	8470	17	8150	17	4420	17	3290
18	12700	18	10100	18	8440	18	8090	18	4350	18	3360
19	12500	19	9900	19	8450	19	8000	19	4250	19	3430
20	12400	20	9720	20	8510	20	7740	20	4100	20	3500
21	12300	21	9450	21	8580	21	7430	21	3900	21	3600
22	12100	22	9150	22	8550	22	7120	22	3500	22	3800
23	11800	23	8990	23	8480	23	7090	23	3350	23	4000
24	11700	24	8930	24	8360	24	6900	24	3250	24	4300
25	11600	25	8730	25	8340	25	6780	25	3150	25	4400
26	11400	26	8630	26	8400	26	6650	26	3100	26	4430
27	11300	27	8550	27	8370	27	6500	27	3000	27	4420
28	11300	28	8450	28	8440	28	6400	28	2950	28	4410
29	11600	29	8440	29	8650	29	6250	29	2900	29	4400
30	11500	30	8630	30	8730	30	6100	30	2870	30	4380
31	11500	31	8640			31	5900			31	4360

ARCTIC RED RIVER AT MOUTH-STATION [10LA002] (FROM WATER SURVEY OF CANADA)

Jan 2003	m^3/s	Feb 2003	m^3/s	Mar 2003	m^3/s	Apr 2003	m^3/s	May 2003	m^3/s	Jun 2003	m^3/s
1	21.4	1	18.3	1	20	1	19.7	1	60	1	655
2	21.2	2	18.4	2	20	2	19.7	2	100	2	749
3	21	3	18.7	3	20	3	19.8	3	85	3	785
4	20.9	4	18.9	4	20	4	19.8	4	75	4	638
5	20.9	5	18.6	5	20	5	19.8	5	68	5	585
6	20.9	6	18.5	6	19.9	6	19.9	6	63	6	535
7	20.9	7	18.9	7	19.9	7	19.9	7	60	7	504
8	20.8	8	19.1	8	19.9	8	20	8	42.8	8	598
9	20.8	9	19.4	9	19.9	9	20.1	9	40.7	9	696
10	20.8	10	19.7	10	19.6	10	20.2	10	40.1	10	633
11	20.8	11	19.9	11	19.6	11	20.3	11	45.6	11	590
12	20.7	12	20.3	12	19.4	12	20.4	12	70	12	534
13	20.7	13	20.4	13	19.3	13	20.5	13	95	13	438
14	20.2	14	20.4	14	19.3	14	20.6	14	200	14	315
15	20.3	15	20.3	15	19.3	15	20.7	15	460	15	258
16	20.7	16	20.3	16	19.3	16	20.8	16	440	16	230
17	20.8	17	20.1	17	19.4	17	21	17	420	17	229
18	20.7	18	19.8	18	19.4	18	21.1	18	460	18	270
19	20.5	19	20.2	19	19.3	19	21.2	19	520	19	325
20	20	20	20.4	20	19.3	20	21.4	20	600	20	360
21	19.8	21	20.4	21	19.3	21	21.6	21	700	21	405
22	19.6	22	20.4	22	19.3	22	21.7	22	800	22	339
23	19.4	23	19.9	23	19.3	23	21.8	23	777	23	320
24	19.2	24	19.9	24	19.4	24	21.9	24	683	24	299
25	19	25	20.2	25	19.4	25	21.5	25	663	25	266
26	18.8	26	20.1	26	19.4	26	22	26	626	26	261
27	18.5	27	20	27	19.5	27	22.2	27	523	27	295
28	18.3	28	20	28	19.5	28	22.6	28	579	28	372
29	18.2			29	19.6	29	24	29	735	29	553
30	18.2			30	19.6	30	28	30	756	30	454
31	18.6			31	19.7			31	700		

