An assessment of hydrological process and landform change: Slave River delta, Northwest Territories

Ronald Brad Hill
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AN ASSESSMENT
OF
HYDROLOGICAL PROCESS AND LANDFORM CHANGE:
SLAVE RIVER DELTA, NWT

By

Ronald Brad Hill
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Nuclear 0610
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Computer Science 0984
Engineering
General 0537
Aerospace 0538
Agricultural 0539
Automotive 0540
Biomedical 0541
Chemical 0542
Civil 0543
Electronics and Electrical 0544
Environmental 0775
Industrial 0546
Marine and Ocean 0547
Materials Science 0794
Mechanical 0548
Metallurgy 0743
Mining 0551
Nuclear 0552
Packaging 0549
Petroleum 0765
Sanitary and Municipal 0554
System Science 0790
Geotechnology 0428
Operations Research 0796
Plastics Technology 0795
Textile Technology 0994

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General 0621
Behavioral 0384
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In memory
of the Slave River Delta's
biggest R.E.M. fan

• ABSTRACT •

The Slave River Delta, 61° 15' N, 113° 30' W, is located at the mouth of the Slave River in the southeast arm of Canada's Great Slave Lake. Although the delta itself lies some 1600 km downstream from the W.A.C. Bennett Dam at Hudson's Hope, British Columbia, recent work by English *et al.* (1996) indicates that the mean annual discharge and sediment load of the Slave River have decreased by 16% and 33% respectively since regulation. Such alterations in the Slave River flow regime have significant implications for the growth of the River Delta since the transfer of sediment to the delta front is one of the most important factors in the landform's continued development.

Using data gathered from field research, historical sources, aerial photography, and two Geographical Information Systems, temporal variations in the distribution of flow throughout the Slave River Delta between 1946 and 1994 were identified along with changes in the extent of subaerial landforms. It is estimated that summer flows through Old Steamboat Channel and Middle Channel decreased by approximately 90% and 94% respectively over the 48 year period while discharge in Resdelta Channel has increased by close to 35%. Observations indicate that this shift has been accompanied by increases in channel length and bar formation in Old Steamboat Channel and Middle Channel. This suggests that energy gradients may be decreasing in these distributaries and may lead to their eventual abandonment.

According to the available data, completion of the W.A.C. Bennett Dam in 1968 appears to have had some impact on the loss of approximately 652 ha within the delta between 1966 and 1977; however, deltaic growth since regulation has increased by almost three times that of the pre-impoundment period.

Examination of depositional environments within the Slave River Delta indicates that most of the growth during the post-impoundment period has occurred within the outer delta region in the quiet sheltered environments of Nagle Bay and Jackfish Bay. Additional growth has been observed in the central portions of the delta as well.

Analysis of suspended sediment concentration ([SS]) and discharge in distributary channels indicates a relatively strong relationship during the summer and autumn seasons; however, the relationship is complicated during the spring by the influence of breakup. The relationship between discharge and [SS] is dependent upon the distribution of flow throughout the delta. Within two channel bifurcations of the main body of the Slave River, [SS] versus discharge is generally characterised by the classic power relationship defined by Leopold and Maddock (1953), although there is some indication that the system may be sediment limited during peak flows in the summer. Beyond two bifurcations, discharge and [SS] tends to be inversely related and channels within these classifications are generally characterized by deposition.

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Thanks to my entire family, especially my parents Ross & Helen and my sister Rhonda, for their unwavering support throughout my academic career and my life in general. Perhaps they were right to push me beyond grade 8!

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• TABLE OF CONTENTS •

• LIST OF TABLES •

• LIST OF FIGURES •

CHAPTER 1.0

Page #

CHAPTER 2.0

CHAPTER 3.0

CHAPTER 3.0 (cont.)

CHAPTER 4.0

• CHAPTER 1.0 •

INTRODUCTION

1.1 THESIS OUTLINE

This thesis has been organized into 5 chapters: Introduction, Literature Review, Manuscript 1, Manuscript 2, and Conclusions.

The first chapter provides a general definition of the term "delta", outlines the significance of deltas in both global and Canadian contexts, and examines the implications of river regulation on deltaic environments. In addition, this chapter justifies and defines the purpose for this research project and contains a brief description of the Slave River Delta site in terms of location, historical development, physical environment, and its importance to the local population.

Chapter two examines the current state of scientific research on deltas in the form of a literature review. Attention is focused on research in the development of deltaic deposits, particularly in Subarctic and Arctic environments and the Slave River Delta. Additional material pertaining to channel processes, morphology, and river regulation is also reviewed.

The third chapter, *Changes in the Slave River Flow Regime and Impacts on Channel Form and Process in the Slave River Delta NWT*, is structured in the form of an extended journal article and focuses on field work conducted during the summer of 1995 to examine the various channel processes occurring within the Slave River Delta. Using data gathered from field research and historical sources as well as channel characteristics taken from aerial photography, this paper looks at the impacts of upstream impoundment on the hydrologic regime of the Slave River Delta and examines some of the complex channel processes responsible for the transport of sediment throughout its drainage network.

Chapter four, *An Assessment of Landform Development within the Slave River Delta NWT during the Pre- and Post-Impoundment Periods, 1946 - 1994*, is a second extended journal article in which the morphometric changes within the Slave River Delta are examined over a 48 year period between 1946 and 1994 using air photo analysis and Geographic Information System (GIS) technology. The article examines changes in deltaic landforms during the pre- and post-impoundment periods, outlines potential causes for inconsistencies over the 48 year period, and explores their impact on the deltaic environment.

Because chapters three and four are each structured to stand on their own, there may, at times, be some repetition of both text and figures; however, steps have been taken to ensure that this occurs as infrequently as possible in order to maintain the flow of this thesis.

The fifth and final chapter contains a summary of the conclusions drawn in Chapters 3.0 and 4.0 and examines some of their implications for the future. In addition, the final chapter provides some possible suggestions for future research which may help improve the current body of knowledge on the Slave River Delta and provide a more comprehensive understanding of the entire area.

1.2 *INTRODUCTION & JUSTIFICATION*

According to sources, it was the fifth century historian Herodotus who first used the term "delta" in an attempt to describe the striking resemblance between the Greek letter "Δ" and alluvial deposits at the mouth of the Nile River. Since that time, deltas have been recognized as some of the most biologically productive areas on the planet due to their rich annual nutrient deposits (Strahler and Strahler, 1987). In addition, ancient deltaic deposits have been identified as significant sources of non-renewable resources such as natural gas and oil (Morgan, 1970; Carrigy, 1971; Dennison, 1971; Rainwater, 1975). As a result, scientific research has been conducted on a number of aspects of the deltaic environment.

In general terms, deltas are simply depositional features which occur where sediment laden rivers flow into larger bodies of relatively still water. As flow velocities gradually decrease, the rivers lose their ability to transport sediment and deposition begins to occur in a sequential pattern where the coarsest materials are laid down first, followed by the finer grained particles (Marsh, 1987). Continual deposition in this sequential manner eventually leads to the formation of three distinctive units known as foreset, topset, and bottomset bed forms (Gilbert, 1885).

The development of a delta is much more complex in reality however, for the deposition of sediment is greatly influenced by a variety of physical and environmental factors (Thakur & MacKay, 1973). As a result, deltaic deposits can vary greatly in terms of sedimentary structure, planimetric shape, and overall size based upon the relative influences of channel morphology, sediment load, depositional environment, and climate.

In terms of total area, deltas make up only a small fraction of the Earth's actual landmass. Despite their relatively small contribution to overall global landmass however, deltas are an extremely important part of the global ecosystem, for they provide a natural refuge for many wetland species of plants, animals, and insects. In addition, their rich, flat, fertile soils support the development of agriculture in many locations (Strahler & Strahler, 1987). This, in turn, provides local communities with a source of economic gain since people are then able to draw upon the natural resources of the delta. The Canadian North is a prime example of this since deltaic environments within the zones of continuous and discontinuous permafrost are significantly more productive than adjacent landforms despite the fact that they make up only a small proportion of the total area (English, 1984).

Interestingly, three of Canada's largest deltas, the Mackenzie River Delta, the Peace-Athabasca Delta, and the Slave River Delta, are all found within this type of environment. In fact, all three are fed by water from the Peace River drainage basin. In comparison to the Mackenzie and Peace-Athabasca deltas, the Slave River Delta has received fairly little attention in the past; however, concern over impacts of existing river regulation on the Peace River at Hudson Hope, British Columbia and the potential for impoundment of the Slave River has lead to a series of studies on the area (English, 1979 & 1984; Bodden, 1981; English *et al.*, 1996). Although located several hundred kilometres upstream, regulation of flow on the Peace River has great potential to alter the hydrologic regime of the Slave River and, therefore, has implications for both geomorphic development and ecology within the Slave River Delta. In 1984, a strong relationship was established between plant succession and water depths within the Slave River Delta. English (1984) indicated that lower water levels caused by upstream impoundment "would allow vegetation of later successional stages to invade and displace the highly productive emergent plants". In addition, the reduced flows would mean a "loss of bedload and the coarse fraction of the suspended sediment" (English, 1979) which comprise most of the material in the outer delta where progradation occurs (Vanderburgh & Smith, 1988).

Considering that many of these studies were carried out within the first 10 years of the dam's operation, the probability of identifying major impacts was quite low. Consequently, most of the conclusions were simply predictions for the future of the Slave River Delta. Today, some 28 years after regulation, it is more probable that changes within this deltaic environment resulting from Peace River impoundment may be observed.

1.3 PURPOSE

In general terms, the purpose of this study is to identify changes within the Slave River Delta that can be attributed to upstream impoundment at the W.A.C. Bennett Dam, Hudson's Hope British Columbia. More specifically however, this means:

1) identifying hydrological changes in the Slave River Delta by examining the flow characteristics before and after regulation,

2) identifying and measuring those areas where deltaic landmass has undergone, and/or are continues to undergo changes in size, shape, and orientation; and

3) identifying the processes taking place within the channels of the Slave River Delta to assess how deposition and erosion are influenced by changes in flow regime as well as how these flows have fluctuated over the time period from 1946 to the present.

Therefore, the objectives for this study will be to identify areas of hydrological and morphometric change within the Slave River Delta, examine the controls which influence such changes, and attempt to assess how these variables have been influenced by changes in river run-off regime due to upstream impoundment.

1.4 STUDY SITE

1.4.1 LOCATION

By definition, the Slave River Delta is composed of sedimentary deposits from the Slave River which cover approximately 8300 km^2 from the rapids at Fort Smith to the southern arm of Great Slave Lake (Vanderburgh & Smith, 1988). According to English *et al.* (1996) however, only about 5% of this area is actively prograding into Great Slave Lake. The active portion of the Slave River Delta, located at approximately 61° 15' N 113° 30' W, is found in the southeast arm of Great Slave Lake in Canada's Northwest Territories. The delta is approximately 150 km north of the Alberta border (Fig. 1.1), extends northeastward in an arcuate shape from Nagle Channel to the Jean River, and is partitioned by numerous channels of varying magnitude (Fig. 1.2).

Fig. 1.1

Location of the Slave River Delta Study Site

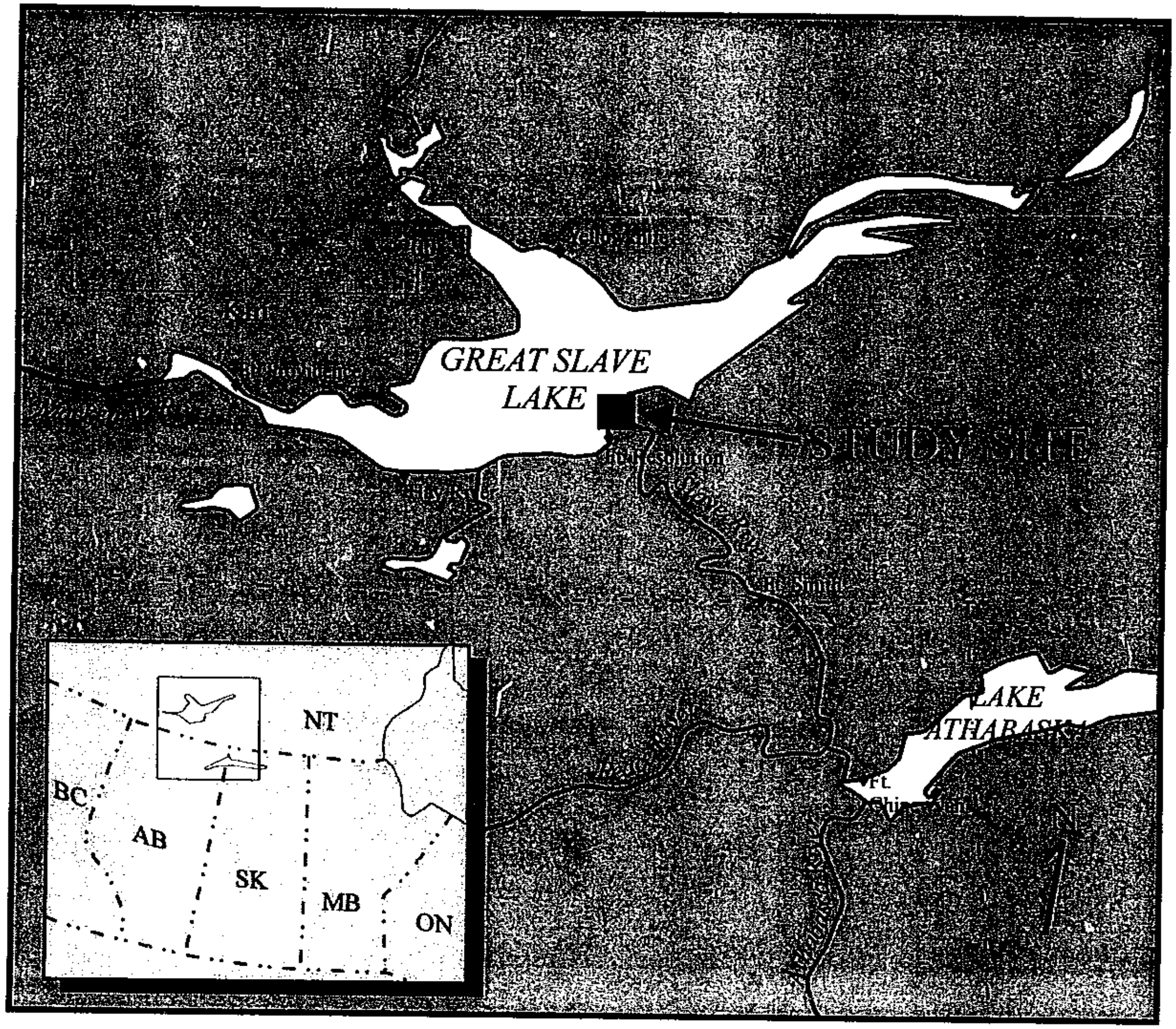
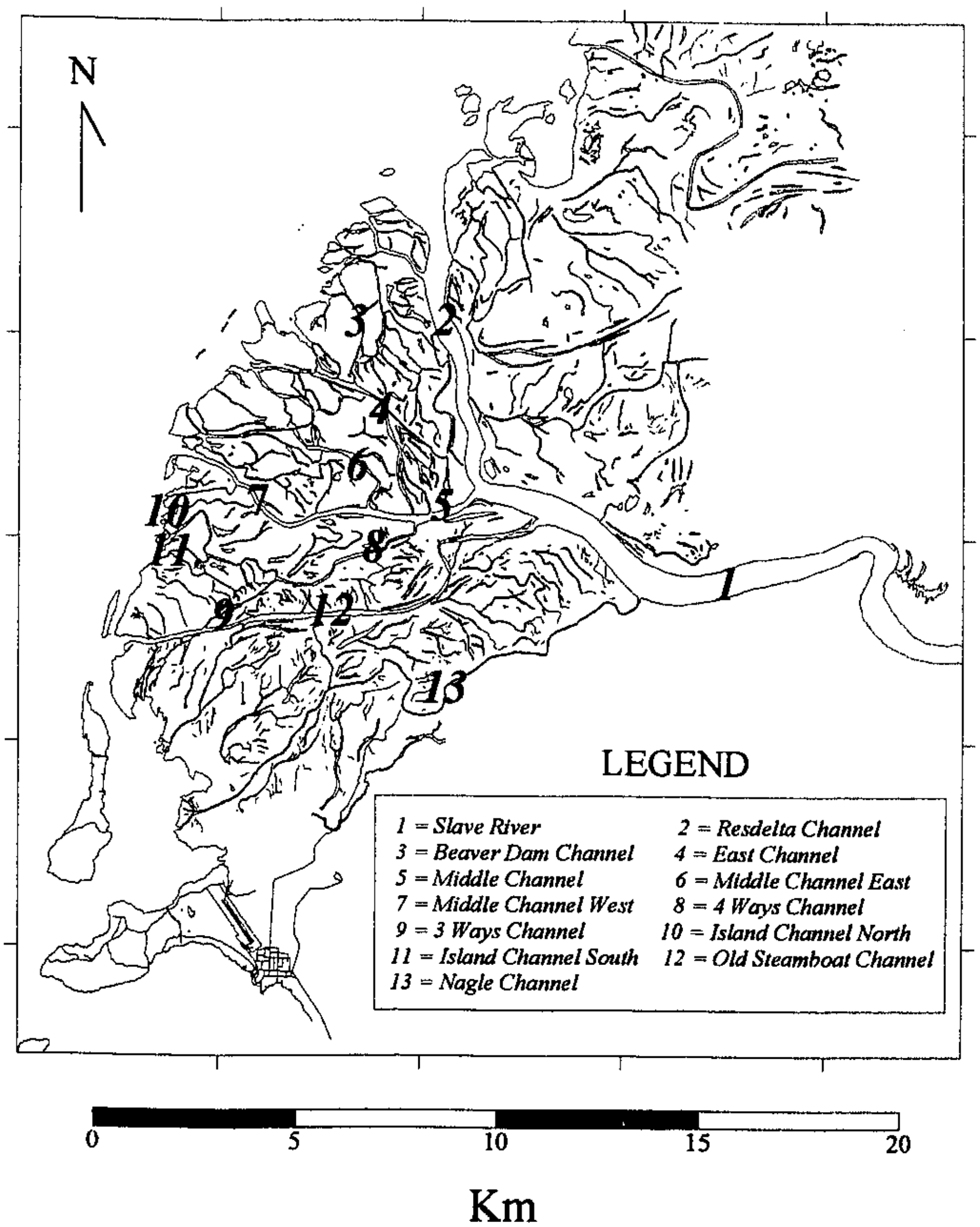


Fig. 1.2

Major Channels of the Slave River Delta



1.4.2 HISTORICAL DEVELOPMENT

The formation of the modern Slave River Delta began approximately 10 000 years before present (BP) with the retreat of the Keewatin ice sheet (Bryson *et al.*, 1969). Prior to this time, ice had extended across the southwestern corner of the Northwest Territories and well into both the Peace and Athabasca River Valleys. The retreating ice eventually lead to the formation of glacial Lake McConnell which, in turn, drained through the present day Churchill River System into Hudson Bay. Flow through this system, however, was restricted by isostatic rebound and, following the retreat of the Selwyn ice tongue, drainage began northward down the Mackenzie Valley (Cameron, 1922).

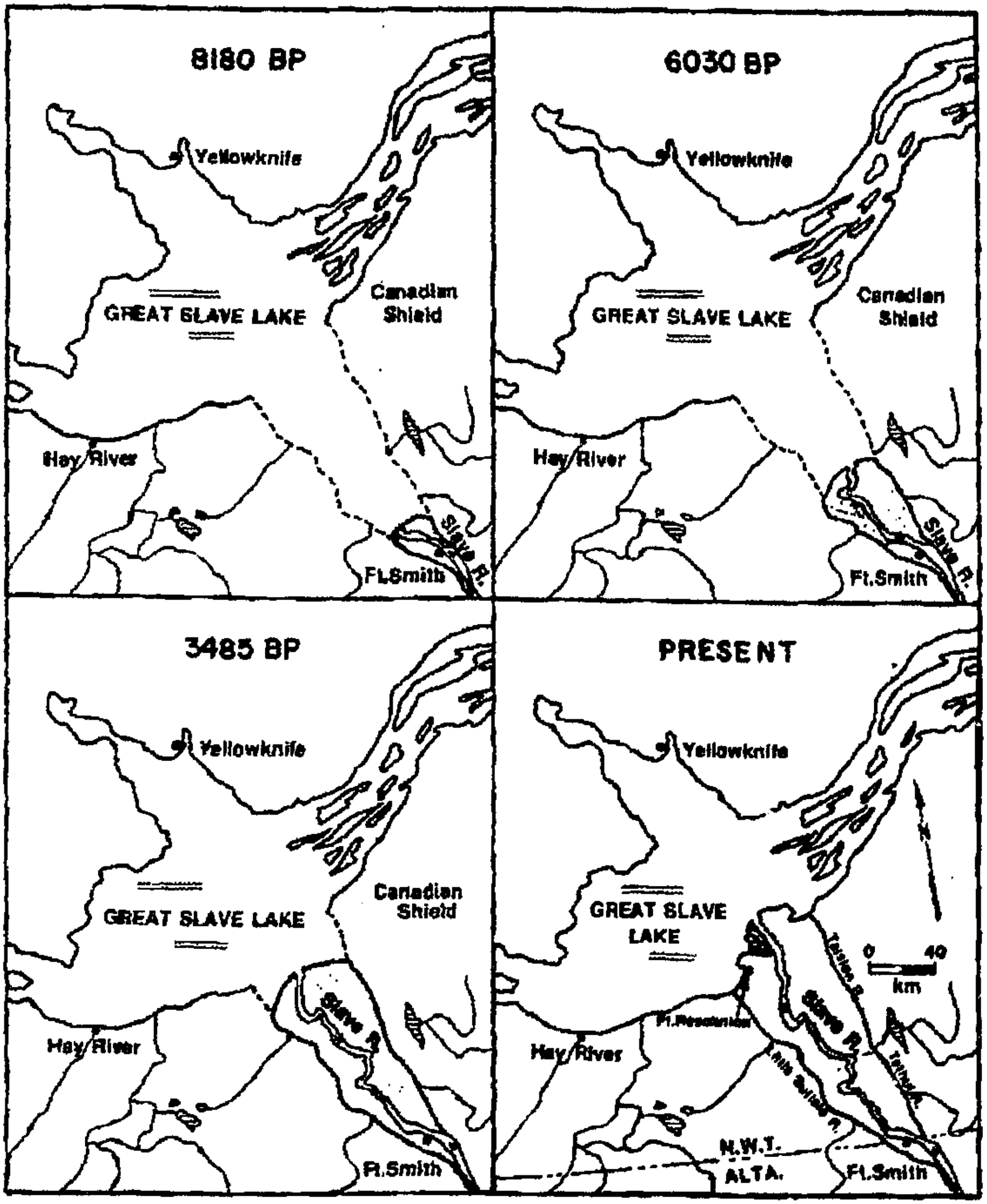
Lower water levels in glacial Lake McConnell resulted in the development of isolated water bodies in the present day location of Great Slave Lake and Lake Athabasca. Since then, sediments carried by the Peace, Athabasca, and Slave Rivers have been continually deposited in a deltaic form by waters flowing into the southeastern arm of Great Slave Lake (Fig. 1.3). As a result, the Slave River Delta has continued to prograde into the lake at an average rate of 20.7 m/year since 8070 BP (Vanderburgh & Smith, 1988).

1.4.3 HYDROLOGY

Fed by flows from the Peace, Athabasca, and Fond du Lac river systems, the Slave River forms an integral part of the Mackenzie River Drainage Basin in that it provides a common drainage for these three large catchments. In addition, the

Fig. 1.3

Historical Development of the Slave River Delta



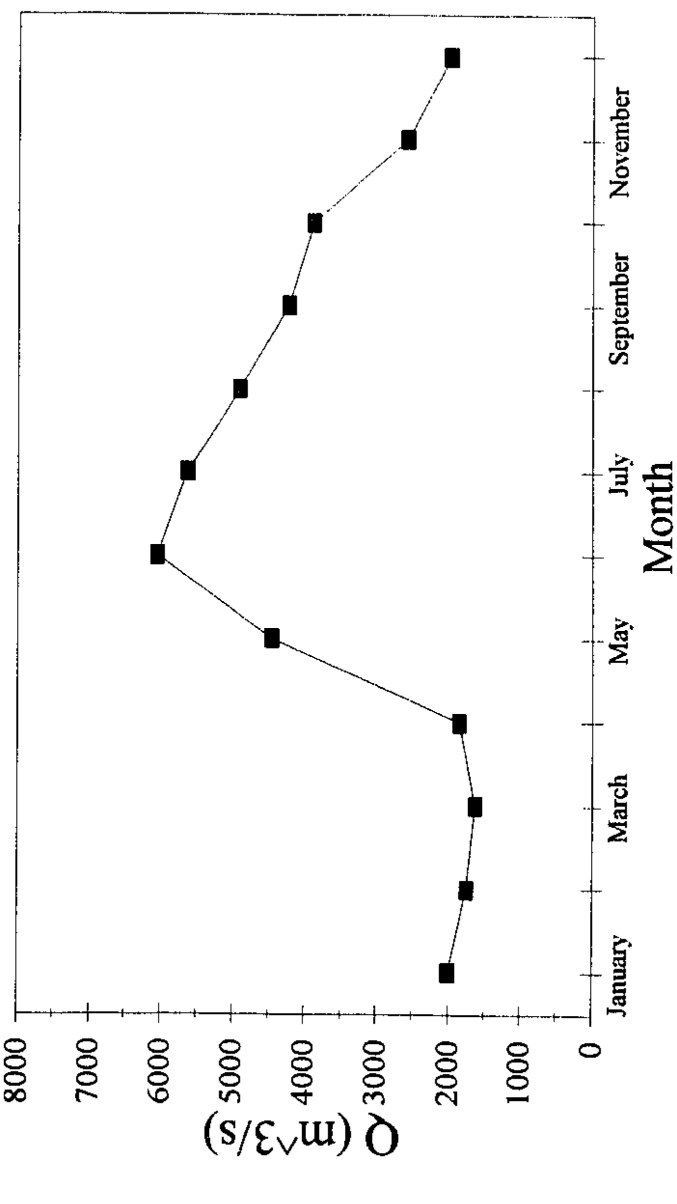
(Vanderburgh and Smith, 1988)

Slave River supplies at least 80% of the water volume in Great Slave Lake (Bennett, 1977) and approximately 85% of the input into the Mackenzie River System (Alta. Dept. of the Environment, 1982). The river itself extends approximately 450 km from the Peace - Athabasca Delta to southern arm of Great Slave Lake. The Slave River drains an area of approximately 15,100 km^2; however, because of its role as a common outlet for the Peace, Athabasca and Fond du Lac catchments, the Slave actually drains an area of around 620,000 km^2 (English, 1979).