Jul 2003	m^3/s	Aug 2003	m^3/s	Sep 2003	m^3/s	Oct 2003	m^3/s	Nov 2003	m^3/s	Dec 2003	m^3/s
1	357	1	212	1	187	1	102	1	53.7	1	29.1
2	318	2	247	2	188	2	158	2	54.2	2	28.3
3	296	3	299	3	195	3	231	3	54.3	3	27.7
4	277	4	268	4	190	4	264	4	54.2	4	27.5
5	405	5	242	5	187	5	259	5	54	5	27.6
6	561	6	234	6	189	6	253	6	53.3	6	27.6
7	408	7	222	7	184	7	238	7	52.5	7	27.7
8	330	8	218	8	176	8	226	8	51.3	8	27.9
9	301	9	218	9	168	9	221	9	50.3	9	28.1
10	278	10	219	10	164	10	214	10	48	10	28.4
11	264	11	210	11	165	11	207	11	46	11	28.7
12	271	12	193	12	160	12	193	12	44.2	12	29.1
13	398	13	183	13	156	13	185	13	41	13	29.4
14	387	14	184	14	163	14	176	14	38	14	29.6
15	423	15	250	15	174	15	160	15	33	15	29.9
16	424	16	284	16	160	16	143	16	28	16	30.4
17	429	17	254	17	149	17	111	17	26.5	17	30.9
18	479	18	237	18	142	18	100	18	25.6	18	31.3
19	559	19	255	19	141	19	96.9	19	25.2	19	31.6
20	498	20	424	20	136	20	91.8	20	25.6	20	32
21	375	21	465	21	131	21	82.9	21	26.3	21	32.4
22	314	22	466	22	129	22	78	22	27	22	32.9
23	311	23	420	23	129	23	76	23	28	23	33.3
24	345	24	359	24	125	24	70	24	29.3	24	33.4
25	339	25	327	25	120	25	62.3	25	30.6	25	33.3
26	297	26	300	26	115	26	58	26	31.3	26	33.1
27	266	27	269	27	115	27	57	27	31.6	27	32.9
28	245	28	244	28	112	28	56	28	31.5	28	32.6
29	231	29	226	29	99.5	29	55	29	30.7	29	32.3
30	216	30	212	30	93.5	30	54	30	29.8	30	31.9
31	207	31	199			31	52.3			31	31.5

Jan 2004	m^3/s	Feb 2004	m^3/s	Mar 2004	m^3/s	Apr 2004	m^3/s	May 2004	m^3/s	Jun 2004	m^3/s
1	31	1	23	1	19.2	1	17.5	1	25.2	1	595
2	30	2	22.8	2	19.1	2	17.5	2	29.2	2	686
3	29.5	3	22.6	3	19	3	17.6	3	35	3	683
4	29	4	22.5	4	18.9	4	17.7	4	37.9	4	738
5	28.6	5	22.3	5	18.8	5	17.8	5	37.9	5	767
6	28.4	6	22.2	6	18.7	6	17.8	6	33.7	6	689
7	28.2	7	22	7	18.6	7	17.8	7	30.2	7	677
8	27.5	8	21.9	8	18.5	8	17.7	8	27.3	8	611
9	28.2	9	21.7	9	18.4	9	17.9	9	25.7	9	517
10	28.1	10	21.6	10	18.3	10	17.9	10	26.5	10	450
11	27.3	11	21.4	11	18.2	11	18.1	11	31.4	11	400
12	26.9	12	21.3	12	18.8	12	18.4	12	41.8	12	358
13	26.6	13	21.1	13	18.6	13	18.9	13	59.3	13	321
14	26.1	14	21	14	18.5	14	19	14	106	14	351
15	26.5	15	20.9	15	18.7	15	18.9	15	234	15	359
16	26.8	16	20.7	16	18	16	18.6	16	502	16	346
17	26	17	20.5	17	17.8	17	17.4	17	750	17	313
18	25.6	18	20.4	18	17.3	18	18	18	1000	18	290
19	25.6	19	20.3	19	17.7	19	19.4	19	1310	19	257
20	25.6	20	20.2	20	17.8	20	17.5	20	1590	20	286
21	25.6	21	20.1	21	18.6	21	17.6	21	1450	21	306
22	25.3	22	20	22	18.5	22	17.6	22	1080	22	275
23	24.7	23	19.9	23	18.3	23	17.6	23	818	23	249
24	24.5	24	19.8	24	17.6	24	17.6	24	702	24	237
25	24.3	25	19.7	25	17.6	25	17.9	25	688	25	232
26	24.1	26	19.6	26	17.7	26	18.3	26	841	26	221
27	23.9	27	19.5	27	17.7	27	18.7	27	849	27	214
28	23.8	28	19.4	28	17.6	28	19.2	28	657	28	226
29	23.6			29	17.6	29	20	29	510	29	288
30	23.4			30	17.5	30	22	30	474	30	221
31	23.2			31	17.5			31	507		