Historically, the Peace River has provided the largest single contribution to the Slave River flow regime. In fact, recent studies indicate that approximately 54% of the Slave's annual flow came from the Peace River system prior to the 1968 completion of the W.A.C. Bennett dam and that this contribution has increased to 66% during the post-impoundment period (English *et al.*, 1996). Despite regulation, mean annual discharge on the Slave River has remained relatively unchanged, decreasing slightly from a pre-impoundment value of 3468.08 m^3/sec (σ2062.46 m^3/sec) to 3368.5 m^3/sec (σ1183.91 m^3/sec) in the post-impoundment period (English *et al.*, 1996). Perhaps more interesting however is the fact that the reduction in standard deviation indicates that there has been a substantial decrease in the amount of variation for the mean annual discharge values since the completion of the dam.

Historically, peak discharges for the Slave River tend to occur during late May or early June (Fig. 1.4) and are generally associated with snow melt and river ice breakup in the upper catchments (English, 1979). The mean date of breakup on the Slave River itself is May 9; however, records indicate that it has happened as early as April 25

Fig. 1.4
Mean Slave River Discharge
at Fitzgerald, NWT (1959 - 1993)



(1980) and as late as May 20 (1979) (English *et al.*, 1996).

1.4.4 ECOLOGICAL & ENVIRONMENTAL ASPECTS

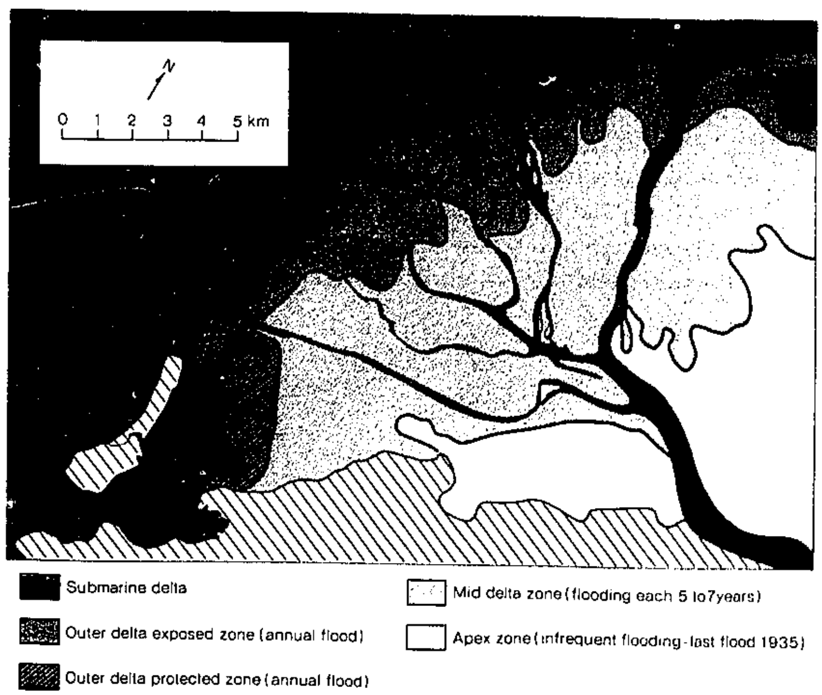
1.4.4.1 Local Geology

The Slave River Valley occupies a niche between the western edge of the Laurentian Plateau and the eastern edge of the Mackenzie Lowlands and is underlain by Devonian and Cretaceous bedrock buried by glaciofluvial and reworked alluvial material deposited by the retreat of the Laurentide ice sheet and subsequent formation of glacial Lake McConnell (English, 1979). Studies of local geology and soil structures have been carried out in the past by Raup (1946), Day (1972), Agriculture Canada (1974), and Vanderburgh & Smith (1988). According to Day (1972), deposits within the active delta which experience frequent flooding are generally composed of Cumulic Regosols. Additional deposits of Cryic Cumulic Regosols and Orthic Humic Gleysols are found in those areas where older levee deposits have increased to an elevation where flooding rarely occurs.

1.4.4.2 Local Vegetation

The active portion of the Slave River Delta, an area of approximately 400 km^2, can be easily divided into distinctive zones based on summer low-water levels (Fig. 1.5). Areas which lie at or below the summer low-water level are classified as submergent while those which lie above the summer low-water level are classified as emergent (English, 1984). In addition, the Delta can be further subdivided

Fig. 1.5
Flood Frequency Zones of the Slave River Delta



(English, 1984)

into three distinctive areas based on local vegetation coverage and geomorphology.

The "outer delta" is approximately 95% submergent and is comprised of large assemblages of *Equisetum fluviatile* which flourish in the nutrient rich sediments replenished by annual spring flooding (English, 1984). This highly productive area also supports the development of some *Salix* and *Carex* assemblages; however, the frequency of spring floods and low topography limit their development.

The transition between submergent and emergent landforms within the "mid-delta" area is reflected in the vegetation coverage which ranges from *Equisetum* assemblages in low lying areas, through *Salix* and *Alnus* assemblages along levees and abandoned channels, to *Populus* assemblages on elevated levees where it is thought that the frequency of flooding generally does not exceed 5 - 7 years (English, 1984). For the most part however, the mid-delta area is dominated by the *Alnus-Salix* assemblages.

The "apex" zone often lies as much as 2.5 m above water level and, as a result, is dominated by large assemblages of *Picea glauca*, small shrubs, and significant expanses of bryophytes which cannot withstand the frequent flooding associated with the lower landforms of the mid- and outer-delta areas. In addition, areas of permafrost have been identified and associated with many of the vegetation communities found within the apex of the delta (Day, 1972; Gill, 1976a; English, 1979).

1.4.5 IMPORTANCE OF THE SLAVE RIVER DELTA

The progradation of the Slave River Delta into Great Slave Lake has led to the development of an ecologically diverse environment which supports a wide variety of flora and fauna (Mackenzie Basin Intergovernmental Liaison Committee, 1977). As outlined in the previous section on vegetation, the delta is composed of a very productive and complex array of wetland plant species; consequently, the area is an extremely important feeding, staging, and breeding habitat for many wildlife species including: waterfowl, muskrats, and fish (Bodden, 1981a). In addition, assemblages in the mid and apex regions provide refuge for larger wildlife and have been used for logging purposes in the past.

Because of this abundance of natural resources, the residents of nearby Fort Resolution depend on the Slave River Delta for economic reasons (Bodden, 1981a & 1981b). The town itself is located to the south of the Slave River Delta, 61° 09' N, 113° 38' W, and is the oldest settlement in the Northwest Territories (Northern Frontier Visitors Association, 1994). The productivity of the adjacent Slave River Delta has greatly assisted in enabling the people of Fort Resolution to maintain some traditional lifestyles, for it still provides many with their annual meat supply and many more with employment opportunities in the fur trade and logging industries. In fact, those who still earn their living by hunting, trapping, and fishing in the delta environment often refer to the delta as their "Garden" (English, pers. comm., 1995). Consequently, any significant changes in river regime which have the potential to impact the biological productivity of the delta would have a profound effect on the economic, social, and cultural stability of Fort Resolution as well.

• CHAPTER 2.0 •

LITERATURE REVIEW

2.1 DELTAS

2.1.1 DEFINITIONS & CLASSIFICATIONS

According to the Oxford dictionary (Pollard, 1994), a delta is defined as "a triangular patch of land accumulated at the mouth of a river between two or more of its branches". In studying deltas however, this definition is often complicated by whether one focuses on subaerial or subaqueous deltas, lacustrine or marine, coarse-grained or fine-grained, modern or ancient.

Lyell (1853) provided one of the earliest definitions of the term "delta", using it to describe "an alluvial land, formed by a river at its mouth, without reference to its precise shape". Several years later, classic papers by Gilbert (1885, 1890) and Barrell and Clark (1912) not only lead to a more comprehensive understanding of deltaic deposits, but further defined the term as well. In fact, Barrell and Clark's definition of "a deposit, partly subaerial, built by a river into or against a permanent body of water" and Gilbert's classic "tripartite" structure of topset, foreset, and bottomset beds are still the basis for many modern day texts on the subject (Axelsson, 1967; Le Blanc, 1975; Miall, 1984; Marsh, 1987; Nemec, 1990a).

Intensive investigation of deltas throughout the world over the past century, however, indicates that few exhibit the relatively simple structure of the Gilbert-type delta (Barrell and Clark, 1912; Busch, 1953; Van Straaten, 1960; Coleman and Wright, 1971; Colella and Prior, 1990). As a result, several classification schemes have been put forward in an attempt to group those deltas which are similar in character. An early paper by Lyell (1853) recognized three types of deltas: lacustrine, mediterranean, and oceanic. Over a century later, Busch (1953) developed a three tiered classification using the terms: birdsfoot, estuarine, and arcuate, a scheme which has been adopted and modified by a number of authors (Bates, 1953; Stoddart, 1969; Thakur and MacKay, 1973; Marsh, 1987).

Additional schemes have been suggested based upon process concepts (Holmes, 1965; Fisher *et al.*, 1969; Galloway, 1975), sedimentary structure (Coleman and Wright, 1975; Orton, 1988; Corner *et al.*, 1990), geographic setting (Etheridge and Westcott, 1984), stage of development (Barrell and Clark, 1912; Dahlskog, 1972), and a variety of other characteristics; however, a universal classification has yet to be accepted.

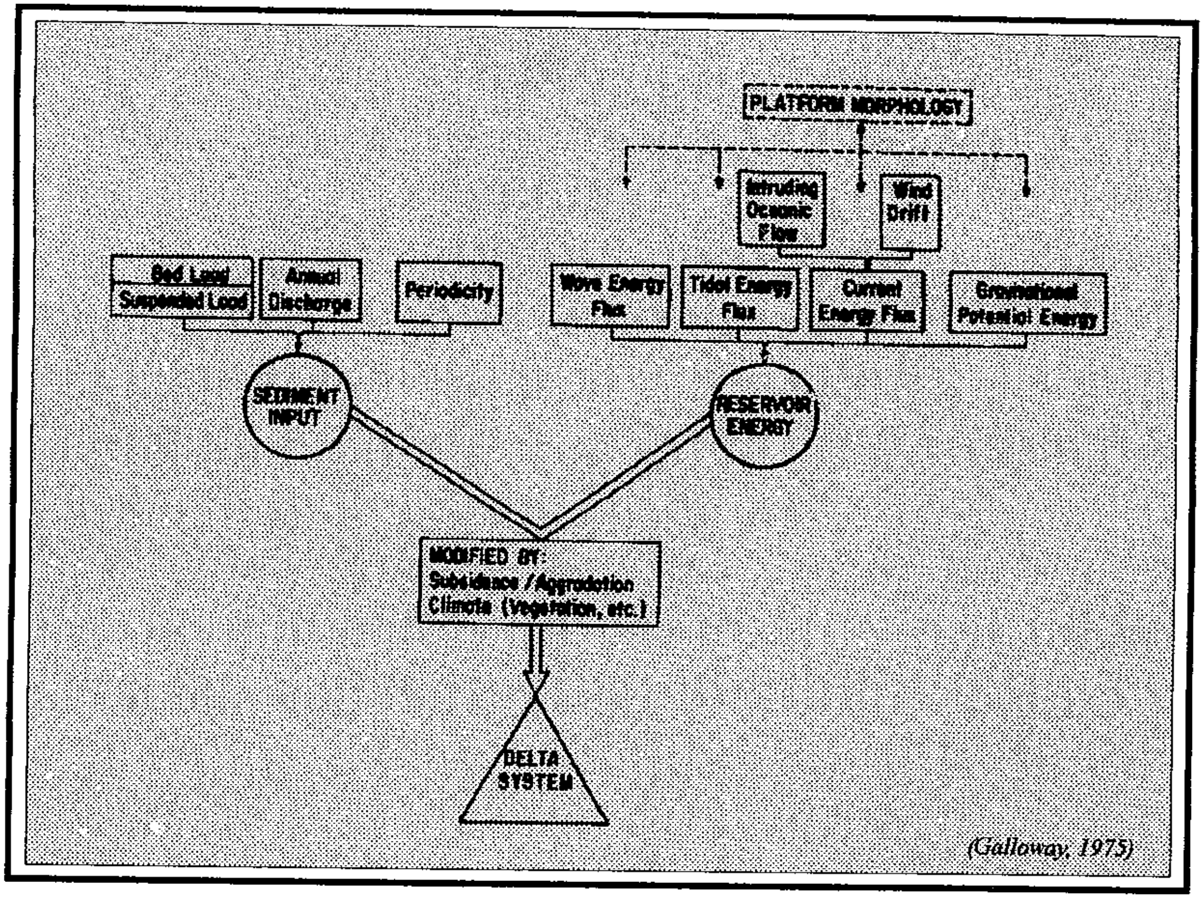
2.1.2. MORPHOLOGY

It is interesting to note that most, if not all, of the previous classification schemes are based upon deltaic morphology in some way or another. Like many authors, Galloway (1975) stated that deltaic morphology is a direct result of the interaction between sediment input and the forces which rework and remove it from the deltaic system (Fig. 2.1). As a result,

> delta morphology in detail reflects the totality of hydrologic regime, sediment load, geologic structure and tectonic stability, climate and vegetation, tides, winds, waves,

Fig. 2.1

Galloway's Model of Deltaic Systems

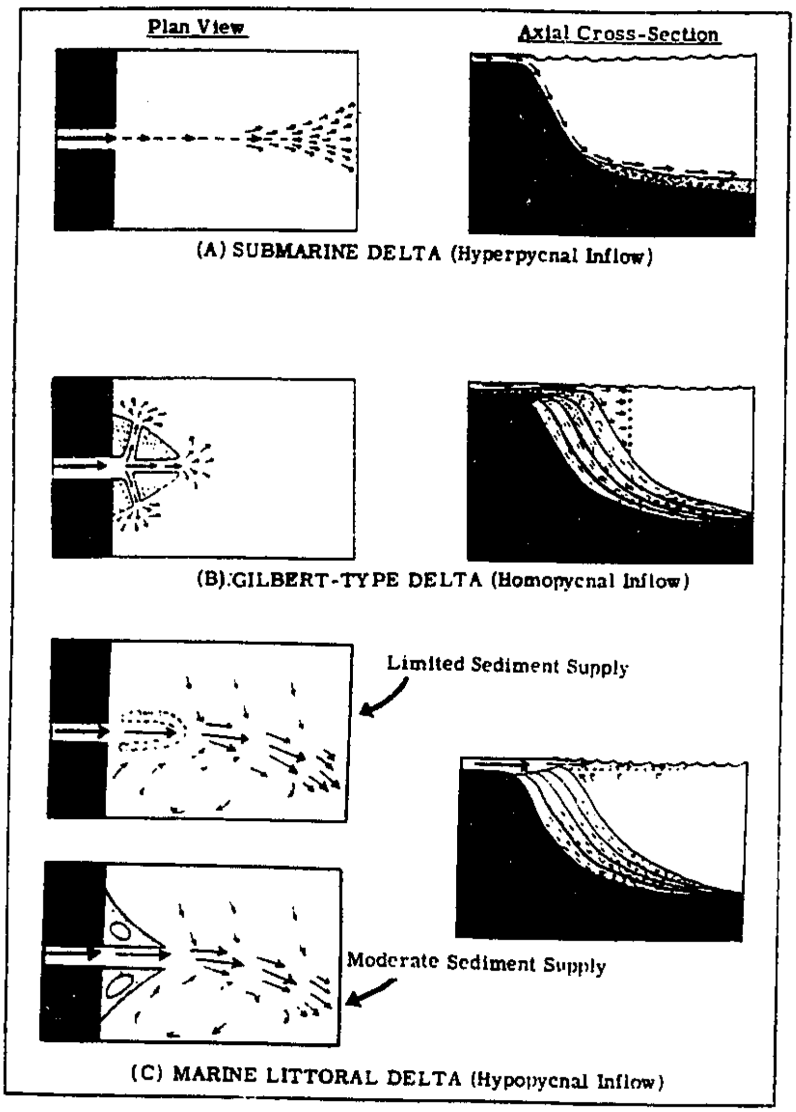


> density contrasts, coastal currents, and the innumerable spatiotemporal interactions of all these factors" (Coleman & Wright, 1971:60)

According to Gilbert (1885, 1890), deltaic morphology is the direct result of a three stage delta building process in which (1) bottomset beds are formed by the settling of suspended sediment under reduced flow conditions; (2) individual coarse-grained particles move down the delta front producing foreset beds inclined at the angle of repose over top of the bottomset beds; and (3) topset beds are formed by the deposition of sediment in the delta plain overlying the foreset beds. A number of authors have since identified deltaic structures which suggest that morphology may not be the result of individual particle movements, but mass movements instead (Henkel, 1970; Coleman *et al.*, 1974; Prior and Coleman, 1979; Coleman, 1982; Kenyon and Turcotte, 1985; Nemec, 1990b). Several other hypotheses have been put forth in an attempt to explain deltaic structure; however, none have received more acceptance than Bates' theory on jet flow.

According to Bates (1953), deltas are the result of three main types of flow (Fig. 2.2): 1) Hyperpycnal, in which the delta outflow is more dense than the surrounding fluid resulting in a plane jet where density currents force sediment laden flow down the delta front and along the bottom of the receiving basin; 2) Homopycnal, in which the density of the outflow and surrounding fluid are approximately equal resulting in a plane jet where mixing occurs in all three dimensions; and 3) Hypopycnal, in which the outflow is less dense than the surrounding fluid resulting in a plane jet where vertical mixing is severely limited. Despite the wide use of Bates' theories (Axelsson, 1967; Russell, 1967; Scheidegger, 1969; Thakur and MacKay, 1973; Wright, 1977; English,

Fig. 2.2
Schematic of Basic Inflow in Deltas



(Bates, 1953)

1979; Coleman, 1982; Miall, 1984), several authors have been rather critical of the work, questioning Bates' conclusions (Crickmay and Bates, 1955; Scrunton, 1956) and pointing out the modifying effects of external factors such as wave action, channel mouth geometry, and sediment characteristics (Axelsson, 1967).

The significance of sediment supply as the governing factor in the formation of deltaic morphology is well documented (Bardach, 1964; Axelsson, 1967; Fisher *et al.*, 1969; Galloway, 1975; Reid and Wood, 1976; Tripp *et al.*, 1981). In fact, "the amount of sediment transported by the delta-building rivers is of vital importance for the rate of advance and development" (Axelsson, 1967:26). The distribution of sediment throughout the complex channel network of a delta often leads to local variations in landform development; consequently, some areas may be undergoing rapid growth while others remain inactive or suffer from erosion (Axelsson, 1967). According to Scrunton (1960), changes in the distribution of sediment influences deltaic morphology by creating both "constructional" and "deconstructional" phases of development. As a result, many deltas undergo a step-wise evolution of localized growth and erosion. Fisher *et al.* (1969) suggest that this cyclical development is a function of sediment size, indicating that flows which contain a high suspended load often lead to fluvial dominated deltas undergoing constructional progradation while those with high bed loads tend to result in deconstructional marine-dominated deltas. Contrasting arguments have been made by English (1979, 1984) and Vanderburgh and Smith (1988) who indicate that progradation of the Slave River Delta is highly dependent upon the delivery of coarse material to the delta front.

Several authors have also made reference to the roll of subsidence in the evolution of deltaic morphology (Mathews and Shepard, 1962; Axelsson, 1967; Dahlskog *et al.*, 1972; Coleman and Wright, 1975; Gill, 1971; Coleman, 1982; Miall, 1984; Vanderburgh and Smith, 1988). The deposition of successive sedimentary layers often leads to a general compaction of the underlying deposits due to the dewatering of clays, thickening of sands, and rearrangement of sedimentary facies (Coleman, 1982).

2.1.3. CHANNEL PROCESSES

According to Bates (1953), the development of channel structures and cleavage bar islands is the direct result of outflow at the delta front. Similar arguments have been made by Russell (1967), Dahlskog *et al.* (1972), Coleman and Wright (1975), English (1979), and Coleman (1982); however, not all researchers subscribe to Bates' theory of jet flow.

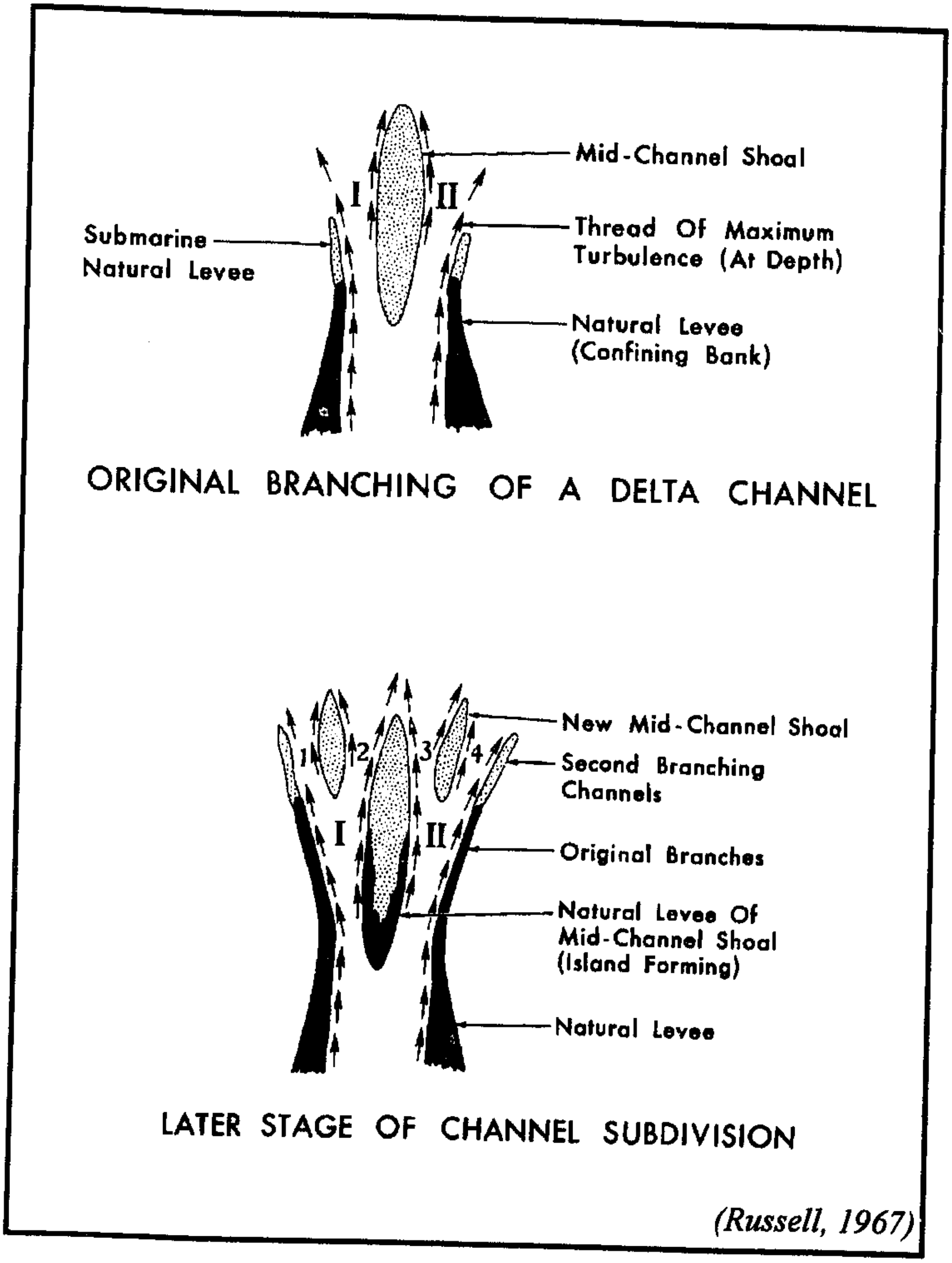
2.1.3.1 Cleavage Bar Development and Channel Evolution

In general, sediment flows are directed towards areas of less turbulence at the channel mouth creating a flared distribution (Fig. 2.3). As a result of both decreased flow and turbulence, sediment is deposited along the margins of flow and toward the widening centre of the channel creating natural submarine levees and a mid-channel shoal or cleavage bar (Russell, 1967).

The continued progradation of the channel through this process often leads to the development of channel bifurcation (Leighly, 1934; Axelsson,

Fig. 2.3

Channel Development in the Deltaic Environment



(Russell, 1967)

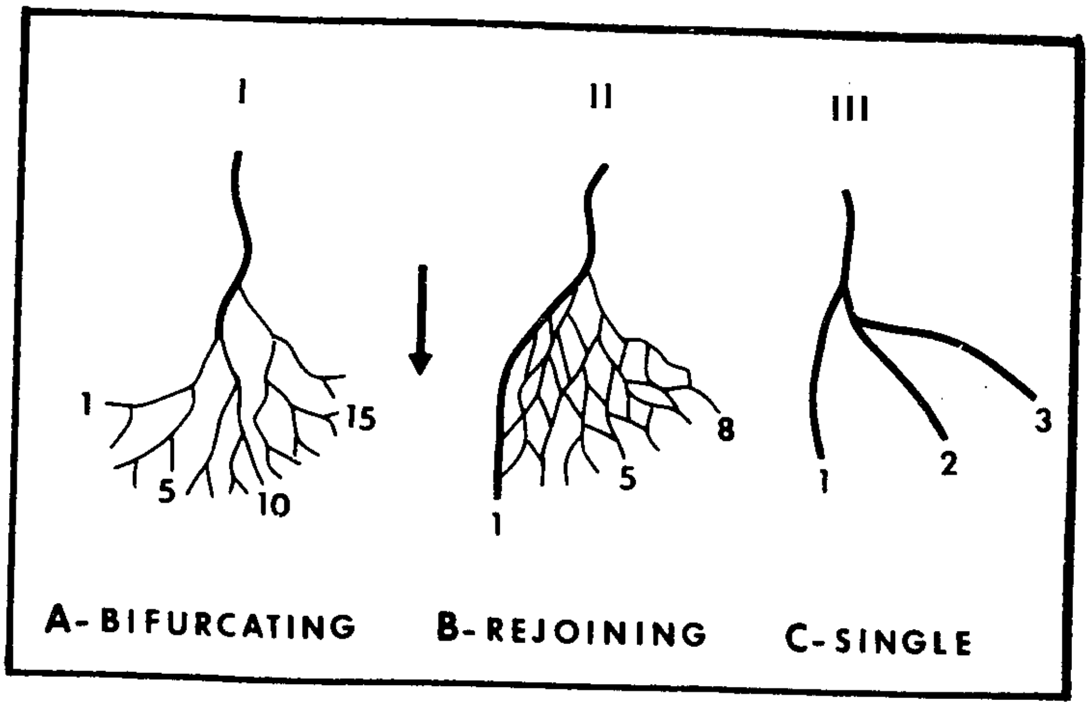
1967; Russell, 1967; Abrahams 1975); however, additional channels may also form when high flood waters cut through a natural levee. The resultant crevasse can remain active for some time and often becomes a permanent part of the distributary network (Welder, 1959; Kuiper, 1960; Russell, 1967; Coleman and Wright, 1971).

Channel closure and abandonment has been discussed by Welder (1959), Axelsson (1967), Russell (1967), Dahlskog *et al.* (1972), Thakur and MacKay (1973), Einstein (1972), English (1979) and others. Axelsson (1967) points out that the channel elongation often leads to a reduction in energy gradient. As a result, sediment begins to deposit closer to the channel entrance, often forming a bar across the entrance and sealing off the channel. In addition, the decreased slope allows backwater to advance upstream, exposing more of the channel to the erosive effects of wave and current action. According to Russell (1967), the development of bifurcating channels also results in the preferential transportation of bedload in one of the two branches. As a result, channels which carry the majority of the bedload are often sealed off when this material is deposited just downstream from the entrance. These deposits lead to the creation of a channel bar which, in time, eventually forms into a natural levee. This process is often enhanced by the invasion of aquatic vegetation and the deposition of woody debris, both of which reduce channel velocity and impede sediment laden flows, thereby creating an excellent environment for deposition (Dahlskog *et al.*, 1972; Gill, 1973; English, 1979; Knighton 1984).

Coleman (1982), has suggested a three-fold classification scheme of distributary networks (Fig. 2.4). Several channel classifications have also been

Fig. 2.4

Common Types of Distributary Channel Networks



(Coleman, 1982)

suggested by researchers in the fluvial environment (Leopold & Wolman, 1957; Schumm, 1963; Scheidegger, 1968; Mayer, 1970; Kellerhals *et al.*, 1976; Knighton, 1984; Rosgen, 1994); however, Coleman and Wright's (1971) "distributary index" and Smart and Moruzzi's (1971) "quantitative properties" have been developed specifically for delta channel networks.

2.1.3.2. Natural Levee and Point-Bar Development

Bates (1953), Bagnold (1960), Leopold and Wolman (1957, 1960), Wolman and Brush (1961), Leopold *et al.* (1964), Axelsson (1967), Russell (1967), Morisawa (1968), Dahlskog *et al.* (1972), Gill (1973), Thakur and MacKay (1973), Ritchie and Brunsden (1978), Knighton (1984), and Van Gelder *et al.* (1994) have discussed natural levee formation and point-bar development in both riverine and deltaic environments. As previously outlined, Bates (1953), Russell (1967), and Thakur and MacKay (1973) have discussed the processes of submarine levee formation. Axelsson (1967), Russell (1967), Gill (1973), Ritchie and Brunsden (1978), and Van Gelder *et al.* (1994) have addressed the significance of flood water and overbank deposits in the continued growth of subaerial levees.

The processes of channel meandering and point-bar development have been covered extensively by Leopold and Wolman (1957, 1960), Bagnold (1960), Wolman and Brush (1961), Leopold *et al.* (1964), Russell (1967), Morisawa (1968), and Knighton (1984). Leopold and Wolman (1960) described point-bar development in terms of a "cross-channel velocity component" which forced surface flows toward the cut-bank and bed flows toward the point bar. The authors also explained that the surface component was more likely responsible for point-bar deposition. Russell (1967) later discussed the role of "austausch" (the transfer of flows from areas of high to low turbulence) in the growth of point-bars. According to Russell (1967), deposition occurs when sediment is transferred from the highly turbulent thread of maximum flow near the cut-bank toward the relatively calm flows over the point-bar.

2.1.3.3 Hydraulic Characteristics

Leopold and Maddock (1953) were among the first to study the relationships between channel width, depth, velocity, suspended sediment, and discharge. In addition, the work of these two authors has lead to an almost universal acceptance of the power function relationship between suspended sediment concentration and discharge, in which

$$ss = cq^n$$

where:
- ss = suspended sediment concentration in mg/l
- q = channel discharge in m^3/s
- c and n = constants.

Similar relationships have since been discussed by Leopold *et al.* (1964), Morisawa (1968), Dury (1969), Knighton (1984), Petts and Foster (1985), Ackers (1988), Bates (1990). Krishnappan (1983), Al-Abed (1989), Loppes and Ffolliott (1993), and Milburn and Prowse (1995) examined the impacts of ice cover on sediment transport. Results from these studies seem to indicate that sediment transport is substantially higher during the ice-free period.

Additional research has also been conducted on the relationship between hydraulic characteristics and their impacts on channel sinuosity and gradient (Miller 1988), the development of concave longitudinal profiles (Morisawa, 1968; Jiongxin 1991), channel stability (Al-Ansari *et al.*, 1988: Ikeda *et al.*, 1988: Robinson and Beschta, 1989; Williams, 1989), equilibrium (Harvey, 1969; Mosley, 1982; Jia, 1990; Miller, 1991), and mathematical models (Ivanov, 1970; Mikhailov, 1970).

2.2 Northern Deltas

The uniqueness of northern deltaic deposits has been discussed by several authors including: Dahlskog *et al.* (1962), Axelsson (1967), MacKay (1970a, 1970b), Walker (1970), Vagin (1970), Gill (1973, 1975, 1976b), Naidu and Mowatt (1975), and Ritchie and Walker (1975). According to Naidu and Mowatt (1975), sedimentary facies such as natural levees and fresh water swamps are often nonexistent in arctic deltas due to low tidal ranges and the lack of bankfull discharges. The authors also point out that the low energy hydraulic conditions in northern deltas often produce poorly sorted sediment and attribute the relative absence of soluble nutrients to low organic productivity and the predominance of mechanical weathering.

An excellent summary of thermoerosional niches is provided by Walker (1970) and Ritchie and Walker (1975). The authors describe the physical processes involved and outline their impacts on depositional and erosional rates in the deltaic environment.

The significant roles of river ice are discussed by several authors including:

Dahlskog *et al.* (1962), Axelsson (1967), Vagin (1970), Walker (1970), Gill (1973), Naidu and Mowatt (1975), English (1979, 1984), Smith (1979), Gerard (1981), Prowse and Marsh (1989), Prowse (1994), Milburn and Prowse (1995), and English *et al.* (1996). Vagin (1970), Prowse and Marsh (1989), and Prowse (1994) address the processes involved in mechanical breakup and the formation of ice dams while Gerard (1981) and English *et al.* (1996) explain why the occurrence of such events is reduced under regulated conditions.

2.3 THE SLAVE RIVER DELTA

The Slave River Delta has received very little attention in terms of scientific research despite the fact that it is one of the largest and most biologically significant deltaic deposits in Canada. Regulation of the Peace River at Hudson's Hope, British Columbia and a proposal to dam the Slave River has lead to the initiation of several studies during the past 30 years. In general, however, most of these studies have focused solely on the ecological aspects of the delta and how they might be impacted by upstream impoundment. Because of this, there is a lack of knowledge pertaining to physical processes in the Slave River Delta.

2.3.1 EARLY LITERATURE

Early accounts of the Slave River Delta focused primarily on physical descriptions and were recorded in the journals of early fur traders and explorers passing through the area (Ross, 1862; Preble, 1908; Fidler, 1934). After the turn of the century, most of the literature written on the Slave River Delta focused on the glacial origins of the region (Hume, 1921; Cameron, 1922; Craig, 1965; Bryson *et al.*, 1969). Hume (1921) interpreted a series of beach ridges south of the Slave River Delta as evidence of isostatic rebound from past glaciation, a conclusion substantiated by Cameron's (1922) work in which the author classified Moose Deer Island and Round Island as roche moutonées. Bryson *et al.* (1969) examined both the spatial and temporal context of glaciation in the area and determined that glacial retreat began approximately 10 000 years ago. As the ice retreated, it left behind a large standing body of water which Craig (1965) has named Lake McConnell. According to Cameron (1922), the combination of retreating ice and isostatic rebound caused Lake McConnell to drain northward and eventually lead to the formation of the present day Great Slave Lake. Development of the Slave River Delta began as alluvial material carried by the drainage of Lake McConnell slowly filled in the southern arm of the lake (Cameron, 1922).

2.3.2 RECENT STUDIES

Most of the recent studies on the Slave River Delta have focused primarily on ecological aspects such as local vegetation assemblages (Harper, 1931; Raup, 1946), waterfowl habitat (Soper, 1949, 1952a, 1952b, 1957), and muskrat populations (Law, 1950; Bodden, 1981a, 1981b; Geddes, 1981). In addition, many of these studies were carried out as part of a larger project established to examine resources on a regional scale. As a result, the Slave River Delta has often received little more than cursory attention. In this vane, Harper (1931) and Raup (1946) each provide only a brief synopsis of the Slave River Delta in their reports, noting some of the dominant plant species and their relative distribution.

Soper's (1949, 1952a, 1952b) work, however, specifically outlined the significance of the Slave River Delta in terms of a natural habitat for waterfowl populations and proposed potential site locations for sanctuaries within the delta and on Egg Island. Since Soper's time, waterfowl studies in the area have continued throughout the past century (Smith *et al.*, 1964; Welleim and Lumsden, 1964; Bellrose, 1976; Thompson *et al.*, 1981). Smith *et al.* (1964) pointed out several key characteristics of the Slave River Delta which make it an excellent natural habitat for waterfowl including rich aquatic vegetation, scarcity of predators, and sparse human population. In addition, the naturally wet conditions of the delta provide a refuge when drought forces waterfowl populations to abandon nesting sites in the prairies (Smith *et al.*, 1964; Thompson *et al.*, 1981).

Other wildlife studies in the Slave River Delta have focused almost exclusively on the muskrat population (Law, 1959; Bodden, 1981a, 1981b; Geddes, 1981). Law's (1950) research focused primarily on the basic biology of the species, examining living habits, behaviour, and physiology. Bodden (1981a), on the other hand, explored the relationship between muskrat populations on the delta and the economic stability of nearby Fort Resolution. He points out that the muskrat population provides not only a large part of the country food for the town's population, but also represents a large portion of the towns economic base due to its significance in the fur trade. Geddes' (1981) work followed after the work begun by Bodden and outlined recommendations for sustaining muskrat populations and suggestions for future research.

Interestingly, the inclusive nature of Law's (1950) research on muskrat ecology provided one of the first data sources on the physical characteristics of the Slave River Delta. Law's (1950) report to the Canadian Wildlife Service contained qualitative descriptions of various plant assemblages, references to the impacts of the seiche effect from Great Slave Lake on water levels in the delta, and a discussion on the effects of high water levels on channel formation and the deposition of sediment. As a result, Law's work established an analogous starting point for later research by Brown (1950), Rowe (1972), Day (1972), Kemper (1972), Raup (1975), Gill (1976a), Gill *et al.* (1977), English (1979, 1984), Mollard (1981), Vanderburgh and Smith (1988), and English *et al.* (1996).

Raup (1946) provided one of the first descriptions of the geology of the Slave River Delta, explaining how the area is bound by the Laurentian Plateau and the Mackenzie Lowlands. As a result, the delta is surrounded by granitic formations to the east and sedimentary formations to the west. Additional summaries of the local geology are furnished in the more recent writings of Brown (1950), Day (1972), Rowe (1972), and Raup (1975). The three latter authors also wrote extensively on the distribution of alluvial deposits in the Slave River Lowlands and the Slave River Delta in particular.

Day (1972) produced a comprehensive soil map of the region, defining most of the deposits as a Cumulic Regosol which result from temporal variations in sediment deposition during flood events. In addition, Day identified the presence of permafrost in association with the delta's white spruce stands.

Descriptions of alluvial deposits within the Slave River Delta were recorded by both Rowe (1972) and Raup (1975); however, their research primarily focused on vegetation - soil relationships across the Great Slave Lake - Lake Athabasca region.

A more recent study of alluvial deposits in the Slave River Delta is found in Vanderburgh and Smith (1988). Examining lithostratigraphic logs taken from river cutbanks, the authors found most to be composed of basal laminated mud, interbedded mud and sand, and planartabular ripple sets interbedded with cross-laminated to flat-bedded sand. They also used radio-carbon dated wood and determined that the Slave River Delta has been prograding at an average rate of 20.7 m/year over the last 8070 years. The author's examined seven cross sectional profiles of Resdelta Channel and found width/depth ratios decreased downstream from 61 to 11. Two additional transects were established perpendicular to the delta front into Great Slave Lake in order to identify the morphology of the delta slope.

As outlined earlier, Rowe (1972) and Raup (1975) attempted to draw links between the alluvial deposits and vegetational assemblages in the Slave River Delta. Rowe (1972) identified a strong association between alluvial deposits and large stands of white spruce and balsam poplar in the Slave River Lowlands. In addition, Rowe (1972) classified the area as Upper Mackenzie Boreal Forest. Raup (1975) discussed the role of environmental factors in the distribution of plant assemblages and identified the problems associated with their classification.

Gill (1976a) and English (1979, 1984) continued the work of Rowe and Raup, attempting to broaden the understanding of plant succession in the wetland environment. Gill (1976a) identified strong similarities in plant distribution and successional patterns within all three of the Peace-Athabasca, Mackenzie, and Slave River Deltas. English's (1979, 1984) work explored the impact of river regulation on deposition downstream and how this relationship effects plant succession. English (1984) noted that lower water levels caused by upstream impoundment "would allow vegetation of later successional stages to invade and displace the highly productive emergent plants". Examining deposits within the Slave River Delta, English (1979) found most to be composed of fine sands and coarse silts (2Φ - 4.25Φ). The author explained that diminished flows could reduce progradation rates at the delta front due to decreased bedload and coarse grained particles.

In 1981, Mollard made an attempt to "determine the historic development of the Delta, the Delta's present rate of change..., and the stability of the distributary channels and status of the water in the Delta". Mollard (1981) examined nine sets of aerial photography and 5 Landsat images and generated maps showing the development of shoreline features and distributary channels over a 50 year period (1930 - 1980). The author observed a dramatic shift in drainage pattern throughout the development of the Slave River Delta and noted that the most dramatic change in delta front progradation (an increase of 1 - 2 km) occurred between 1930 and 1946. Mollard also indicated that the areal advance of the delta could be predicted "on the basis of certain assumptions" about sediment inflow, deposition, and water depth at the delta front

(Mollard, 1981). As the delta has matured however, such estimates have been made somewhat difficult due to the complex structure of the drainage network which influences the availability of sediment and the progradation of the delta into deeper waters.

Very little is known about the channel processes in the Slave River Delta. Law (1950) attributed changes in water levels to sudden thaw and heavy rains in the upper basins, seasonal lowering of the water table, changes in channel configuration, and the development of a seiche off Great Slave Lake. The latter, caused by prevailing north westerly winds "piling up" water at the mouth of distributary channels has been identified by both Law (1950) and Davies (1981). Davies (1981) observed a 10 - 20 cm rise in channel water levels on the Slave River Delta due to wind setup while Law (1950) indicated that seiche effects increased Great Slave Lake levels by approximately 24 cm after only a few hours of strong wind conditions.

English (1979) wrote extensively on the relationships among vegetational development, channel water depth, flood frequency, suspended sediment, and deposition within the Slave River Delta. He also described the hydrologic and morphologic processes governing the evolution of cleavage bars, cut-bank levees, point bars, and channel closures.

Davies (1981) examined stream flow, water level, suspended sediment and water quality data throughout the delta over a 27 month period from June, 1978 to September, 1980 and observed that water levels fluctuated up to 3 m during this period, reaching their lowest point in the fall and peaking in the spring during breakup. By establishing automatic water level recorders and converting stage levels to daily stream flows, Davies determined that "86% of the Slave River flows through the Resdelta Channel, 5% through the Middle Channel West, and 9% through the remaining five channels" during the summer months. Davies indicated that these percentages changed to 93%, 5%, and 2%, respectively during the winter. Suspended sediment and water quality samples were taken and compared to measurements upstream at Fort Smith. According to Davies (1981), "the long-term data at Fort Smith were found to be representative of the short-term delta measurements".

The most recent study of the Slave River Delta (English *et al.*, 1996) focused on the impacts of upstream impoundment on the flow dynamics of the Slave River and their effects on the hydrology and morphology of the Slave River Delta. The authors observed only a slight decrease in mean annual discharge from the pre- to post-impoundment period; however, because of the seasonal fluctuations in sediment concentration, projected a 33% decrease in the average annual sediment load. The altered sediment regime of the Slave River Delta has dramatic implications for not only the development of the Slave River Delta, but the diverse ecological environment it supports as well. By examining aerial photography, English *et al.* (1996) observed a relative decrease in active progradation and a general shift toward a drier environment in the outer delta during the post-impoundment period.

2.4 *RIVER REGULATION*

Because of the importance of hydrologic regime in the delivery of sediment to the delta front, the effects of upstream impoundment have significant implications for the deltaic environment. Several studies on the effects of river regulation have been conducted and documented throughout the world (Day, 1971; Fraser, 1972; Blench, 1972; Taylor *et al.*, 1972; Knighton, 1984; Petts & Foster, 1985; Graf, 1988; Gore and Petts, 1989; Gurnell *et al.*, 1990; Jiongxin, 1990b, 1990c; Nouh, 1990; Wyzga, 1993; Maheshwari, 1995), several of which have focused on cold region environments (Blench, 1972; Peace-Athabasca Delta Project Group, 1972; Gill, 1971, 1973, 1976b; English, 1979, 1984; Jiongxin, 1990c; Vuglinsky, 1990; English *et al.*, 1996). In most cases the post-impoundment period is characterized by a general reduction in flow variability, often with a reduction in peak flows and a corresponding increase in low flow conditions. According to Al-Taiee (1990), regulation of the Tigris has resulted in a dramatic loss of suspended sediment in downstream flows as well as a reduction in sediment grain size. Changes in the hydrologic regime have been shown to have direct impacts on channel morphology downstream as width, depth, gradient, and bed material readjust to regulated flows (Taylor *et al.*, 1972; Graf, 1988; Gore and Petts, 1989; Jiongxin, 1990a, 1990b; Wyzga, 1993).

The ecological implications of alterations in the hydrological regime and channel morphology of regulated rivers have been discussed by Dirschl (1971), Fraser (1972), Blench (1972), Gill (1971, 1973, 1976b), English (1979, 1984), Gore and Petts (1989), and English *et al.* (1996). Gill (1973, 1976b) also pointed out the effects of river regulation on northern environments such as the Mackenzie River Delta where alteration of the natural hydrological regime would theoretically result in decreased temperatures which, in turn, could lead to increased permafrost development, longer ice cover periods, and a general reduction in the overall productivity of the area. Similar trends have been observed in the Peace-Athabasca delta (Dirschl, 1971; Peace-Athabasca Delta Project Group, 1972; Blench, 1972) and more recently on the Slave River delta (Bodden, 1981a, 1981b; English, 1979, 1984; English *et al.*, 1996).

• CHAPTER 3.0 •

CHANGES IN THE SLAVE RIVER FLOW REGIME AND IMPACTS ON CHANNEL FORM AND PROCESS IN THE SLAVE RIVER DELTA, NWT

3.1. INTRODUCTION

The Slave River Delta is located at the mouth of the Slave River in Canada's Northwest Territories and lies approximately 1600 km downstream from the W.A.C. Bennett Dam which was completed on the Peace River at Hudson's Hope, British Columbia in 1968 (Fig. 3.1). The active portion of the delta covers approximately 400 km^2 and is composed of lacustrine sediments deposited by a complex network of distributary channels (Fig. 3.2).

Because the Slave River receives as much as 80% of its flow directly from the Peace River (Fig. 3.3) it is assumed that any impacts on flow conditions in the Peace will be reflected in the hydrology of the Slave. In fact, recent research by English *et al.* (1996) indicates that mean discharge on the Slave River has decreased by 16% during the ice free period since regulation while under-ice flows have increased by 40% (Fig. 3.4).