Jul 2004	m^3/s	Aug 2004	m^3/s	Sep 2004	m^3/s	Oct 2004	m^3/s	Nov 2004	m^3/s	Dec 2004	m^3/s
1	190	1	332	1	106	1	83.8	1	39	1	27.6
2	168	2	278	2	104	2	76.8	2	38	2	27.4
3	150	3	344	3	104	3	78.5	3	37.5	3	27.2
4	139	4	429	4	102	4	75.3	4	36.5	4	27
5	133	5	325	5	100	5	75.8	5	36	5	26.8
6	135	6	276	6	100	6	80.1	6	35.5	6	26.6
7	134	7	239	7	99	7	75.7	7	35	7	26.5
8	146	8	204	8	98.9	8	72.4	8	34.5	8	26.4
9	183	9	180	9	98.7	9	70.3	9	34	9	26.2
10	169	10	162	10	96	10	68.8	10	33.5	10	26.1
11	170	11	149	11	93.4	11	67.3	11	33	11	26
12	157	12	145	12	91.7	12	66	12	32.5	12	25.9
13	139	13	152	13	91.4	13	63	13	32	13	25.8
14	130	14	208	14	92.9	14	62	14	31.7	14	25.7
15	124	15	199	15	92.3	15	60	15	31.4	15	25.6
16	120	16	175	16	90.6	16	58.8	16	31	16	25.5
17	116	17	160	17	88.3	17	52.2	17	30.5	17	25.4
18	122	18	148	18	85.2	18	49.1	18	30	18	25.2
19	135	19	141	19	82.2	19	48.3	19	29.4	19	25.1
20	128	20	136	20	79.5	20	37.6	20	30.1	20	25
21	122	21	131	21	77.5	21	32.6	21	29.6	21	24.9
22	118	22	126	22	77	22	32.9	22	28.2	22	24.8
23	115	23	123	23	78.7	23	40.5	23	26.8	23	24.7
24	119	24	121	24	78.9	24	50.6	24	28.3	24	24.6
25	123	25	120	25	77.5	25	48	25	29.3	25	24.5
26	121	26	125	26	78	26	46.5	26	28.5	26	24.4
27	122	27	124	27	79.3	27	45	27	28.3	27	24.3
28	129	28	119	28	80.8	28	43	28	28.1	28	24.2
29	122	29	116	29	82.7	29	41.5	29	27.9	29	24.1
30	193	30	112	30	85.9	30	41.5	30	27.7	30	24
31	396	31	109			31	40			31	23.9

PEEL RIVER ABOVE FORT MACPHERSON-STATION [10MC002] (FROM WATER SURVEY OF CANADA)