The alteration of the Slave River flow regime has very significant implications for progradation of the Slave River Delta since the transfer of sediment to the delta front is one of the most important factors in maintaining the landform's continued growth (Bardach, 1964; Reid and Wood, 1976; Tripp *et al.*, 1981). By reducing Slave River discharge during the ice-free period, regulation has lead to a decrease in channel

Fig. 3.1

Study Site

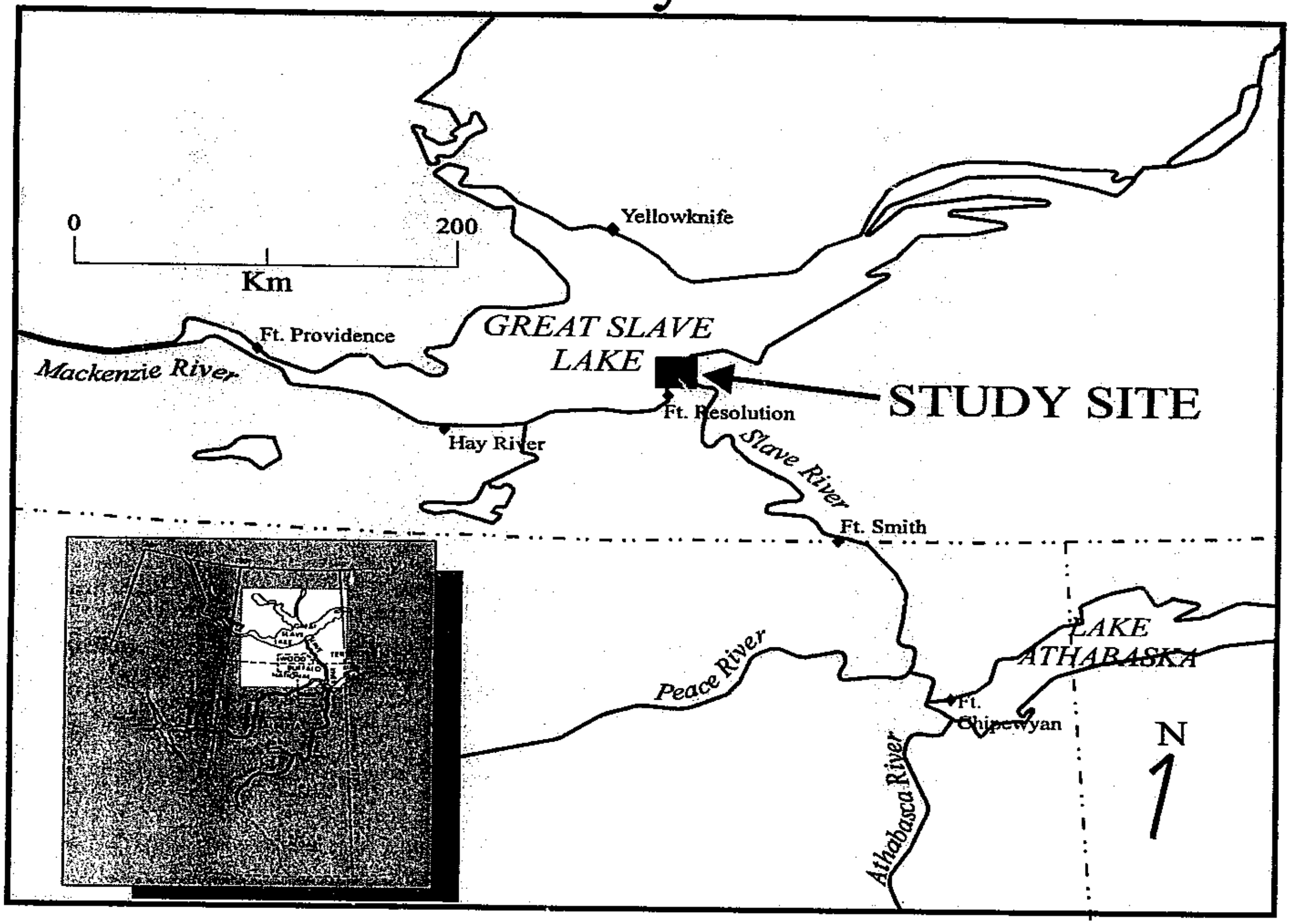
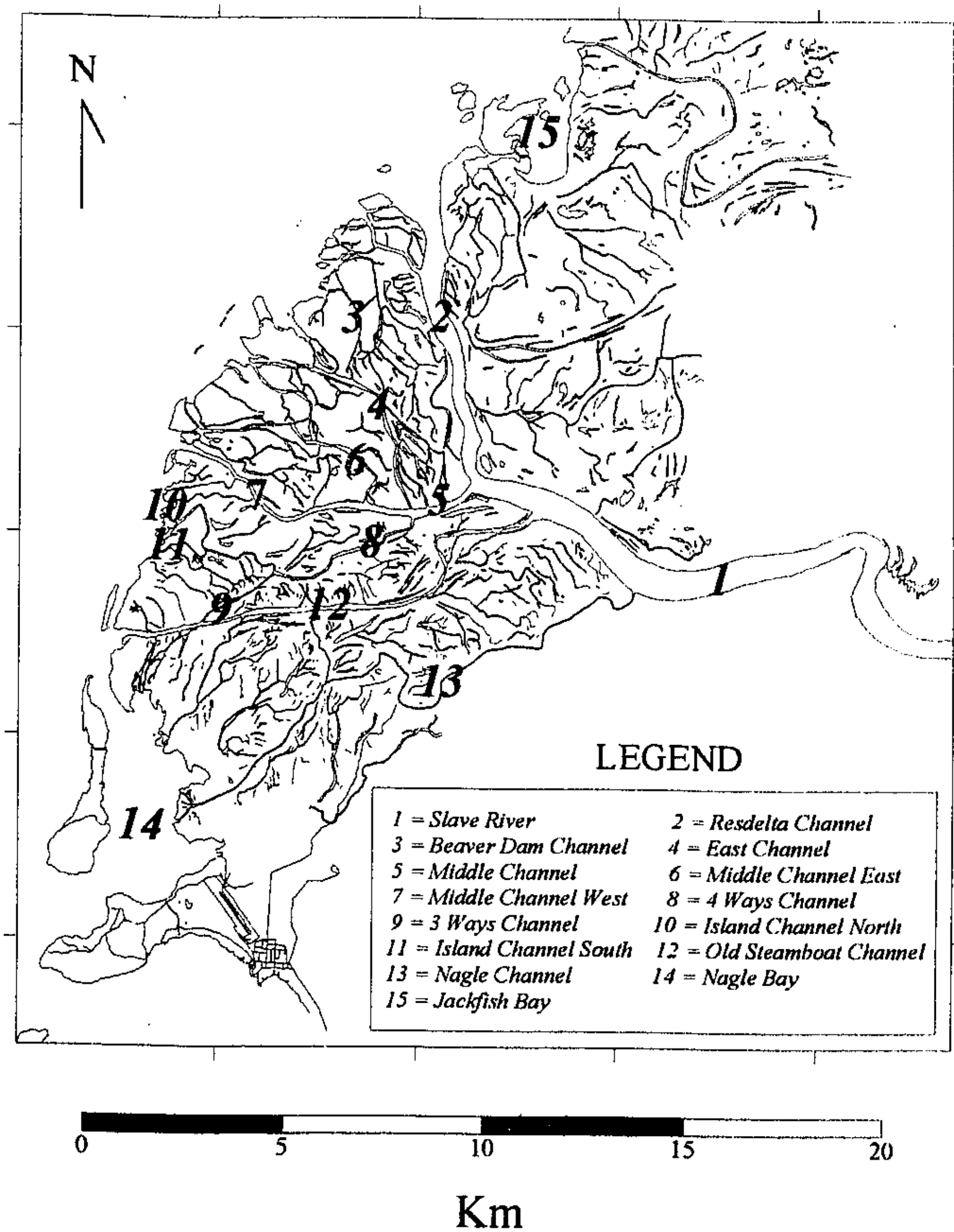


Fig. 3.2

Slave River Delta Channel Network



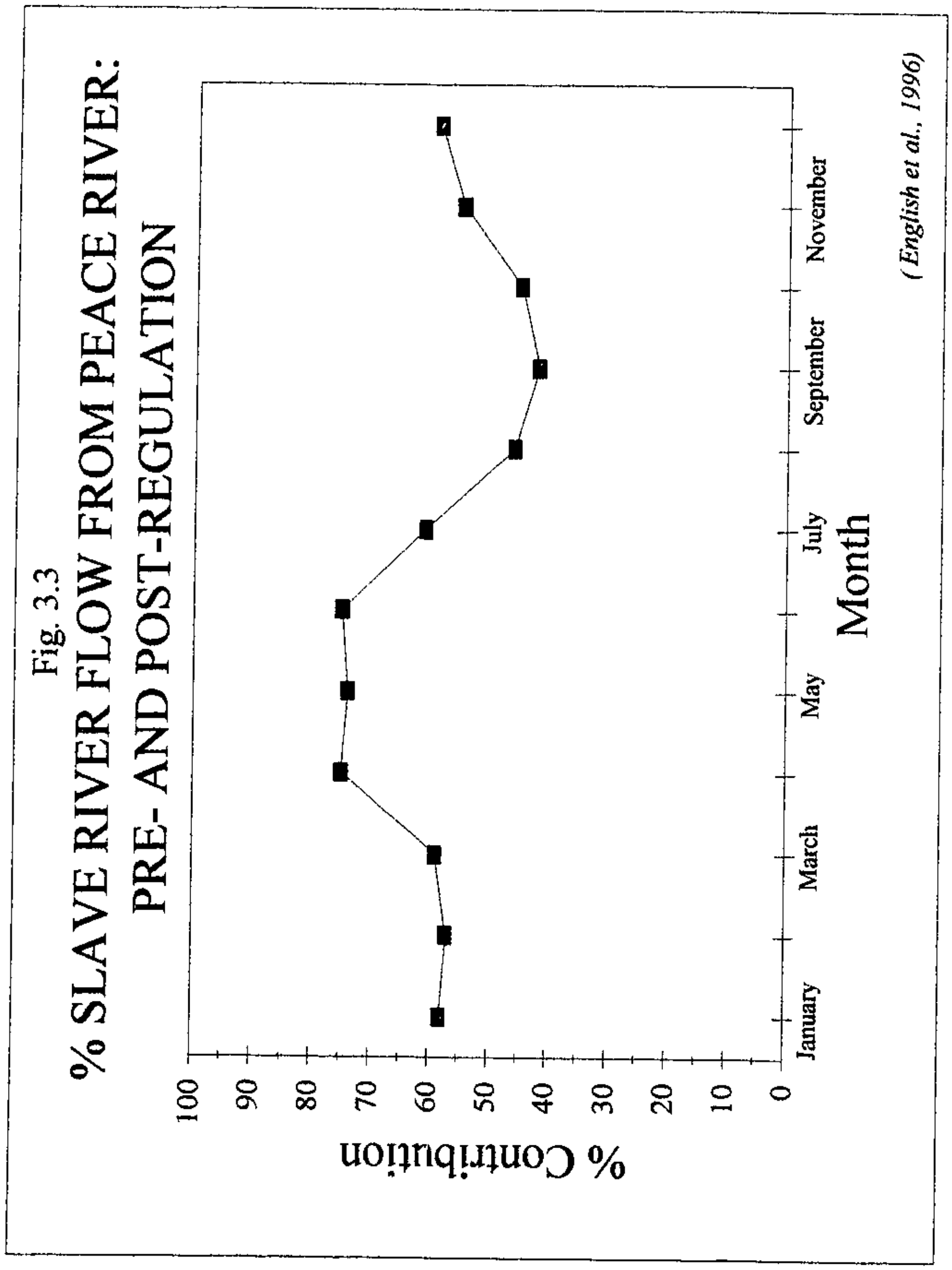
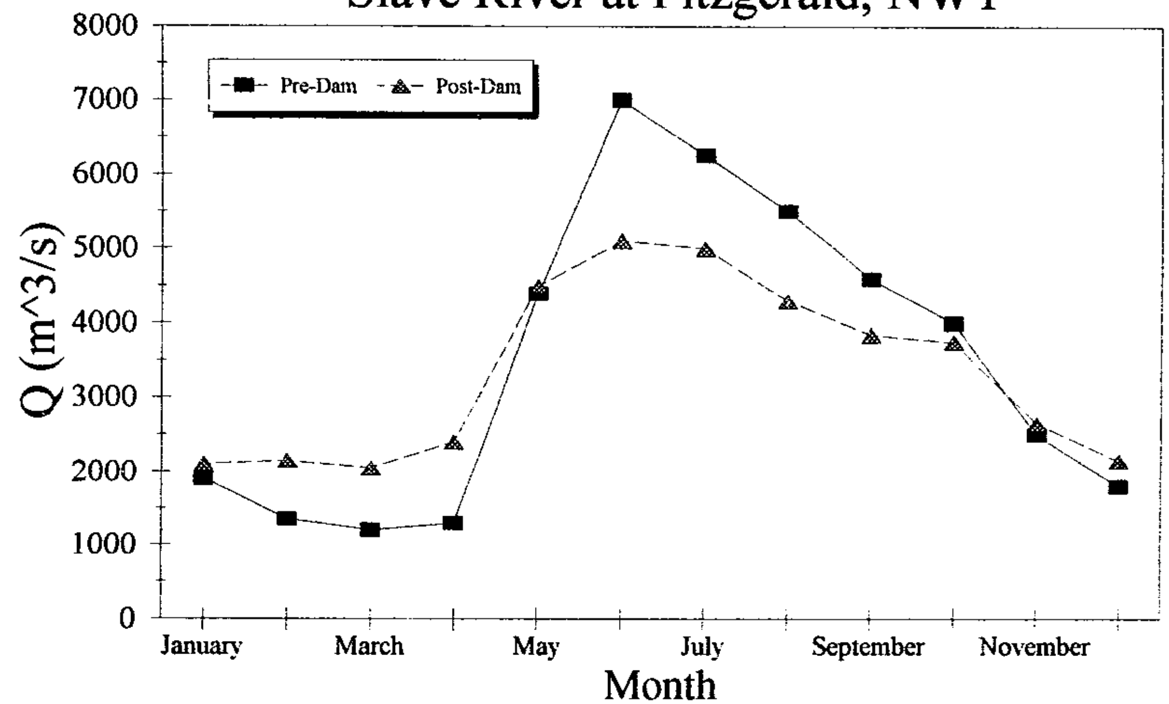


Fig. 3.3
% SLAVE RIVER FLOW FROM PEACE RIVER:
PRE- AND POST-REGULATION

Fig. 3.4 Mean Monthly Discharge
Slave River at Fitzgerald, NWT



(English et al, 1996)

competency as well as the overall transport of sediment to the delta during the summer months (English *et al.*, 1996). In order to assess the full implications of impoundment on past developments within the Slave River Delta and address environmental concerns for the future, it is essential to develop a stronger understanding of the hydrological processes which are actually occurring in the present.

The purpose of this chapter is to identify hydrological changes within the Slave River Delta by examining flow characteristics before and after regulation and to identify the processes taking place within the channel network in order to assess their influence on deposition and erosion. Data gathered from field research, historical sources, and aerial photography are used to estimate past and present hydrological conditions as well as to examine the impacts of seasonal variations in the annual hydrograph and channel bifurcation on the relationship between sediment transport and deposition within the Slave River Delta.

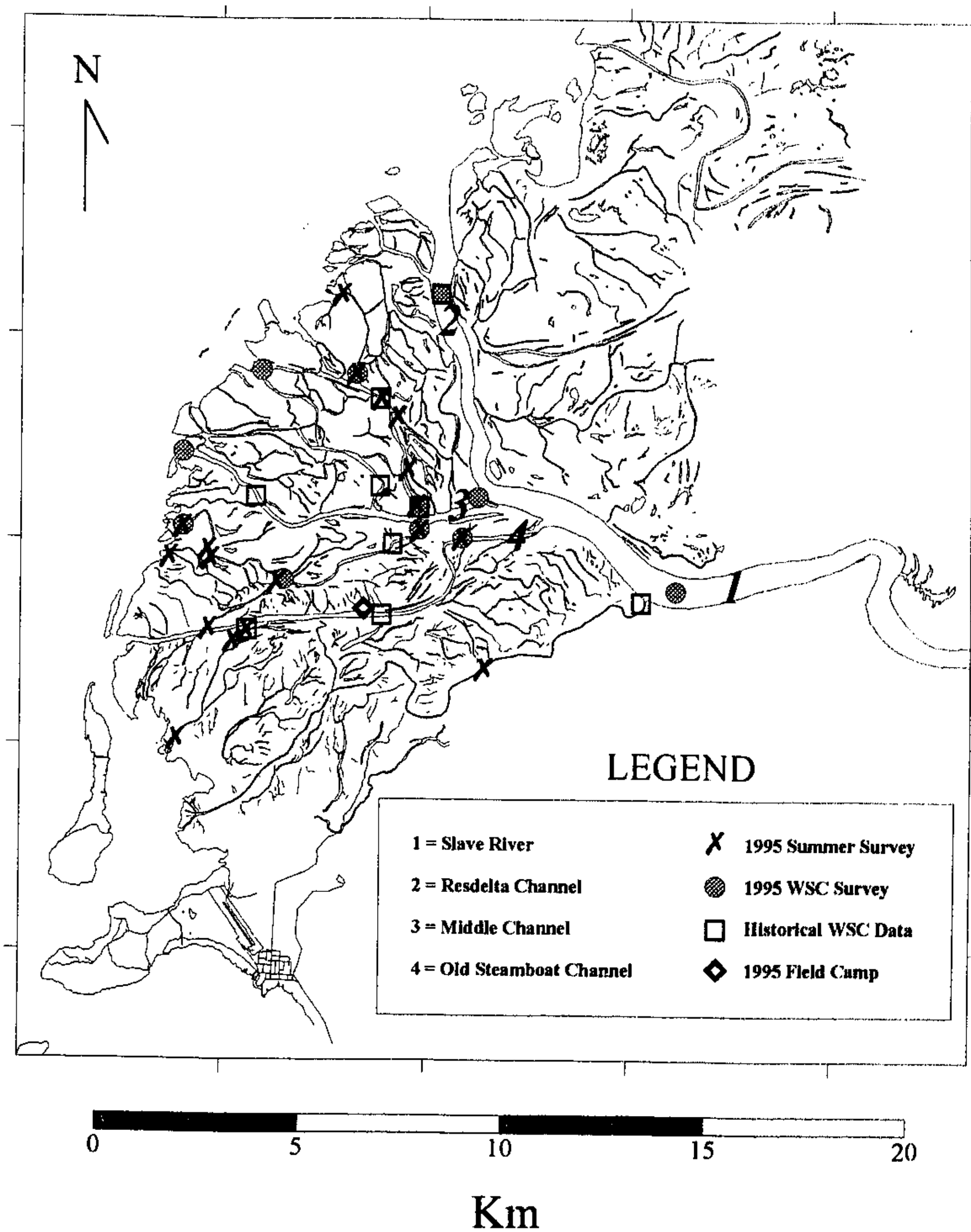
3.2. METHODOLOGY

3.2.1 STUDY AREA

A total of 22 sites were selected throughout the Slave River Delta during the summer of 1995 in order to study flow characteristics and channel morphology (Fig. 3.5). The choice of suitable study sites was made through the combined examination of aerial photography and reconnaissance within the delta. Areas of notable change or senescence in channel morphology were identified from the photographs taken before and after regulation and specific study sites were chosen after conducting on-site investigations

Fig. 3.5

Sampling Sites



in each area.

3.2.2. FIELD METHODS

3.2.2.1 Channel Morphology & Hydrology

Water level fluctuations in Old Steamboat Channel (Fig. 3.2) were measured with potentiometers connected to Cr21X data loggers. Daily observations were also made on stage boards positioned at the base camp, the mouth of Old Steamboat Channel, and at the mouth of Beaver Dam Channel (Fig. 3.2).

Eighteen transects were established across selected channels within the delta (Fig. 3.5) for the measurement of width, depth, discharge, and suspended sediment concentration ([SS]). Transects were surveyed using a Pico Transit to determine the cross sectional profile of the channel levees. The channel portion of each transect was evenly divided into 5 panels and a cross sectional depth profile was constructed by measuring the depth at the centre of each panel.

A velocity measurement was taken at 60% of the measured depth in each panel using a Marsh McBirney velocity meter and recorded for discharge calculations. Suspended sediment samples were taken from the centre three panels with a DH-48 suspended sediment sampler and saved for future analysis. It was assumed that these locations were representative of the suspended sediment load within the channel since the highest flows are generally recorded towards the centre of the channel. This methodology was repeated for each transect over the course of the field season.

During the month of September, the Water Survey of

Canada (WSC) resurveyed and sampled suspended sediment at 7 of the 18 transects as well as 4 new sites (Fig. 3.5). The WSC used similar methods to determine depth and flow velocity; however, each transect was divided into 20 panels rather than 5. In addition, suspended sediment samples were drawn from each panel using a D-49 suspended sediment sampler.

3.2.3. HYDROLOGICAL ANALYSIS

Discharge values were calculated for each sample period by multiplying the recorded depth, width and velocity measurements for each panel of the transect. Discharges for each panel were then summed in order to determine the total discharge for the channel cross section.

A relationship between channel width and discharge was developed by taking widths from all the channel profiles surveyed during the summer field season and plotting them against their respective discharge values. The "curve - fit" option of the REGRESSION menu in SPSS for Windows was used to develop an equation to represent the relationship between channel width and discharge based on a total of 85 observations. This option produced several possible equations; however, a third order polynomial was chosen to represent the relationship based upon the fact that it had the highest R^2 value which, in turn, means that it best describes the relationship between the two variables. Estimates of past hydrological regimes were then developed by measuring the channel widths from aerial photography of the delta taken in 1946, 1966, 1977, and 1994 and using these values in the cubic equation.

Because all four sets of photography were taken at different times of the year, steps had to be taken to adjust the estimated discharges to a common time period. Since the most recent set of photos were taken in June of 1994, this month was chosen as the common reference. To do this, discharge values were calculated for selected channels based on the water levels in the 1946, 1966, 1977, and 1994 photography. After examining hydrographs of the Slave River at Fitzgerald before and after regulation (Fig. 3.4), it was concluded that July flows, estimated from the 1946 photography, would be 10.7% lower than those in June. As a result, discharge values estimated from channel widths in the 1946 photography were multiplied by a correction factor of 1.12 to in order to arrive at an adjusted estimate for June flows. Similar steps were taken for 1966 and 1977 photography whose September discharge values were multiplied by 1.50 and 1.37 respectively in order to reach a June estimate.

3.2.4. SUSPENDED SEDIMENT ANALYSIS

3.2.4.1. Field Calculations

At the base camp, the volume of each DH-48 sample was measured and air dried on pre-weighed foil plates for several days. The [SS] values were then determined gravimetrically in the field (Environment Canada, 1984).

3.2.4.2. Laboratory Calculations

Suspended sediment samples taken near the end of the field season were returned to Wilfrid Laurier University (WLU) and used to determine [SS] and particle size distributions. Similar steps were taken with the suspended sediment samples taken by the WSC during September.

Each of these samples were run through a filtration process to determine the [SS]. By measuring the volume of the sample along with the dry weight of the filter before and after filtration, the mass of sediment was determined for the given volume of each sample and used to calculate [SS] in mg/L.

3.2.4.3. Errors

There appears to be some discrepancy between [SS] values calculated in the field and those calculated in the laboratory. In fact, [SS] taken less than one week apart with approximately the same discharge values were, in some cases, different by at least an order of magnitude (Table 3.1). It was assumed that imprecision of measurement in the field samples was to blame for most of the problem since these samples were weighed out on a triple beam balance which could only be read to one decimal place.

In order to test this hypothesis, a brief analysis was conducted on two samples drawn from the Laurel Creek near the Weber Street WSC station in Waterloo (Appendix B). An aliquot of 515 ml was extracted from the first sample which was taken during low flow conditions and an aliquot of 290 ml was extracted from the second sample taken under storm flow conditions. Each of these two aliquots were then processed using the field methodology outlined in section 3.2.4.1.

Table 3.1

Potential Errors in Suspended Sediment Concentrations Calculated From Field Methods

Date	Site	Discharge (m^3/s)	[SS] (mg/l)	
jun 02 95	3 ways entrance	25.688	319.149	✓
jun 08 95	3 ways entrance	30.066	280.749	✓
jun 21 95	3 ways entrance	29.167	78.947	
jun 08 95	3 ways mouth	24.710	491.228	✓
jun 21 95	3 ways mouth	28.943	78.125	
jun 02 95	4 ways entrance	40.057	215.070	✓
jun 21 95	4 ways entrance	37.092	76.087	
may 25 95	beaver dam entrance	5.900	473.389	✓
jun 07 95	beaver dam entrance	4.970	212.019	✓
jun 20 95	beaver dam entrance	4.435	76.190	
jun 29 95	beaver dam entrance	4.024	47.297	
may 25 95	beaver dam mouth	4.797	643.853	✓
jun 07 95	beaver dam mouth	4.171	211.694	✓
jun 20 95	beaver dam mouth	3.895	90.909	
jun 29 95	beaver dam mouth	4.119	64.935	
jun 07 95	east channel entrance	14.433	938.342	✓
jun 20 95	east channel entrance	15.928	94.937	
jun 07 95	east channel mouth	31.335	631.579	✓
jun 20 95	east channel mouth	29.707	73.333	
jun 29 95	east channel mouth	31.816	50.314	
jun 02 95	island north entrance	8.641	377.806	✓
jun 08 95	island north entrance	6.888	422.546	✓
jun 21 95	island north entrance	6.183	69.892	
jun 30 95	island north entrance	5.698	37.634	
jun 08 95	island north mouth	7.919	282.941	✓
jun 21 95	island north mouth	6.081	56.995	
jun 02 95	island south entrance	10.484	287.030	✓
jun 08 95	island south entrance	11.401	425.532	✓
jun 21 95	island south entrance	10.252	75.269	
jun 30 95	island south entrance	11.792	46.875	
jun 08 95	island south mouth	10.164	424.412	✓
jun 21 95	island south mouth	10.332	93.750	
jun 30 95	island south mouth	8.592	42.105	
jun 01 95	steamboat channel entrance	28.960	358.740	✓
jun 22 95	steamboat channel entrance	34.680	112.821	
jun 29 95	steamboat channel entrance	32.350	60.606	
jun 07 95	v north	4.749	840.690	✓
jun 20 95	v north	3.411	67.568	
jun 07 95	v south	10.945	924.951	✓
jun 20 95	v south	11.375	79.268	
may 31 95	whiteman's entrance	5.078	431.109	✓
jun 12 95	whiteman's entrance	4.167	423.292	✓
jun 28 95	whiteman's entrance	2.879	52.083	
may 31 95	whiteman's mouth	5.661	429.222	✓
jun 12 95	whiteman's mouth	3.494	295.390	✓
jun 28 95	whiteman's mouth	2.829	46.875	
jun 12 95	whiteman's pt. bar	3.042	279.986	✓
jun 28 95	whiteman's pt. bar	3.058	42.328	

✓ *Potential Error*

Aliquots of 234 ml and 242 ml were also taken from sample one and two respectively; however, they were processed in accordance with the filtration method outlined in section 3.2.4.2.

After conducting the test, results from the first sample gave a [SS] of 388 mg/l and 51.3 mg/l for the field and lab methodologies respectively. Similarly, the field method gave a [SS] of 689.7 mg/l for sample 2 while the lab method gave only 140.5 mg/l. It was therefore concluded that concentrations calculated using the pan drying method were approximately 524% larger than those calculated using the filtration method. To compensate, values derived using the field method were reduced accordingly. As a result, these values should not be taken as exact measurements; however, the analysis of additional samples (Appendix D) indicates that this reduction provides a relatively accurate depiction of trends observed in the field.

3.2.5. SUSPENDED SEDIMENT CONCENTRATION VS. DISCHARGE

An attempt was made to develop a relationship between [SS] and discharge similar to that of channel width versus discharge. To do this, a plot of [SS] versus discharge was developed using data from all sampled channels of the Slave River Delta. In addition, similar plots were developed for three time periods in the annual hydrograph and various locations within the delta in an attempt to isolate particular trends or patterns.

3.3 *DISCUSSION*

3.3.1 CHANGES IN CHANNEL NETWORK AND FLOW DISTRIBUTION

The complex channel network of the Slave River Delta has undergone considerable change from 1946 to 1994. Maps drawn from the four sets of aerial photography under study show a dramatic decrease in channel widths in the central portions of the delta as well as the development of large shoals across Middle Channel and Old Steamboat Channel (Fig. 3.6). At the same time, Resdelta channel has continued to increase in size while Nagle Channel has remained virtually unchanged. This alteration of flow has lead to changes in the proportional distribution of flow through various channels and, as a result, has implications for the distribution of sediment throughout the delta.

A close examination of data collected during the summer field season shows a strong relationship between channel width and discharge within the Slave River Delta (Fig. 3.7). As a result, it is apparent that discharge can be estimated for specific locations within a chosen channel based on width measurements taken in the field or from remote sensing imagery.

Table 3.2 shows the discharges estimated from width measurements in each of the four major channels of the Slave River Delta over the 48 year period between 1946 and 1994 as well as the proportional distribution of Slave River flow through each. A comparison of these values and data gathered by the WSC during the fall of 1995 (Table 3.3) show very little difference and, therefore, indicate that this method of estimating channel discharge is quite accurate.

Fig. 3.6

The Slave River Delta

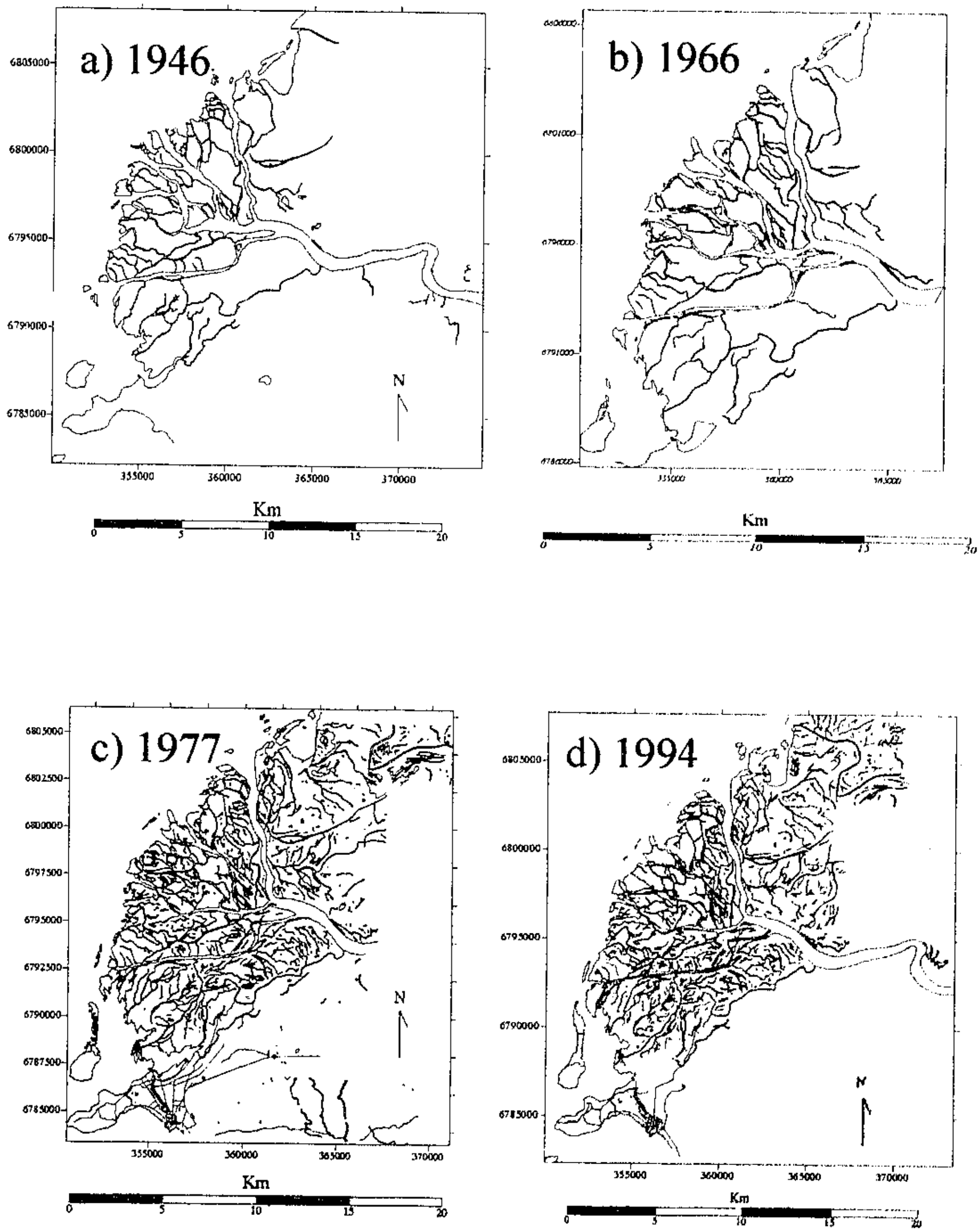
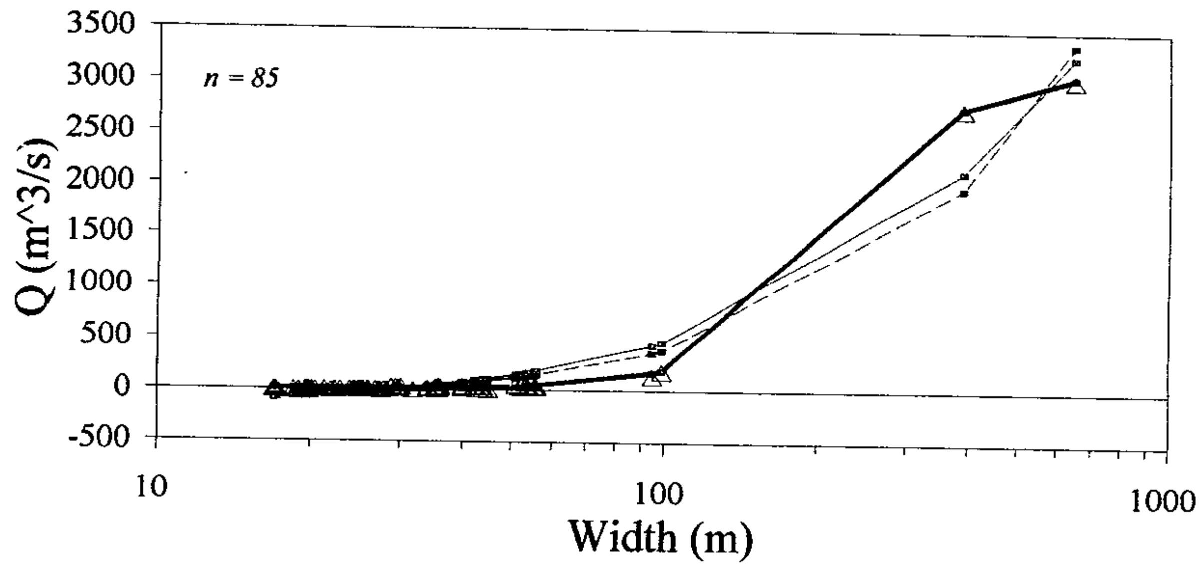


Fig. 3.7

Discharge Versus Channel Width



$Q=5.45W-157.88$ $R^2 = .937$

$Q=6.96W-.0025W^2-202.25$ $R^2 = .941$

$Q=-2.2W+.043W^2-5X10^{-5}W^3+37.69$ $R^2 = .991$

Table 3.2

Estimates of Past Flow Regimes

Year	Channel	Width (m)	Estimated Q (m^3/s)	Proportion (%)
1946	Nagle	25.00	10	0.16
	Old Steamboat	175.00	786	12.63
	Middle	450.00	3582	57.60
	Resdelta	275.00	1842	29.61
		Total	6220	
1966	Nagle	24.00	13	0.21
	Old Steamboat	156.00	827	12.86
	Middle	168.00	967	15.04
	Resdelta	432.00	4622	71.89
		Total	6429	
1977	Nagle	24.00	12	0.31
	Old Steamboat	108.00	326	8.16
	Middle	120.00	419	10.47
	Resdelta	348.00	3242	81.07
		Total	4000	
1994	Nagle	24.00	9	0.32
	Old Steamboat	72.00	84	3.00
	Middle	102.00	208	7.45
	Resdelta	360.00	2486	89.23
		Total	2786	

Table 3.3

Actual Flow Regime (1995)

Channel	Actual Q (m^3/s)	Proportion of Slave Flow (%)
Slave River	3040.269	100.000
Old Steamboat	24.200	0.796
Middle	187.177	6.157
Resdelta	2742.488	90.205

The dramatic reduction in channel width at the entrance to Middle Channel between 1946 and 1966 has lead to a considerable decrease in flow. During this time period, estimated discharge through the entrance of Middle channel dropped by 73%, resulting in a substantial decrease in the proportion of Slave River flow directed through this distributary. Estimated flows through Middle Channel continued to decrease through the next two time periods; however, the rate of estimated flow reduction has been relatively slow compared to this initial drop.

Despite a similar temporal pattern, discharge within Resdelta Channel has increased over the 48 year period. In this case, discharge is estimated to have increased more than 150% over the first 20 years; however, it actually decreased by close to 46% over the next 28 years. Because of this, the proportion of flow from the main body of the Slave River through Resdelta Channel more than doubled between 1946 and 1966, and increased by more than 200% during the entire 48 year period.

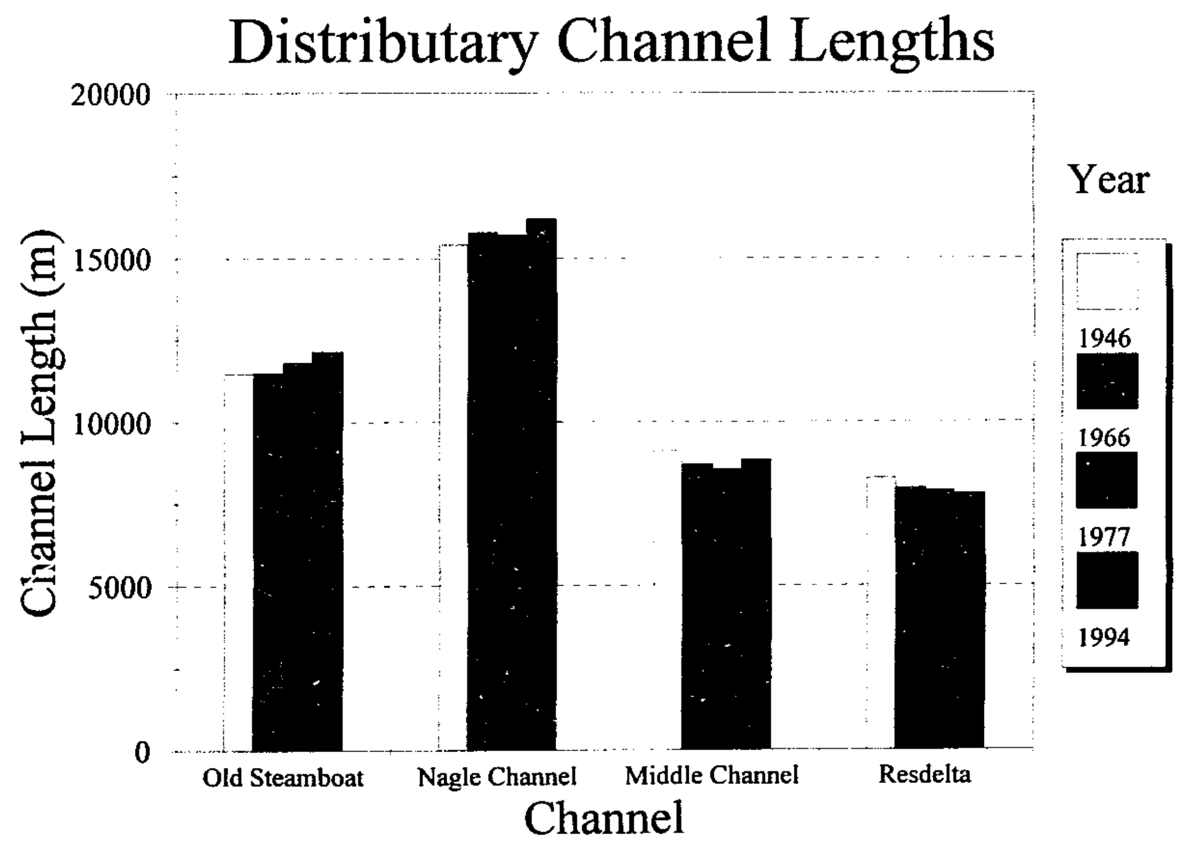
The changes in Old Steamboat Channel and Nagle Channel are less dramatic; however, they are still notable in terms of analysing the changing flow patterns within the delta. Unlike Middle Channel and Resdelta Channel, the proportion of flow through Old Steamboat and Nagle between 1946 and 1966 remained relatively unchanged. Over the next 28 years, however, the proportion of Slave River flow through Old Steamboat Channel dropped from approximately 13% to 3% due to the fact that discharge in the channel itself has decreased by almost 90%. Should this trend continue, it would appear that Old Steamboat Channel may soon be abandoned.

Nagle Channel, on the other hand, appears to be the most stable of these four channels. Despite the fact that the proportion of Slave River flow directed through Nagle Channel is estimated to have increased from 0.16% to 0.32% between 1946 and 1994, Table 3.2 illustrates that estimated discharge in this channel has remained relatively unchanged. As a result, the increase in Nagle Channel's proportional flow is undoubtedly due more to the decline of Middle Channel and Steamboat Channel than to those in Nagle itself.

One of the more probable explanations for the decline of both Old Steamboat and Middle Channels is the alteration of channel lengths in these distributaries between 1946 and 1994. Axelsson (1967), Russell (1967), and Coleman and Wright (1971) have all addressed the fact that increased channel lengths, caused by continual deposition at the mouth, often yield a reduction in channel slope. As a result, the carrying capacity of the channel is reduced and flows are diverted into adjacent channels. In addition, the reduced channel gradient often leads to rapid deposition along the entire length of the channel and the entry point as well. As a result, the rate of channel abandonment increases considerably.

Changes in channel length for Resdelta Channel, Middle Channel, Old Steamboat Channel, and Nagle Channel between 1946 and 1994 are shown in Figure 3.8. According to this data, Old Steamboat Channel increased in length by close to 695 m over the 48 year period while both Resdelta Channel and Middle Channel have, in fact, become shorter. What is interesting to note is the fact that most of the change in the Old Steamboat and Middle channels occurred in the post-impoundment period. In fact, despite its general decrease in length, Middle Channel has actually increased in length by

Fig. 3.8


Distributary Channel Lengths
Channel Length (m)
20000
15000
10000
5000
0
Old Steamboat
Nagle Channel
Middle Channel
Resdelta
Channel
Year
1946
1966
1977
1994

close to 500 m since 1977. Conversely, more than 60% of the decrease in the length of Resdelta Channel occurred in the pre-impoundment period between 1946 and 1966.

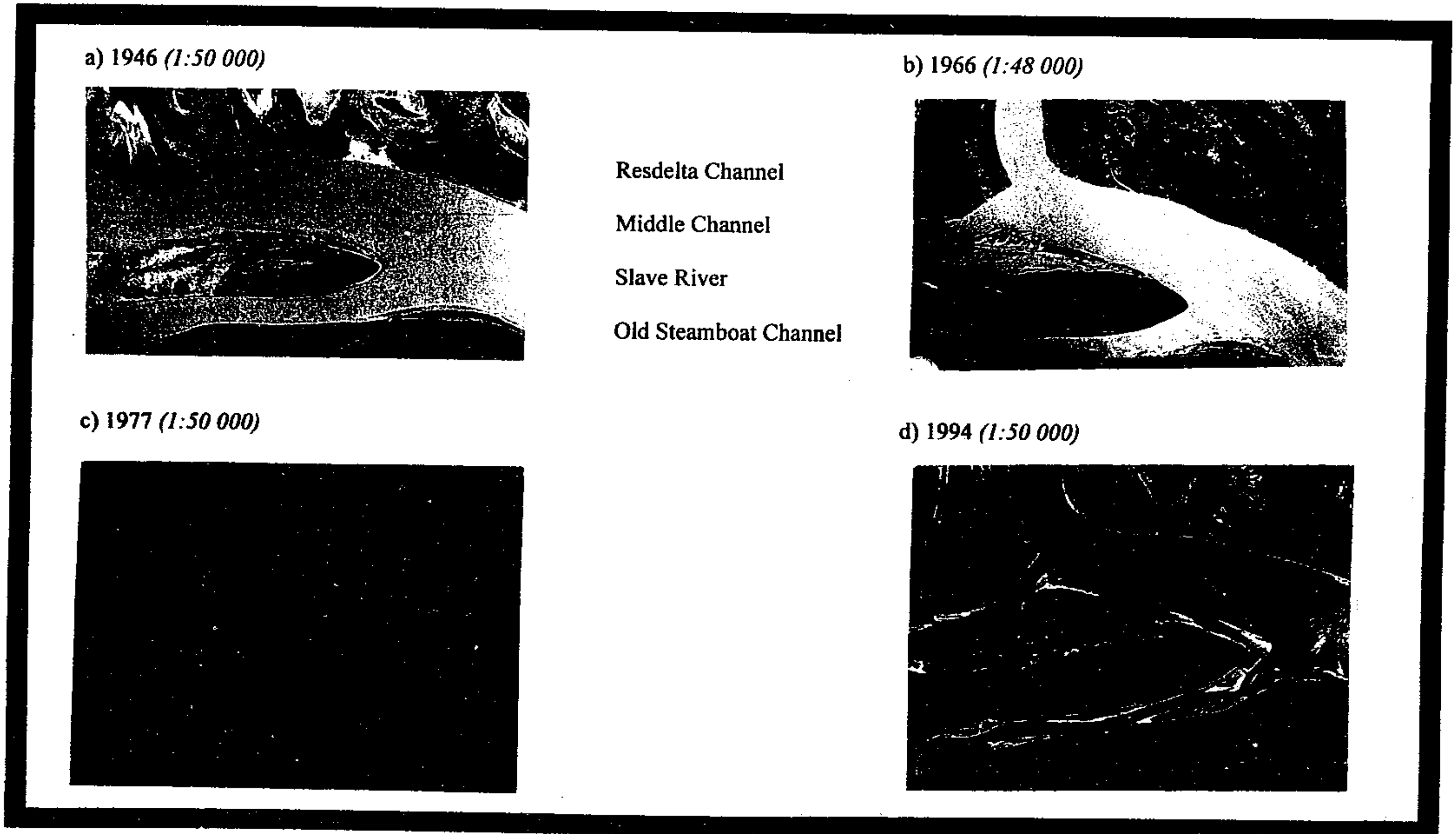
In addition to changes in channel length, the development of bar formations at the entry points of both Old Steamboat Channel and Middle Channel between 1946 and 1994 has undoubtedly contributed to the decreased carrying capacity of each. Fig. 3.9 illustrates the growth of entry point bar formations on Old Steamboat Channel and Middle Channel from 1946 to 1994. Measurements taken from these photographs indicate that deposition has closed off more than 60% of the original entry to Old Steamboat Channel and close to 70% of Middle Channel. As a result, these structures have influenced the distribution of flow through the Slave River Delta by limiting the quantity of water entering into these channels.

According to suggestions by Axelsson (1967) and Russell (1967), this is mainly due to the orientation of the main branch of the Slave River. Russell (1967) stated that very little bed load is deposited in a channel branching off a concave bank. Conversely, those which branch off the convex side of the main channel attract considerable quantities of bed load due to the transfer of water and suspended sediment into the less turbulent conditions of the point bar environment. Because Old Steamboat branches off the convex bank of the Slave (Fig. 3.2), it diverts a large proportion of the sediment load. This sediment quickly deposits in the slower moving waters of the smaller distributary, leading to the development of an entry point bar which may eventually block off the channel entirely.

A similar situation existed in Middle Channel during the 1946 and

Fig. 3.9

Entry Point Bar Development in the Apex Region



1966 periods; however, changes in the orientation of the Slave River near the entrance to Middle Channel and Resdelta Channel (Fig. 3.2) around 1966 and 1977 have now placed the entry point of Middle Channel close to the concave bank. As a result, deposition along the Middle Channel entry bar has slowed considerably.

It has now been suggested that the entry point of Resdelta has begun to fill in with deposits (Beaulieau, pers. comm., 1995); therefore, there is some indication that the dynamic nature of deposition and erosion may produce another significant shift in the future distribution of flow through the Slave River Delta.

3.3.2 SUSPENDED SEDIMENT CONCENTRATION VS. DISCHARGE

The relationship between [SS] and discharge is not as clearly defined for the entire Slave River Delta as is the relationship between discharge and channel width (Fig. 3.10). Despite the relatively broad scatter of data points, however, there does appear to be a weak correlation between the two which suggests the influence of additional channel characteristics.

3.3.2.1 Seasonal Influence

Given the fact that Slave River Delta hydrology data is only available for the ice-free period, an attempt was made to distinguish relationships between [SS] and discharge throughout this portion of the annual hydrograph. Figure 3.11 shows the relationship between these two variables for spring (May & June), summer (July & August), and autumn (September & October) respectively. Both summer and autumn seem to show some correlation between [SS] and discharge; however, a closer inspection

Fig. 3.10

Suspended Sediment Vs. Discharge

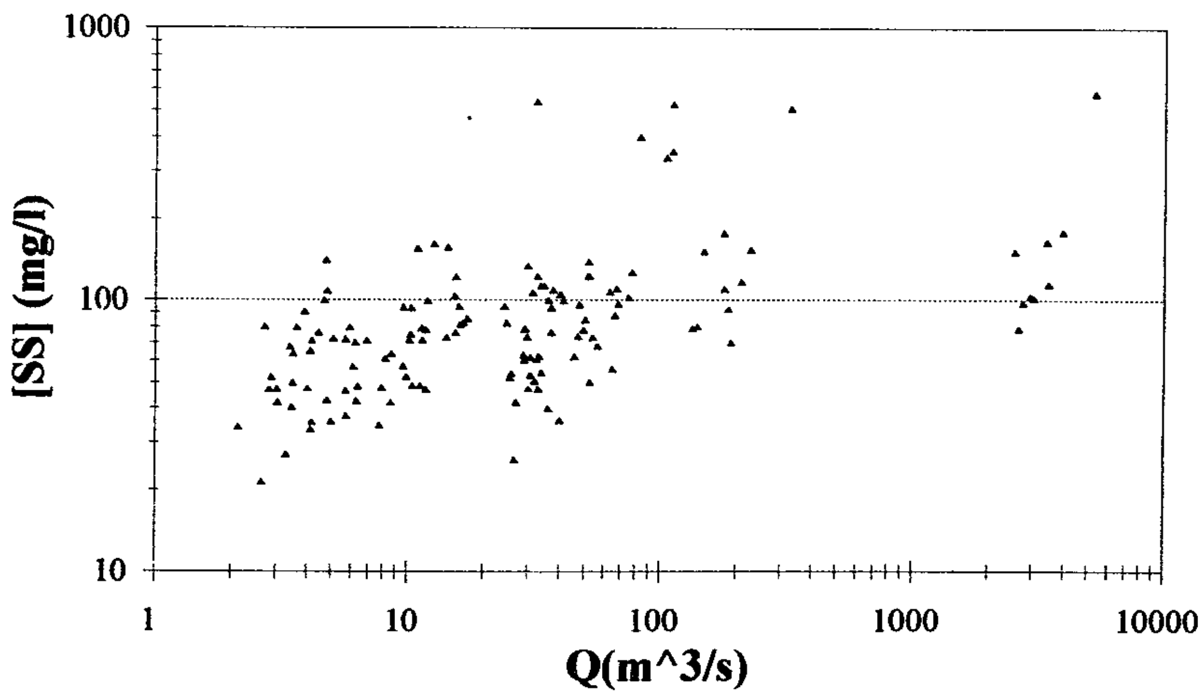
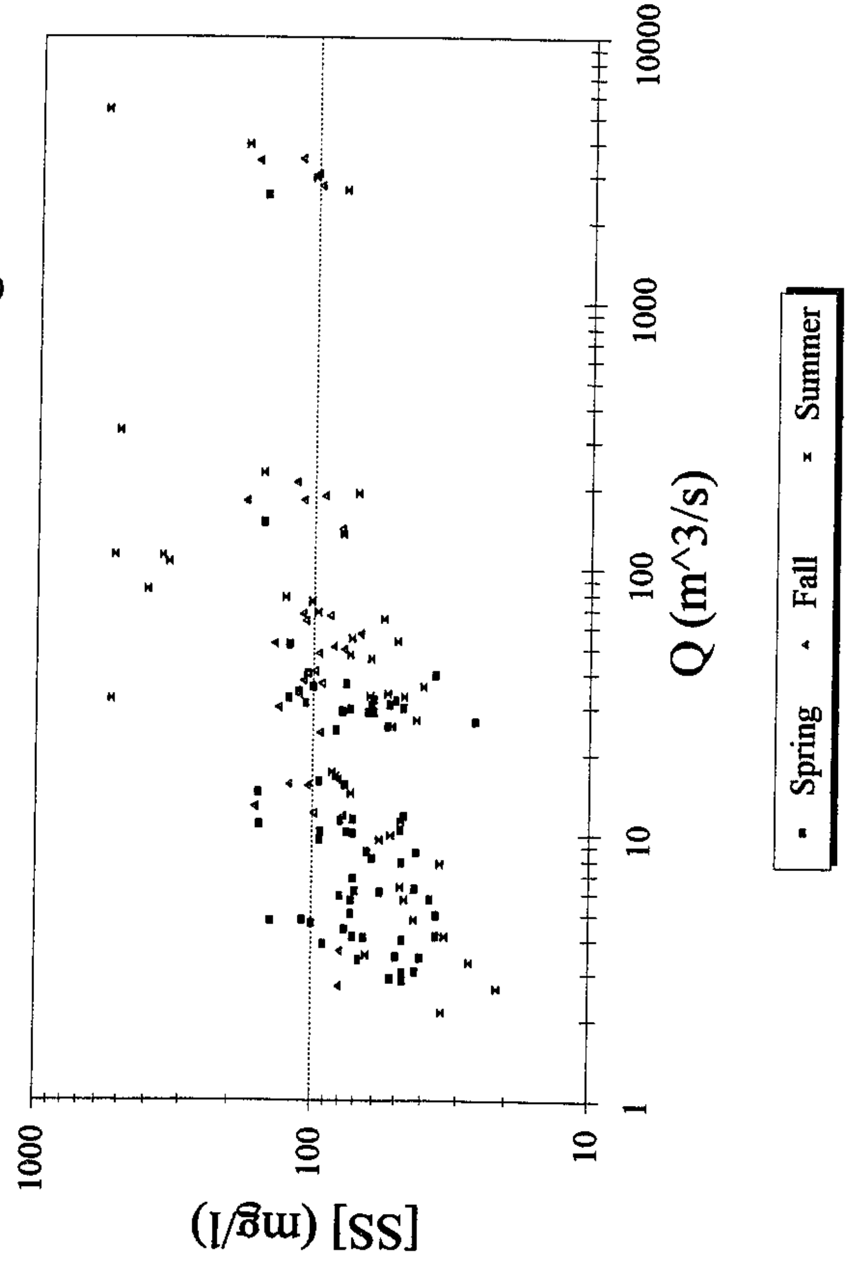


Fig. 3. 11
Seasonal [SS] Vs. Discharge



shows that their relationships are quite different (Figs. 3.12 & 3.13). Despite the fact that both cover a similar range in flow, [SS] are higher under low flow conditions during the fall and lower under high flow conditions.