Jan 2003	m^3/s	Feb 2003	m^3/s	Mar 2003	m^3/s	Apr 2003	m^3/s	May 2003	m^3/s	Jun 2003	m^3/s
1	191	1	167	1	166	1	153	1	285	1	3240
2	195	2	165	2	166	2	153	2	410	2	3150
3	194	3	165	3	166	3	153	3	737	3	3000
4	191	4	165	4	166	4	153	4	1040	4	2850
5	188	5	165	5	166	5	153	5	1040	5	2530
6	188	6	166	6	166	6	152	6	915	6	2190
7	190	7	168	7	165	7	152	7	771	7	1980
8	195	8	169	8	165	8	152	8	654	8	1930
9	199	9	169	9	164	9	151	9	587	9	2170
10	202	10	169	10	164	10	151	10	573	10	2280
11	205	11	170	11	164	11	151	11	607	11	2200
12	206	12	173	12	163	12	150	12	746	12	2150
13	204	13	173	13	163	13	150	13	1590	13	2010
14	200	14	173	14	163	14	149	14	2280	14	1710
15	199	15	173	15	162	15	150	15	2320	15	1410
16	198	16	173	16	162	16	150	16	2200	16	1200
17	193	17	174	17	161	17	151	17	2080	17	1100
18	190	18	174	18	160	18	151	18	2110	18	1120
19	189	19	173	19	160	19	152	19	2280	19	1180
20	188	20	171	20	159	20	154	20	2840	20	1230
21	187	21	168	21	159	21	155	21	3640	21	1220
22	187	22	167	22	158	22	156	22	4450	22	1220
23	185	23	166	23	158	23	158	23	3940	23	1160
24	182	24	164	24	157	24	158	24	2740	24	1080
25	180	25	164	25	157	25	158	25	2130	25	990
26	180	26	165	26	156	26	163	26	1850	26	936
27	179	27	166	27	156	27	171	27	1850	27	959
28	178	28	166	28	156	28	179	28	2470	28	1060
29	176			29	155	29	202	29	3070	29	1100
30	173			30	154	30	239	30	3320	30	1150
31	170			31	154			31	3300		

Jul 2003	m^3/s	Aug 2003	m^3/s	Sep 2003	m^3/s	Oct 2003	m^3/s	Nov 2003	m^3/s	Dec 2003	m^3/s
1	1120	1	808	1	884	1	577	1	369	1	226
2	1030	2	832	2	850	2	710	2	365	2	226
3	960	3	892	3	857	3	994	3	356	3	224
4	931	4	952	4	978	4	1140	4	350	4	221
5	948	5	958	5	1150	5	1160	5	341	5	217
6	1600	6	938	6	1220	6	1110	6	322	6	213
7	2140	7	940	7	1220	7	1040	7	308	7	206
8	1880	8	984	8	1180	8	967	8	298	8	203
9	1640	9	1010	9	1120	9	904	9	297	9	201
10	1870	10	1000	10	1060	10	846	10	300	10	199
11	1890	11	967	11	1020	11	799	11	302	11	197
12	1680	12	1000	12	998	12	769	12	297	12	194
13	1640	13	1040	13	977	13	742	13	292	13	192
14	1810	14	975	14	949	14	708	14	280	14	190
15	1850	15	923	15	924	15	660	15	257	15	187
16	1880	16	962	16	903	16	613	16	238	16	185
17	1820	17	969	17	878	17	572	17	227	17	183
18	1810	18	933	18	845	18	511	18	216	18	181
19	1800	19	923	19	814	19	420	19	205	19	179
20	1810	20	1010	20	780	20	365	20	194	20	179
21	1630	21	1160	21	756	21	350	21	187	21	176
22	1400	22	1370	22	728	22	332	22	185	22	174
23	1220	23	1480	23	699	23	341	23	185	23	173
24	1110	24	1430	24	678	24	358	24	189	24	172
25	1050	25	1330	25	665	25	365	25	200	25	171
26	1000	26	1240	26	636	26	374	26	215	26	171
27	959	27	1150	27	606	27	378	27	224	27	171
28	912	28	1070	28	584	28	385	28	228	28	168
29	873	29	1010	29	565	29	385	29	233	29	164
30	843	30	957	30	556	30	380	30	231	30	160
31	823	31	913			31	383			31	156