During the summer, low [SS] are generally associated with small discharges while higher concentrations tend to be associated with higher discharges. This is generally due to the fact that the high discharge values are found in major distributaries like Resdelta Channel, Middle Channel, and Old Steamboat Channel which carry a large percentage of the total flow of the Slave River. Because of this, these channels also carry a more substantial portion of the sediment load. As these channels bifurcate, both the proportional flow and carrying capacity of the downstream channel decrease; consequently, large quantities of sediment are deposited and the suspended sediment concentrations decrease.

The plot of summer values (Fig. 3.12) also indicates that relatively high concentrations of suspended sediment do occur during this period. As such, sediment sources must be available during this time in order to produce these concentrations. Conversely, the relatively flat distribution of data in the [SS] versus discharge plot for the autumn season (Fig. 3.13) indicates that fall flows within the Slave River Delta may be sediment limited. The plot of summer discharge versus [SS] indicates that flows of more than 20 m^3/s have the potential to transport concentrations of close to 600 mg/l; however, flows of a similar magnitude are carrying less than 200 mg/l during the fall. The reason for this may lie in the fact that mean discharge and water levels are generally lower during the fall and, therefore, do not have the same ability to erode the

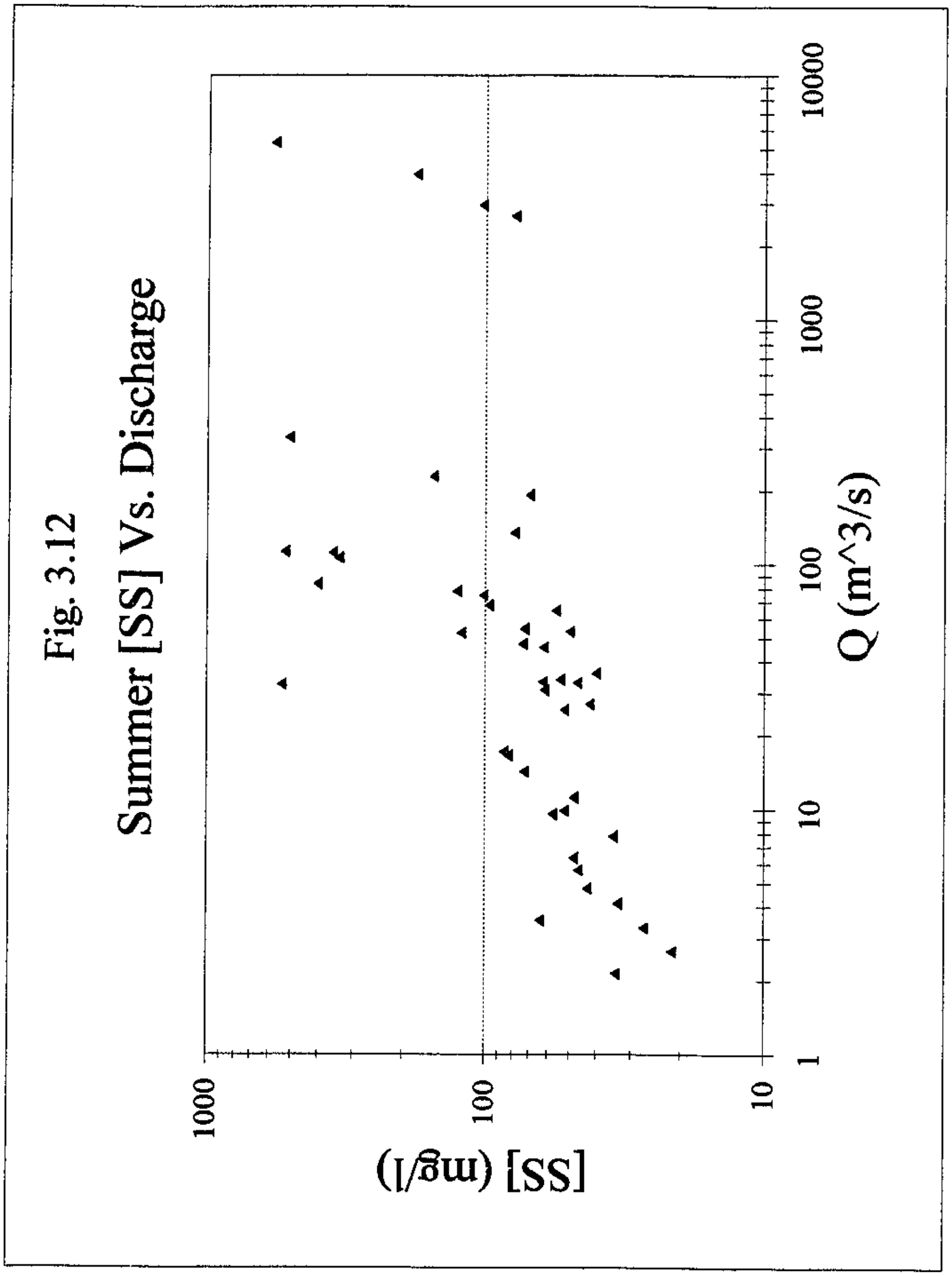


Fig. 3.12
Summer [SS] Vs. Discharge

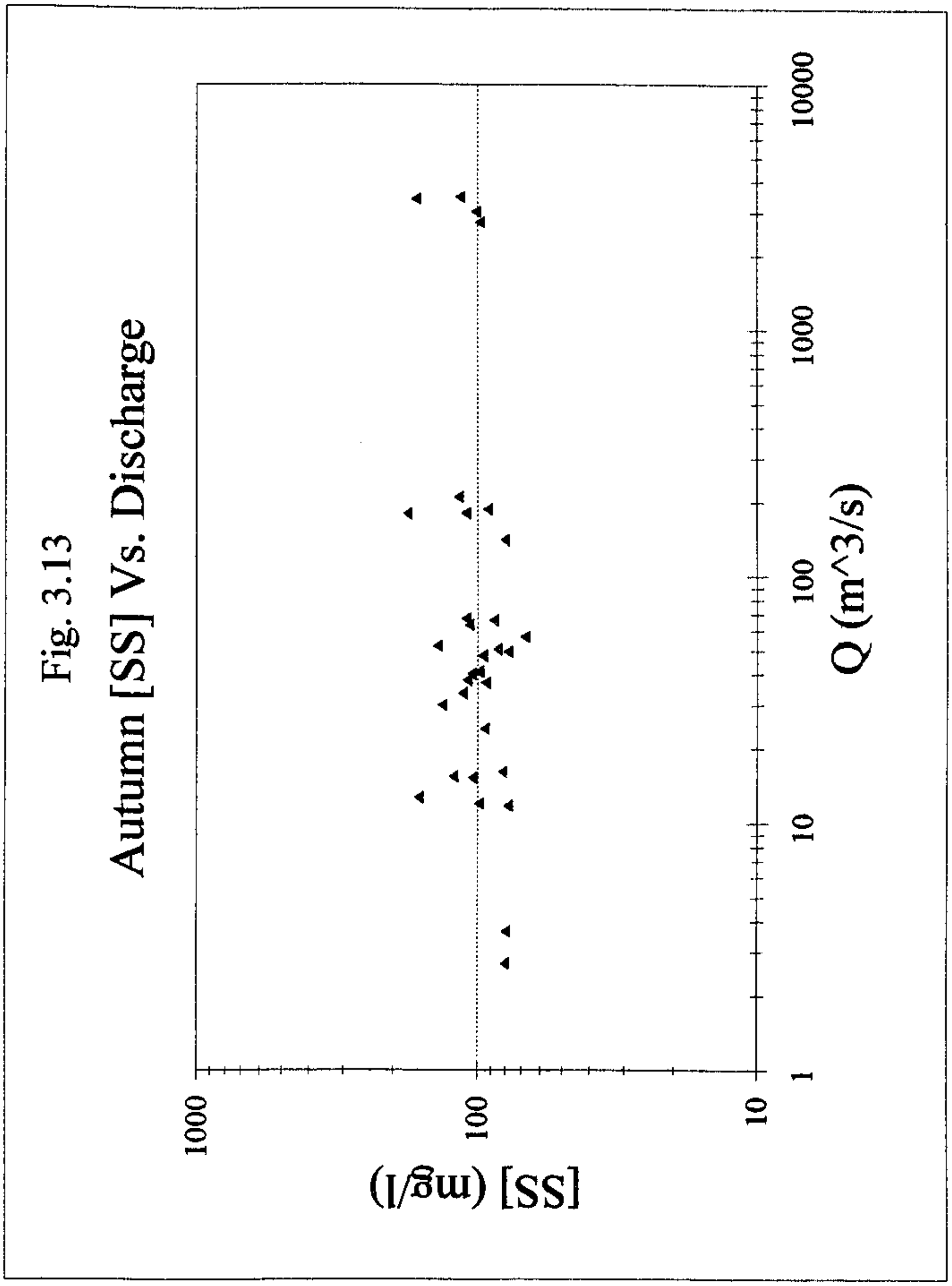


Fig. 3.13
Autumn [SS] Vs. Discharge

banks and entrain bed material. The growth of aquatic vegetation in the late summer and early fall also stabilizes bank formations, creating excellent environments for deposition and preventing further erosion (English, 1979). In addition, the effects of spring break-up, including elevated flows and ice-rafting, often extend into the early summer, thereby adding a considerable amount of material to the flow regime at this time.

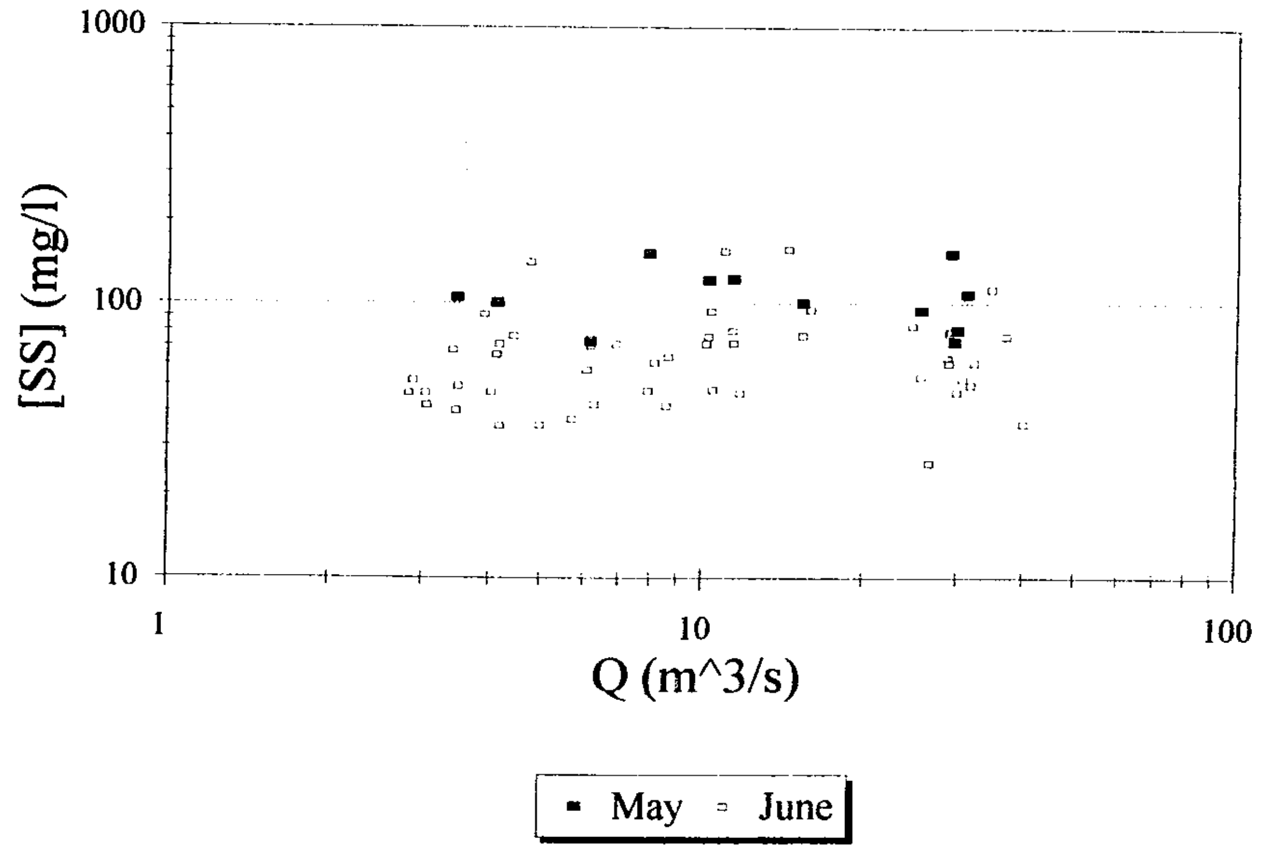
Also of note is the fact that fall flows generally have higher sediment concentration under lower flow conditions than those in the summer. This is due, in part, to the regulation of the Peace River and its impacts on the hydrology of the Slave River. Since impoundment, fall discharge within the Slave River has decreased by approximately 12 - 20%; however, sediment loads are predicted to be close to 25% higher (English *et al.*, 1996).

It should be pointed out, however, that most of the channels sampled during September and October are relatively large branches like Middle Channel and Four Ways Channel (Fig. 3.2). As a result, the plot of [SS] versus discharge for the autumn period may show an artificial shift toward higher [SS] concentrations since smaller distributaries which carry less flow like Whiteman's Channel, V Channel North, and Beaver Dam Channel were ignored.

Of the three seasons under study, spring flows tend to show the weakest relationship between [SS] and discharge (Fig. 3.14). The influence of breakup during the spring season is one possible explanation for the distribution of data. At this time, sediment concentrations within the system are often elevated due to thermoniche erosion, ice scoured banks, rafted deposits, and the release of bottom fast ice,

Fig. 3.14

Spring [SS] Vs. Discharge



all of which are flushed downstream by elevated flows during spring melt. During breakup, ice jams often impede flow through certain channels or block them entirely; as a result, these impoundments produce relatively low discharges with artificially elevated [SS]. Similarly, the presence of lake ice adjacent to the outer delta may reduce the dispersion of flows at the channel offings which, in turn, may contribute to a decrease in measured discharge upstream. Finally, complete closure of one or more channels may also produce high [SS] at high discharge values as well. Because the blockage of flow forces more water into adjacent channels it dramatically increases both the volume of flow and the total sediment load in these channels.

According to Gerard (1981) and English *et al.* (1996), river regulation often leads to a reduction in the potential for ice jamming. This is due to the fact that regulated rivers are generally characterised by smaller spring discharges which reduce the probability of mechanical breakup. The influence of the spring breakup on hydrologic data for the Slave River Delta may be questionable due to the fact that data have only been collected since the 1968 regulation of the Peace River. During the post-impoundment period, however, significant floods due to ice jamming have occurred within the delta (Davies, 1980; Boucher, pers. comm., 1995). Despite the fact that ice jams have occurred in the post-impoundment period, the random distribution of spring data relating discharge and [SS] (Fig. 3.14) implies that the effects of breakup are not uniformly distributed across the entire channel network of the Slave River Delta. Similarly, the scatter of data points on the summer and autumn plots (Figs. 3.12 & 3.13) also indicates that there are unique processes occurring within individual channels during these time periods as well. Consequently, any attempt to formulate general theories on channel form and process within the Slave River Delta must be based upon the assessment of individual channels.

3.3.3 CHANNEL FORM AND PROCESS

3.3.3.1 Channel Bifurcation and the Impacts on [SS] Versus Discharge

One of the predominate characteristics of the deltaic environment is the continual bifurcation and abandonment of distributary channels. As new channels are produced, each begins to carry a proportion of the total flow; consequently, the distribution of energy throughout the delta is directly influenced by the configuration of the channel network. This is seen in the Slave River Delta where discharge generally decreases as the number of bifurcations increases with respect to increasing distance from the main channel (Fig. 3.15).

Because of the strong relationship between channel discharge and sediment transport, there should be some kind of trend in the relationship between the two as the number of bifurcations changes throughout the delta. In fact, by identifying the bifurcation number for various channels of the Slave River Delta (Fig. 3.16) and sorting the available discharge versus [SS] data according to these values, it becomes apparent that discharge and [SS] both tend to decrease as you move away from the main body of the Slave River while the relationship between the two increases in complexity (Fig. 3.17).

Fig. 3.15

Channel Discharge Versus Number of Bifurcations

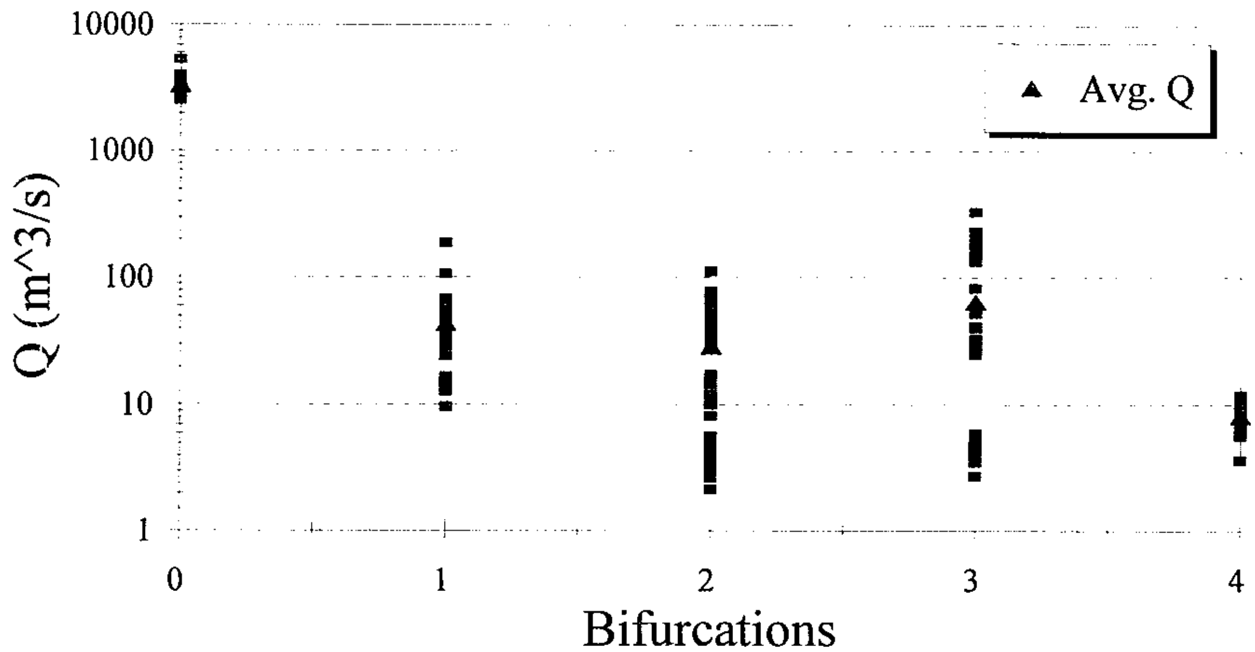


Fig. 3.16

Bifurcation Classification of Selected Channels

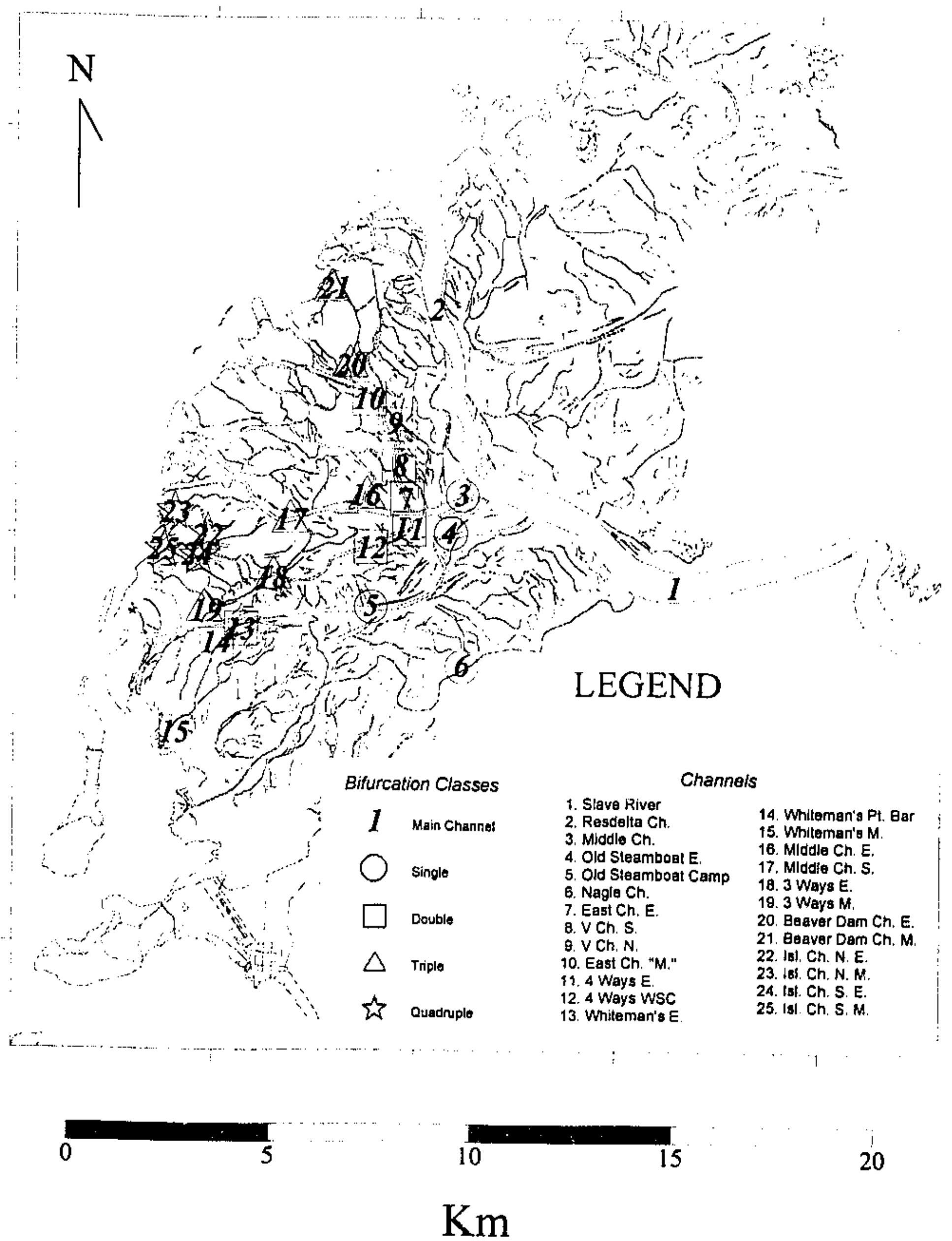
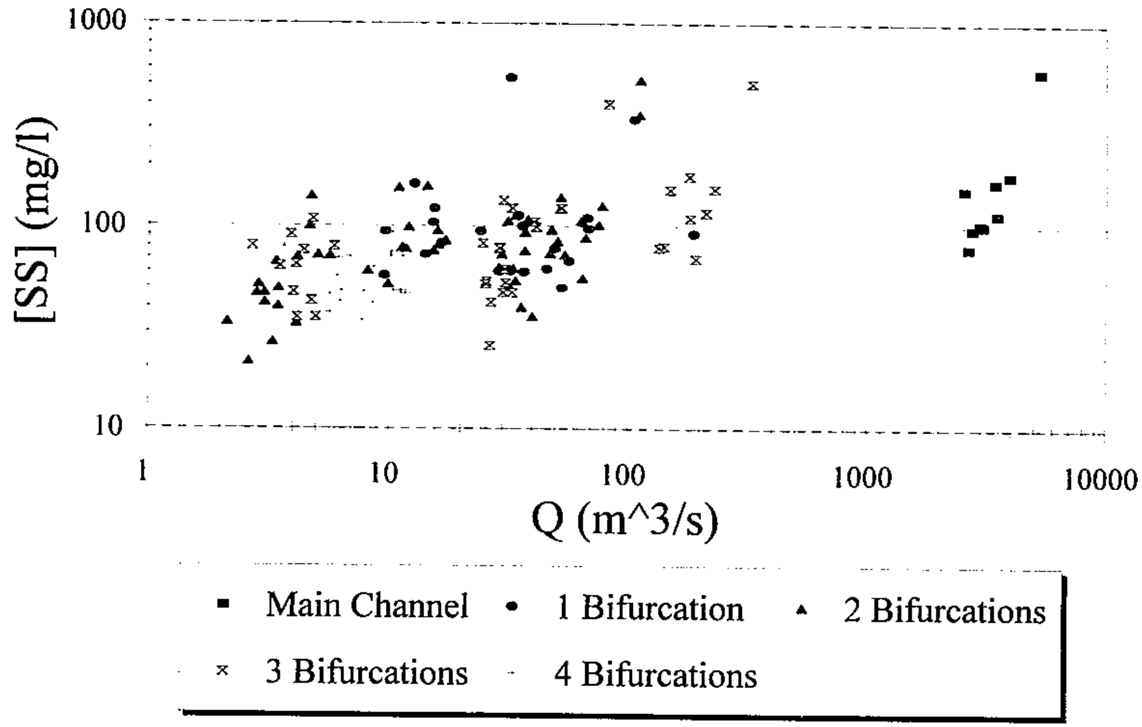


Fig. 3.17

Influence of Channel Bifurcation on [SS] Vs. Q



3.3.3.2. Main Channel Characteristics

By definition, the main body of the Slave River ends near the apex of the Slave River Delta as it branches into Nagle Channel, Old Steamboat Channel, Middle Channel, and Resdelta Channel (Fig. 3.16). As a result, the latter should be classified as a single bifurcation channel; however, because Resdelta Channel carries as much as 85 - 90% of the flow from the Slave River and exhibits a number of similar characteristics, the two were considered one and the same.

A cursory examination of the relationship between discharge and [SS] in the main body of the Slave and Resdelta Channel illustrates the large volume of flow carried by these channels (Fig. 3.18). Because Resdelta Channel carries the bulk of flow through the Slave River Delta, it stands to reason that discharge and [SS] values are similar to those of the main channel. In addition, the two variables exhibit the classic "power" relationship first defined by Leopold and Maddock (1953). In this case, [SS] is directly related to discharge; however, a closer inspection of the relationship within Resdelta Channel seems to indicate that a dampening in the upper range (Fig. 3.19). The reason for this is the fact that peak discharges in Resdelta Channel, like those on the Slave itself, occur toward the mid to late summer. At this time, most of the readily available material from surface run-off has been carried away by spring flows. The increase in discharge during the spring melt (Fig. 3.4) tends to provide a flushing flow which may entrain a significant portion of the available bed load material. Because discharge remains relatively unchanged after this time, Slave River flows may not have the potential to entrain additional material. As a result of this, the hydrological regime of the Slave River

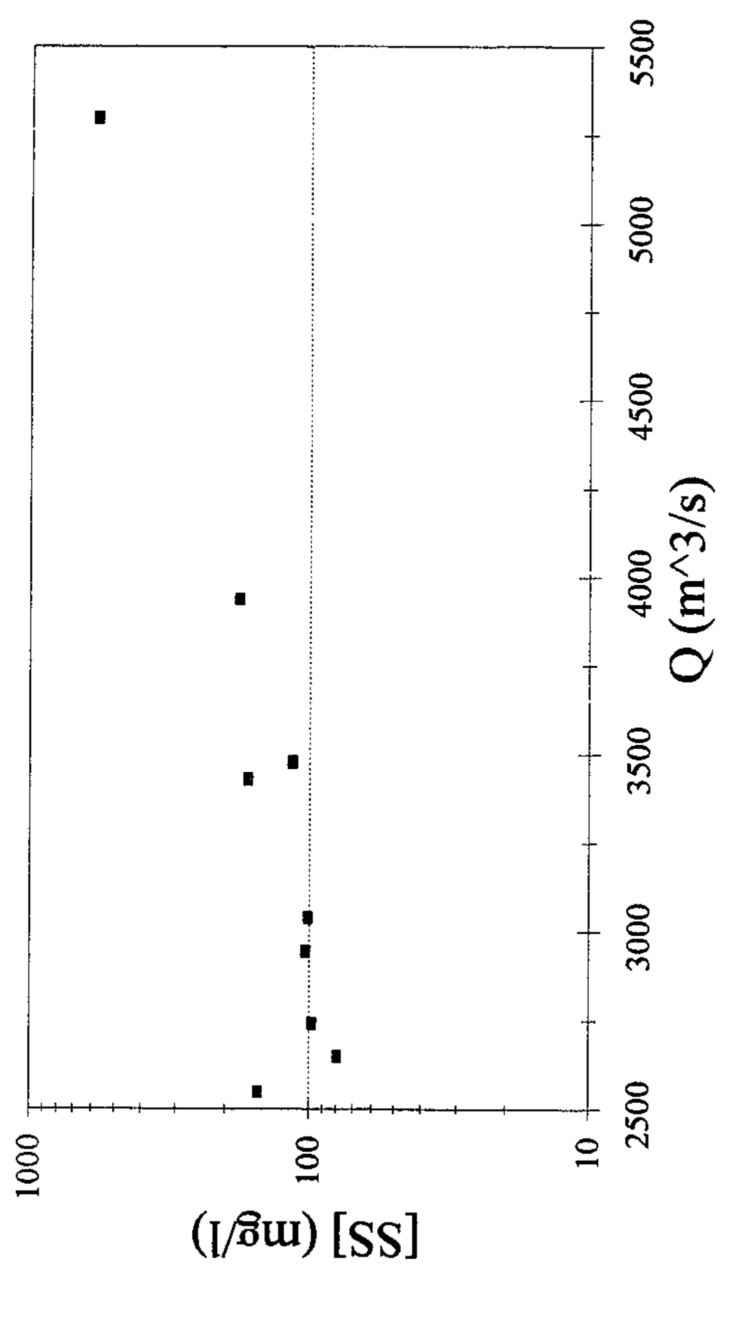


Fig. 3.18
[SS] Versus Discharge
In the Main Body of the Slave River

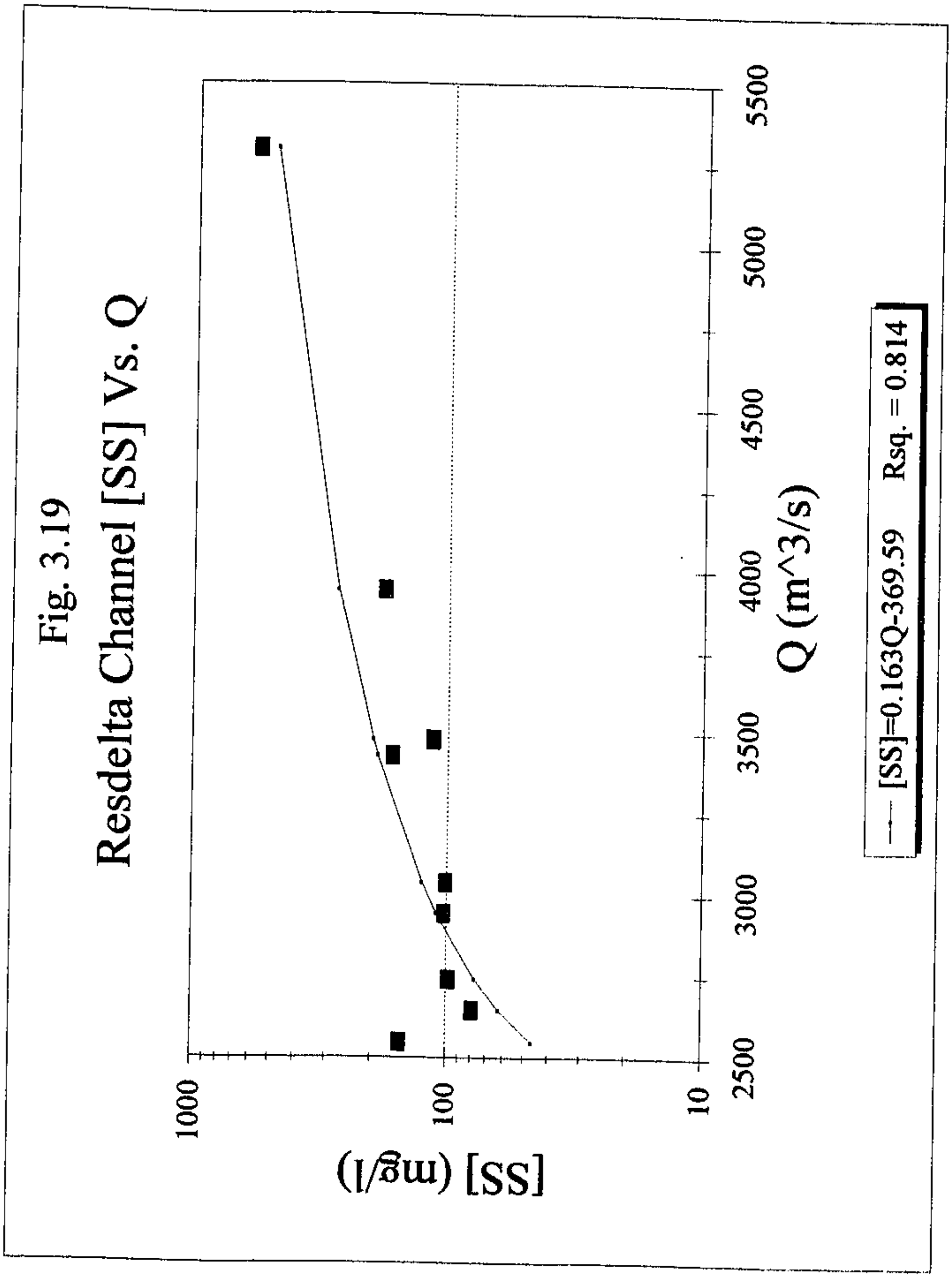


Fig. 3.19
Resdelta Channel [SS] Vs. Q

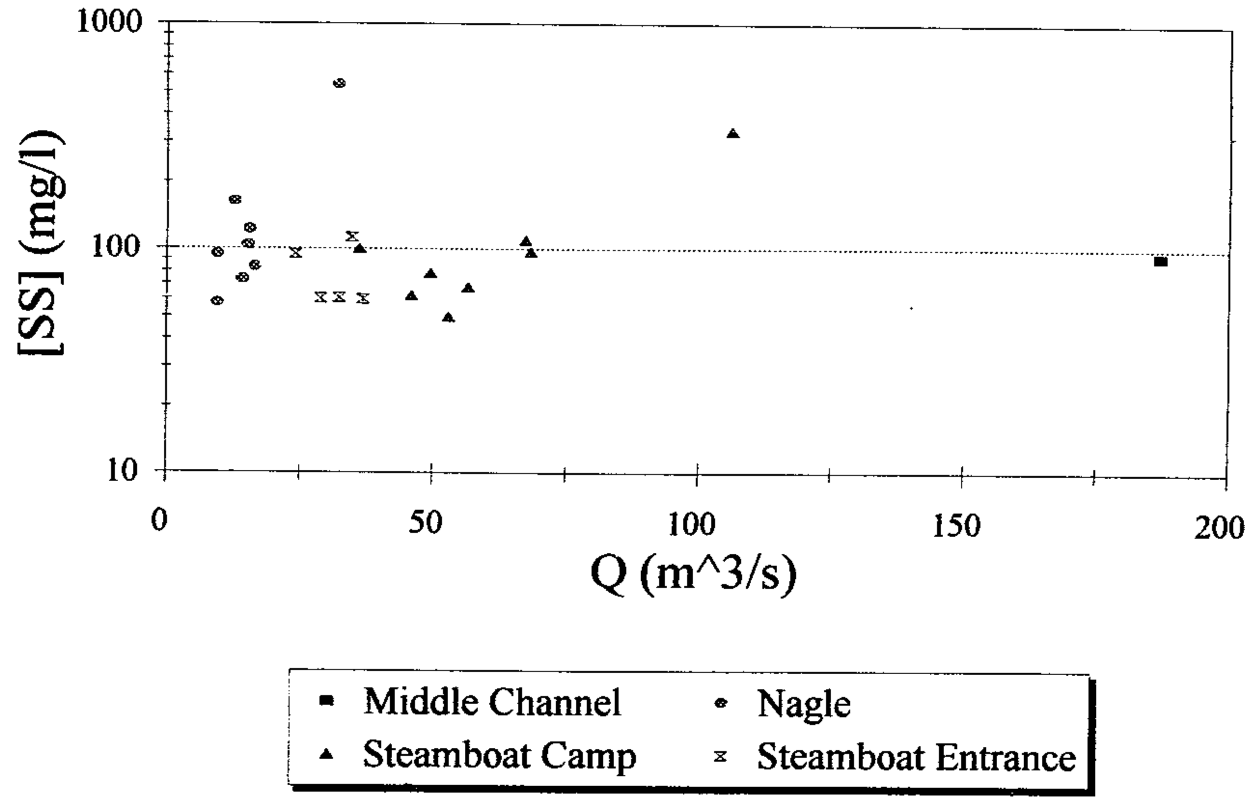
appears to become sediment limited. In addition, regulation of the Peace River has led to a decrease in the overall sediment load within the Slave River which may serve to intensify this deficit.

3.3.3.3. Single Bifurcation Channel Characteristics

As the Slave River enters the Slave River Delta, it splits into Nagle Channel, Old Steamboat Channel and Middle Channel (Fig. 3.16). Each of these channels have been classified as "single bifurcation channels" since they are one bifurcation away from the main body of the Slave River. As Figure 3.15 illustrates, there is a considerable drop in the mean channel discharge as the Slave River divides into these channels. There is also an increase in the range of flow due to the variation in both channel width and depth found within this class. As a result, discharge versus [SS] for channels within the single bifurcation class (Fig. 3.20) is characterized by a more random distribution of data points than that of the main body of the Slave. Upon closer inspection, the relationship between discharge and [SS] each of the individual channels in this class indicate strong similarities to Resdelta Channel.

In Old Steamboat Channel, historical data from WSC suggests a strong positive relationship between discharge and [SS] (Fig. 3.21). The scatter of points created by more recent data gathered near the entry point, however, seems to indicate an opposite trend (Fig. 3.22). One of the main discrepancies between the two sets of data seems to lie in the differences in measured discharge. The most simple explanation for this lies in the sampling period for each data set. According to the WSC,

Fig. 3.20
[SS] Versus Discharge
In Single Bifurcation Channels



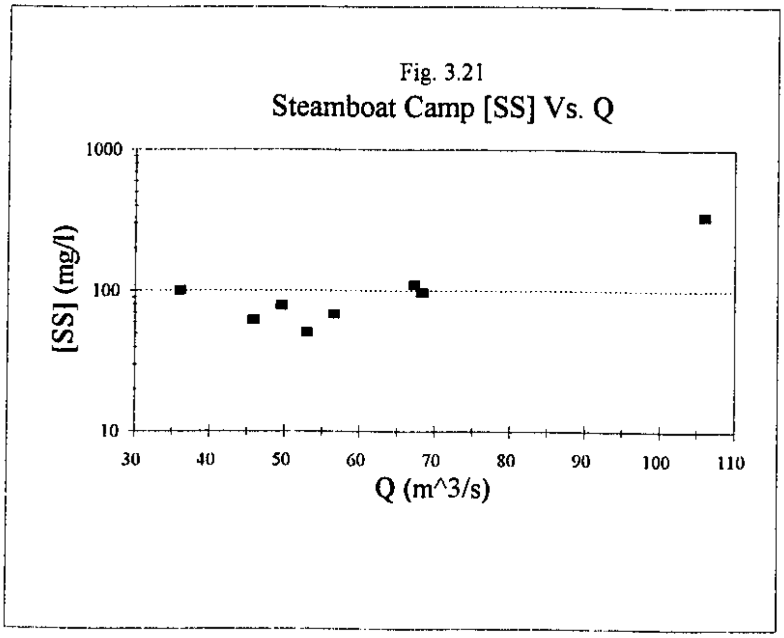


Fig. 3.21
Steamboat Camp [SS] Vs. Q
1000
100
10
[SS] (mg/l)
30
40
50
60
70
80
90
100
110
Q (m^3/s)

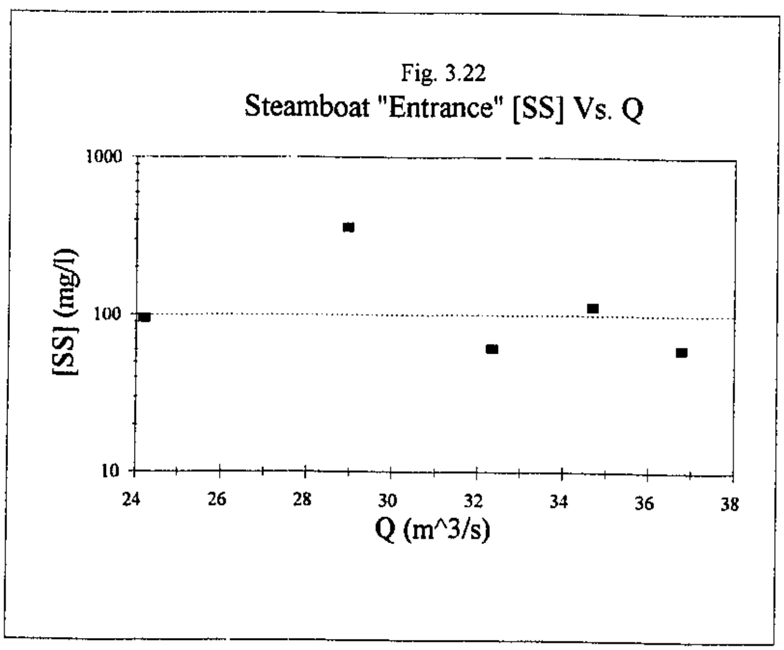


Fig. 3.22
Steamboat "Entrance" [SS] Vs. Q
1000
100
10
[SS] (mg/l)
24
26
28
30
32
34
36
38
Q (m^3/s)

Great Slave Lake water levels during the summer of 1995 were at a record low while the historical data gathered in the late 1970's and early 1980's were taken at a much higher level. In fact, significant flooding has been reported during this earlier period (Davies, 1980). According to English (1979), as much as 85% of the annual input into Great Slave Lake comes from the Slave River; therefore, it seems relatively safe to assume that discharges in Old Steamboat Channel were higher at this time due to higher water levels in both the main body of the Slave and the Slave River Delta. This, in turn, may explain the difference in the hydrological regime of the channel as well, for lower water levels during the most recent sampling season would expose more of the bar formation across the entry point and prevent water from entering the channel. The lower water levels may also produce decreased flow velocities through the channel which would result in lower [SS] due to increased deposition. Conversely, the higher water levels would have been more likely to overtop the bar, especially since the deposits would have been somewhat smaller at that time.

In the case of Nagle Channel, the relationship between discharge and [SS] more closely resembles that of the Resdelta Channel and the main body of the Slave River (Fig. 3.23). Here, [SS] increases with discharge up to approximately 20 - 25 m^3/s after which it begins to level off as if reaching a threshold level. Despite the relatively high R^2 value of this relationship, the clustering of data points around the 15 m^3/s seems to indicate that it may not be that simple. During the field season, large boils and bar formations were observed near the entry point of Nagle Channel which tend to indicate the presence of significant bed formations in this location

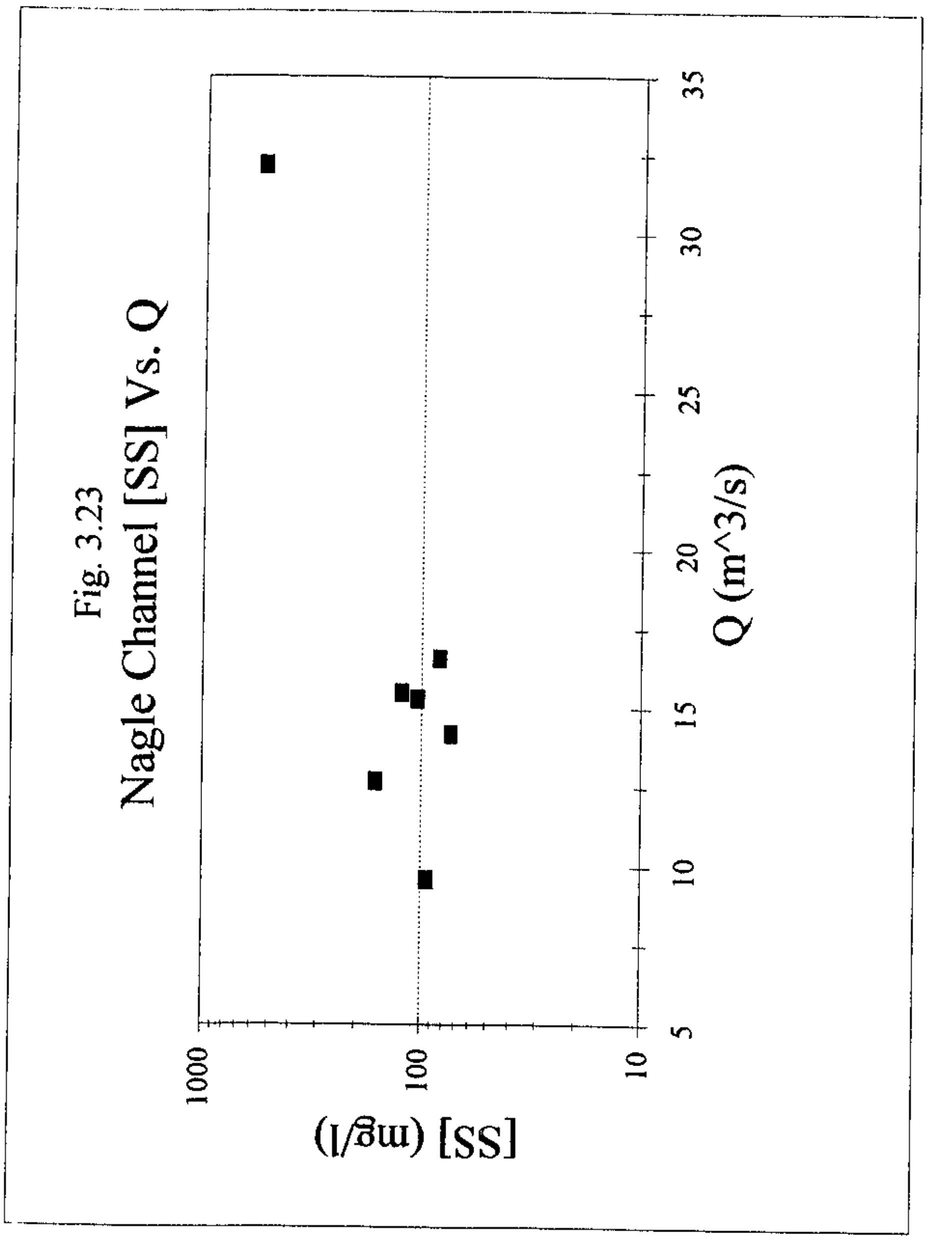


Fig. 3.23
Nagle Channel [SS] Vs. Q

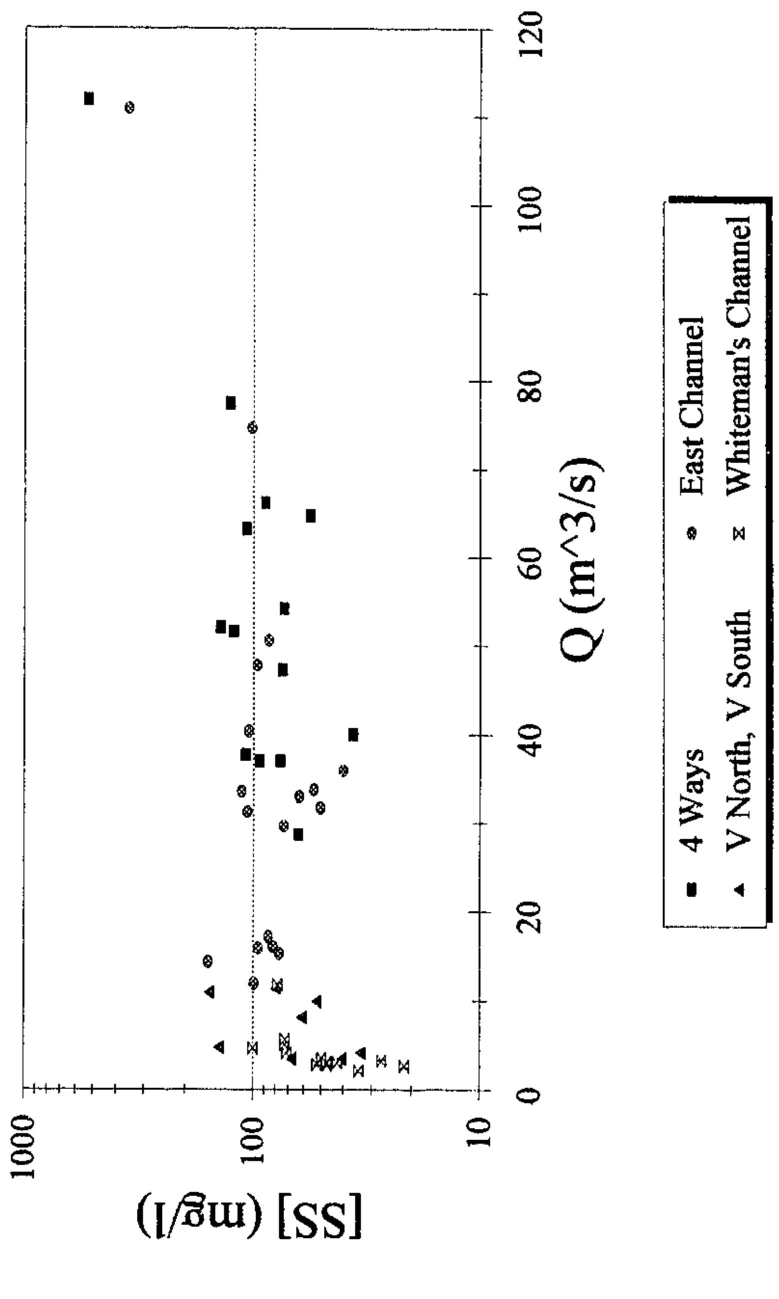
(English *et al.*, 1996). Given these factors, it would appear that deposition near the entry point of Nagle Channel may be influencing the flow regime in this area which, in turn, leads to variation in the amount of sediment entering the channel itself.