Jan 2004	m³/s	Feb 2004	m³/s	Mar 2004	m³/s	Apr 2004	m³/s	May 2004	m³/s	Jun 2004	m³/s
1	152	1	142	1	161	1	179	1	195	1	3280
2	148	2	143	2	162	2	179	2	196	2	3190
3	148	3	144	3	163	3	179	3	198	3	2930
4	145	4	145	4	164	4	180	4	199	4	2630
5	142	5	145	5	164	5	180	5	200	5	2500
6	140	6	146	6	165	6	180	6	202	6	2570
7	139	7	147	7	165	7	181	7	204	7	2410
8	136	8	148	8	166	8	181	8	207	8	2280
9	135	9	149	9	166	9	182	9	210	9	2140
10	134	10	150	10	167	10	182	10	213	10	1910
11	132	11	150	11	167	11	183	11	217	11	1680
12	131	12	151	12	168	12	183	12	222	12	1510
13	134	13	152	13	168	13	184	13	227	13	1380
14	138	14	153	14	169	14	184	14	235	14	1330
15	141	15	153	15	170	15	184	15	246	15	1300
16	144	16	154	16	170	16	185	16	270	16	1260
17	134	17	154	17	170	17	185	17	360	17	1200
18	133	18	155	18	171	18	186	18	1000	18	1140
19	135	19	155	19	172	19	186	19	3800	19	1070
20	135	20	156	20	173	20	187	20	6200	20	1050
21	135	21	156	21	173	21	187	21	4360	21	1060
22	134	22	157	22	174	22	187	22	3950	22	1040
23	134	23	158	23	175	23	188	23	3200	23	996
24	137	24	158	24	175	24	188	24	3000	24	950
25	138	25	159	25	175	25	189	25	2950	25	921
26	139	26	159	26	176	26	190	26	2990	26	898
27	140	27	160	27	176	27	191	27	3050	27	868
28	138	28	160	28	177	28	192	28	3100	28	819
29	139			29	177	29	193	29	3200	29	781
30	140			30	178	30	194	30	3260	30	750
31	141			31	178			31	3330		

Jul 2004	m^3/s	Aug 2004	m^3/s	Sep 2004	m^3/s	Oct 2004	m^3/s	Nov 2004	m^3/s	Dec 2004	m^3/s
1	710	1	509	1	333	1	251	1	165	1	116
2	660	2	693	2	328	2	243	2	156	2	116
3	618	3	766	3	329	3	226	3	147	3	117
4	584	4	825	4	333	4	211	4	132	4	113
5	553	5	884	5	355	5	207	5	120	5	113
6	537	6	853	6	379	6	202	6	111	6	113
7	549	7	778	7	382	7	200	7	106	7	112
8	558	8	697	8	374	8	198	8	104	8	112
9	561	9	628	9	367	9	196	9	102	9	112
10	584	10	573	10	361	10	193	10	101	10	111
11	596	11	532	11	352	11	197	11	109	11	111
12	592	12	499	12	343	12	193	12	117	12	111
13	565	13	470	13	333	13	195	13	119	13	110
14	524	14	461	14	326	14	190	14	123	14	110
15	488	15	489	15	318	15	189	15	125	15	110
16	465	16	497	16	311	16	188	16	126	16	109
17	448	17	481	17	301	17	187	17	125	17	109
18	430	18	463	18	286	18	187	18	126	18	109
19	429	19	442	19	276	19	186	19	130	19	108
20	438	20	422	20	267	20	186	20	132	20	108
21	442	21	406	21	260	21	185	21	133	21	107
22	435	22	391	22	255	22	185	22	130	22	107
23	418	23	381	23	251	23	184	23	126	23	107
24	401	24	380	24	249	24	184	24	124	24	106
25	399	25	379	25	247	25	183	25	124	25	106
26	404	26	378	26	248	26	183	26	126	26	106
27	417	27	377	27	251	27	186	27	120	27	107
28	423	28	375	28	253	28	182	28	118	28	107
29	423	29	363	29	251	29	180	29	117	29	107
30	408	30	351	30	250	30	179	30	116	30	105
31	406	31	342			31	172			31	105