3.3.3.4. Double Bifurcation Channel Characteristics

Double bifurcation channels are classified as those distributaries produced by the branching of single bifurcation channels. As a result, channels in this class are generally smaller, shallower, and carry less flow than those in the single bifurcation class. What is interesting to note, however, is the fact that double bifurcation channels tend to produce a more uniform relationship between [SS] and discharge than the single bifurcation class even though they show a broader range of discharge (Fig. 3.24). By grouping data points by channel, however, it appears that these distributaries have little in common. While Four Ways Channel exhibits the classic power relationship of the larger channels, V Channel North, V Channel South and Whiteman's Channel (Fig. 3.16) show considerable variation in [SS] over a very short range of discharge. Part of the reason for this may lie in the fact that the latter three channels are all discharging into a larger body of water. As a result, discharge through these distributaries may be strongly limited by conditions occurring at their mouths such as reverse eddies, turbidity currents, and seiche effects.

Examination of [SS] versus discharge for each individual channel reveals that both East Channel and Four Ways Channel exhibit a relatively flat distribution of data points at their entry point and a positive relationship downstream

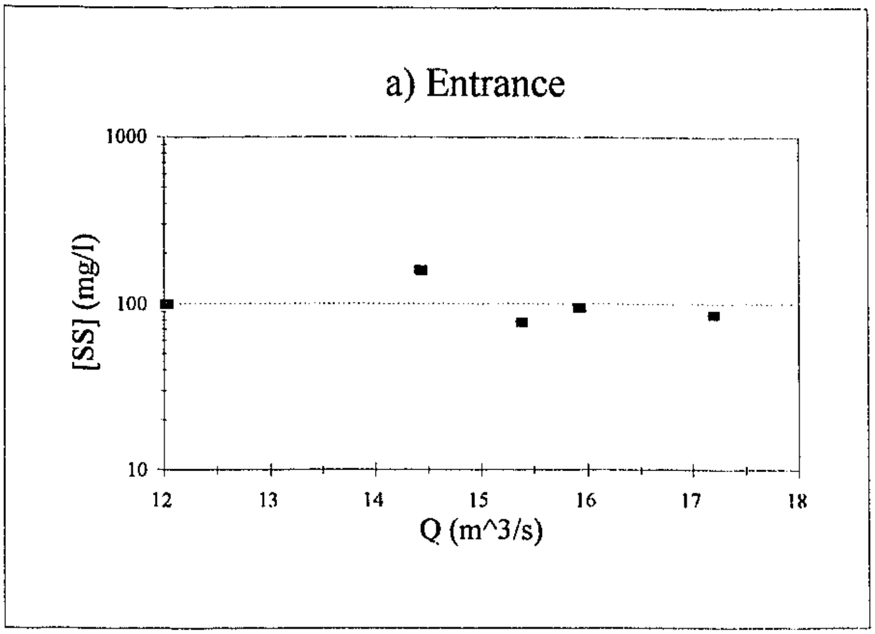
Fig. 3.24
[SS] Versus Discharge
In Double Bifurcation Channels



(Figs. 3.25 and 3.26). A closer examination of similar plots for the remaining channels reveals the same positive relationship in varying degrees for V Channel North, V Channel South, and Whiteman's Channel (Figs. 3.27, 3.28, and 3.29). One possible explanation for this lies in the angle of bifurcation. As Fig. 3.16 illustrates, virtually all of the double bifurcation channels are oriented at close to 90 degrees to the single bifurcation channels. Because of this, the transfer of water and suspended sediment into these channels may be strongly affected by flow velocity and turbulence. As the angle of bifurcation increases, turbulence within the smaller branch also increases due to helicoidal flow and reverse eddies (Welder, 1959). Since water tends to flow into areas of less turbulence (Russell, 1967), both discharge and [SS] within the smaller branch would be reduced. In addition, Axelsson (1967) identified a significant damming effect at bifurcation points during periods of high discharge. As a result, [SS] at the entry points of these channels may be reduced under high flow condition due to the deposition of sedimentary material caused by local reductions in flow.

Another possible explanation for the flattened [SS] versus discharge relationship in these channels may be the timing of peak flows and the availability of sediment. As previously outlined, most of the peak flows occur during the summer when sediment is not as readily available. Consequently, higher discharges may be entering these channels during the summer transporting less material than they are able to transport. This, in turn, may provide some explanation for the strong positive relationship observed downstream from the entry points of these channels. Because the higher flows still have the potential to carry more sediment, it appears that they may be

Fig. 3.25
East Channel [SS] Vs. Q



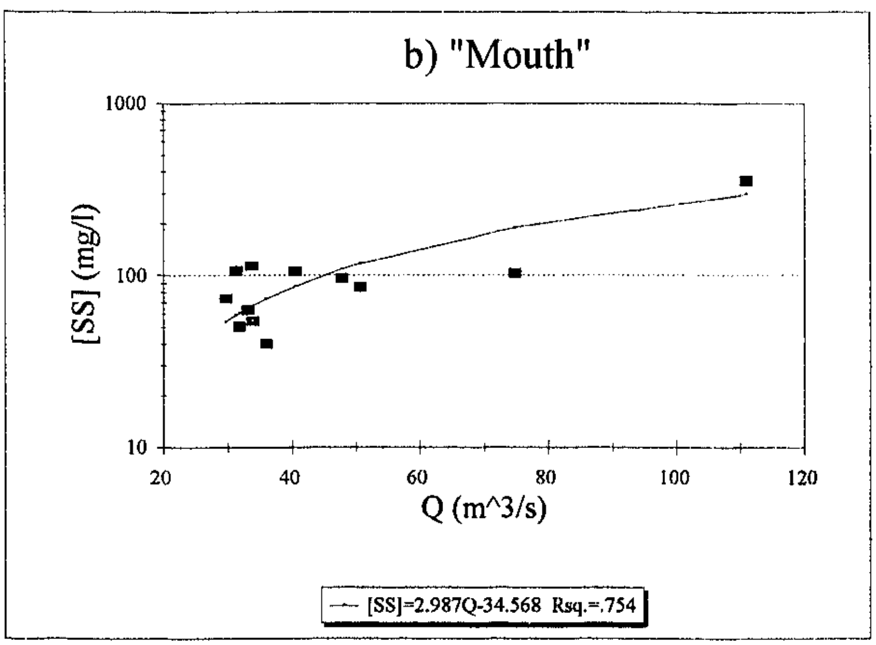
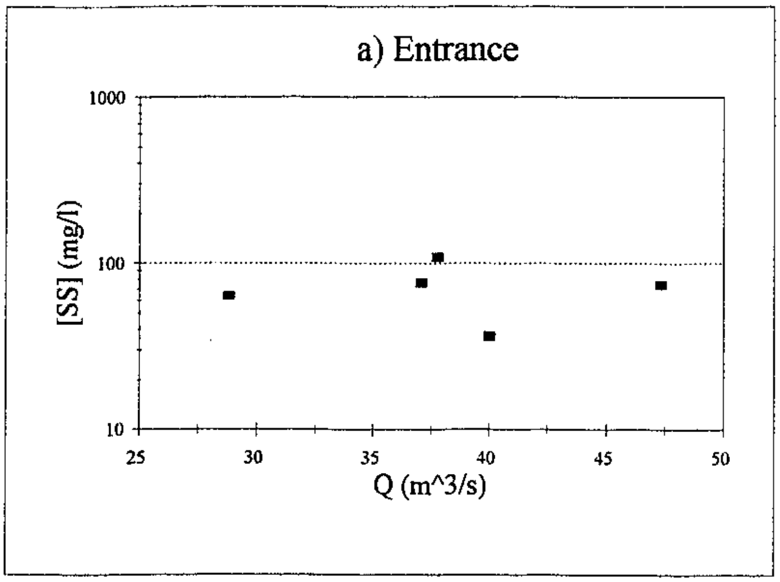


Fig. 3.26

Four Ways Channel
[SS] Vs. Q



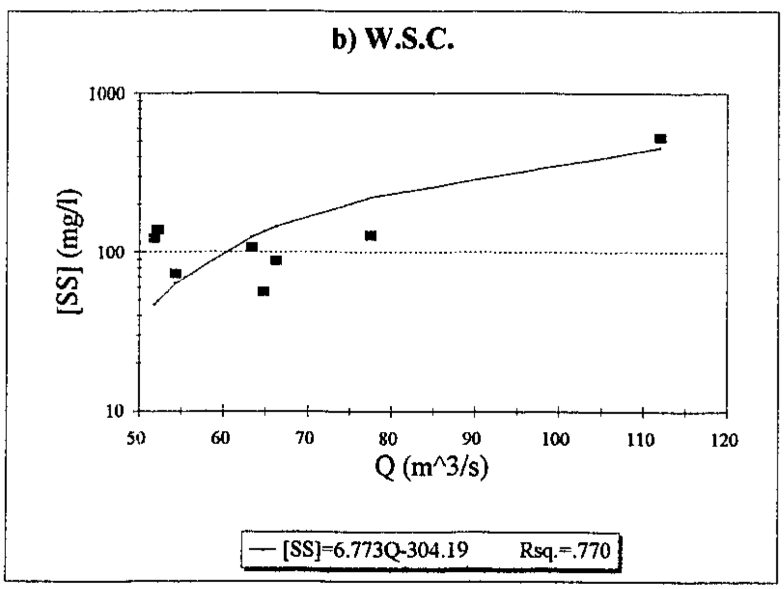


Fig. 3.27

V Channel North [SS] Vs. Q

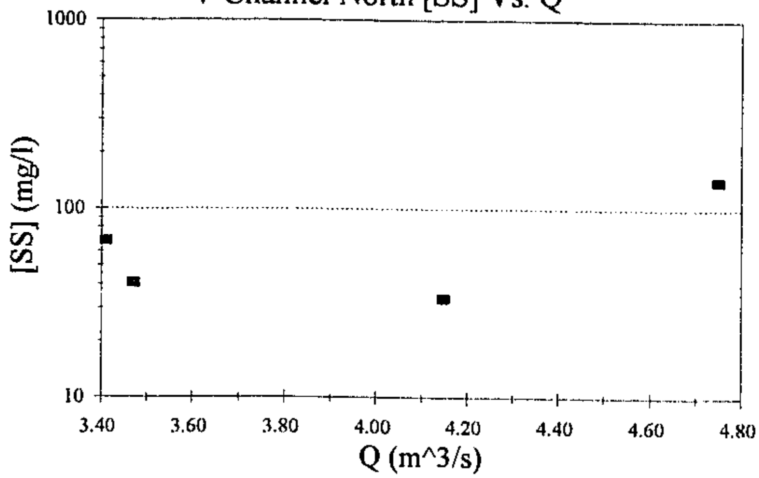


Fig. 3.28

V Channel South [SS] Vs. Q

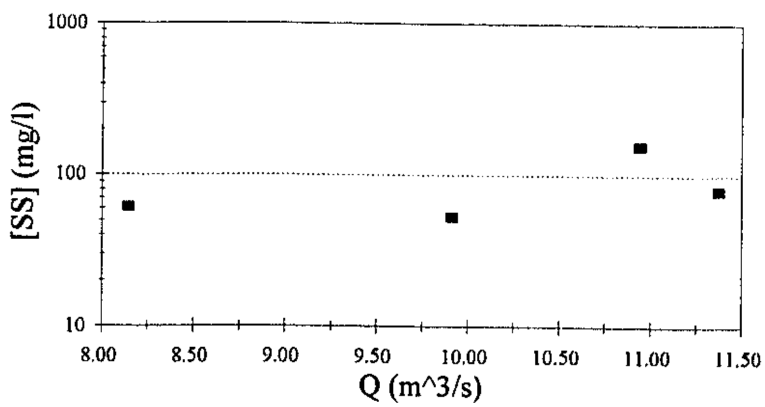
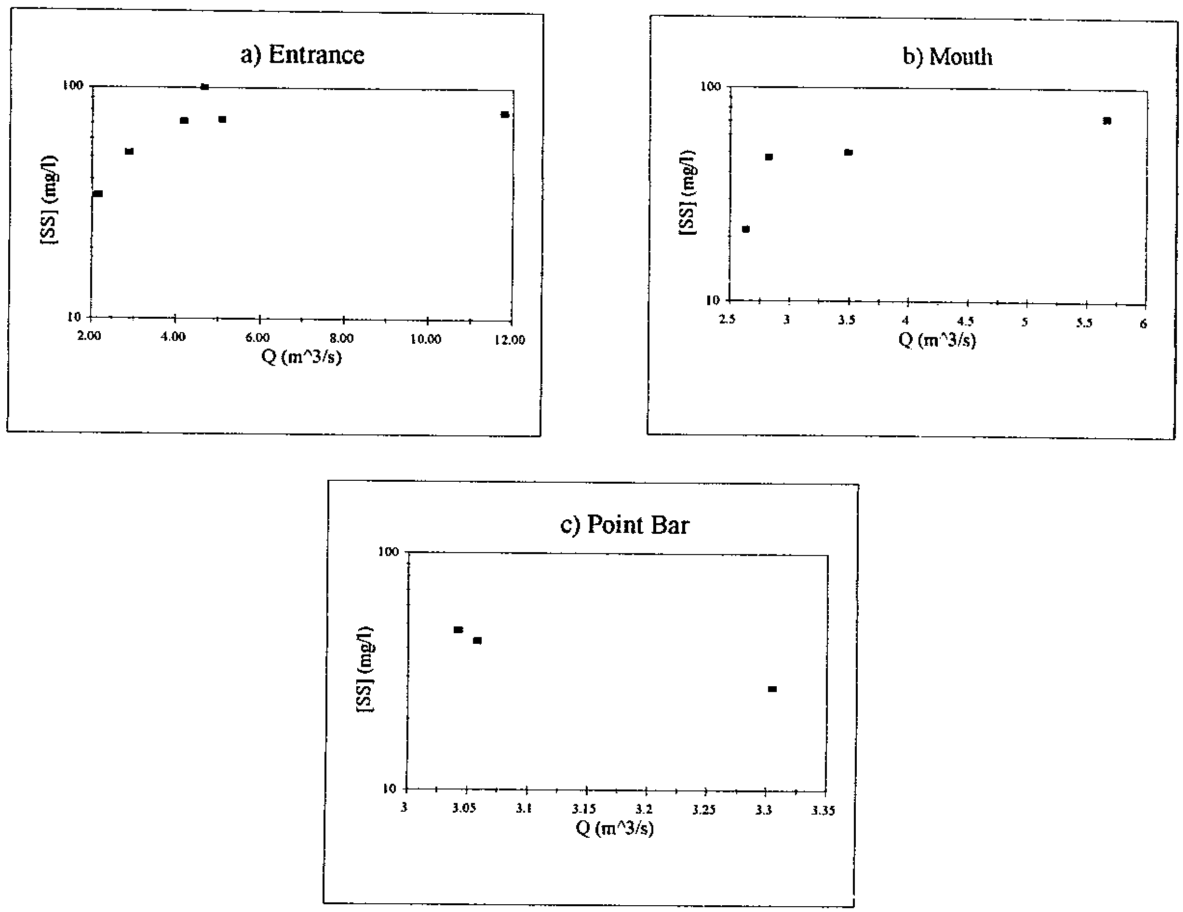


Fig. 3.29

Whiteman's Channel
[SS] Vs. Q



eroding material from within the channel itself and transporting it downstream.

3.3.3.5. Triple Bifurcation Channel Characteristics

With the triple bifurcation channel class, the trend toward an increasing range of discharge continues. In addition, another trend toward increased scatter on the discharge versus [SS] plot also becomes more apparent (Fig. 3.30). Here, the range of discharge (2.5 m^3/s to more than 250 m^3/s) reflects the differences in channel widths within this class which range from 17 m to approximately 100 m. In addition, all four channels are found in different parts of the delta and are, therefore, influenced by somewhat dissimilar circumstances (Fig. 3.16). Middle Channel East and Middle Channel West are the most similar in that they both originate in the middle portion of the delta as distributaries of Middle Channel. Because each of these channels are notably larger than the remaining two channels in the triple bifurcation class, they tend to have higher discharge and [SS] values. In fact, because of their channel dimensions and close proximity to a major distributary like Middle Channel, Middle Channel East and Middle Channel West are probably more characteristic of a double bifurcation channel or perhaps even a first. For this very reason, it is not surprising to see that both channels exhibit the strong positive relationship between discharge and [SS] that is found in channels closer to the main body of the Slave River (Fig. 3.31 and 3.32).

The remaining two channels appear to have very little in common with the first two channels. A cursory examination of Beaver Dam Channel and Three Ways Channel shows that neither exhibit the strong positive relationship between

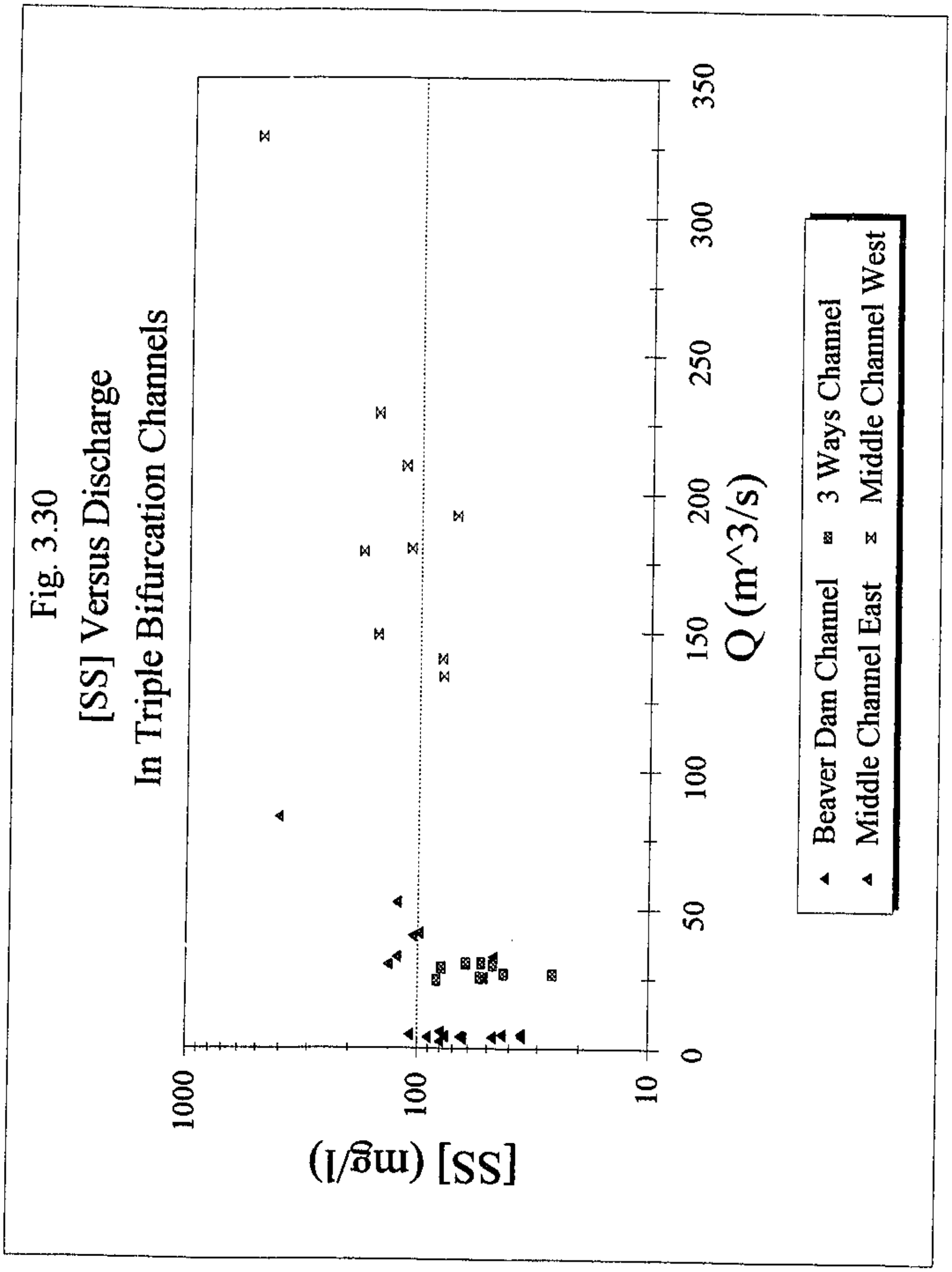


Fig. 3.30
[SS] Versus Discharge
In Triple Bifurcation Channels

Fig. 3.31

Middle Channel East [SS] Vs. Q

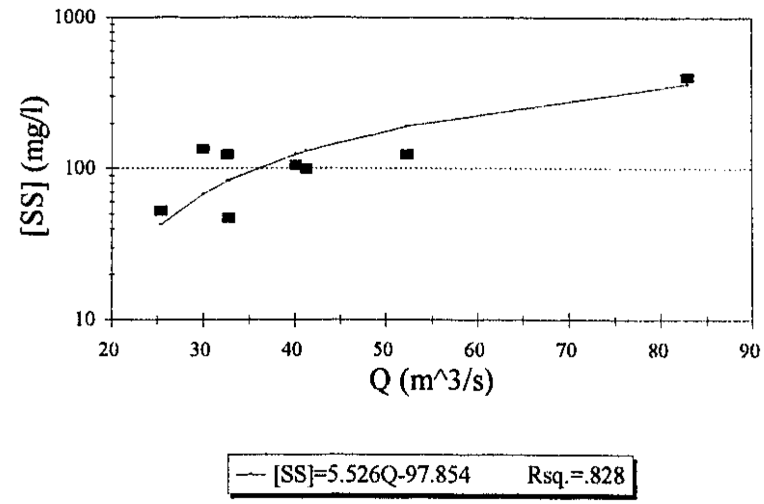
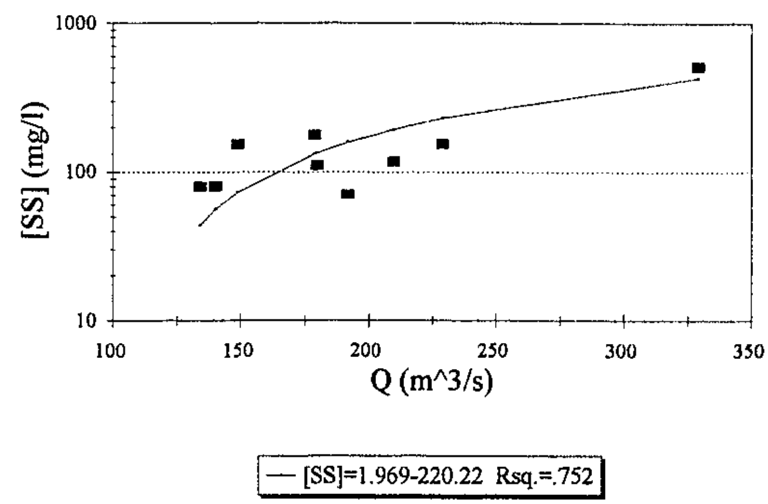


Fig. 3.32

Middle Channel West [SS] Vs. Q



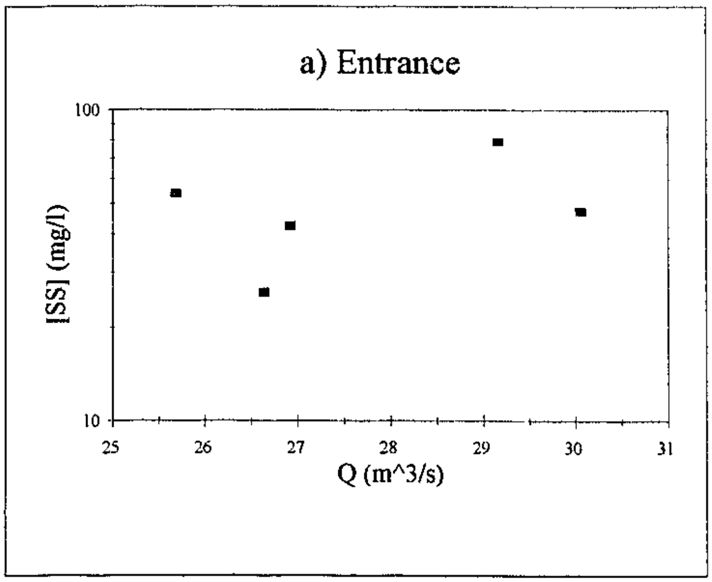
[SS] and discharge seen in the previous two channels. In fact, both appear to be characterised by a broad range of [SS] values with very little variation in discharge (Fig. 3.30). Closer inspection of data from the individual channels, however, indicates that this trend may not be entirely true.

In Three Ways Channel, [SS] tends to increase with discharge at the entry point and decrease with discharge at the mouth (Fig. 3.33). The initial conclusion here would be that this channel is characterised by deposition which may lead to its eventual abandonment. Temporal analysis, however, indicates that on the same dates, sediment load **and** discharge at the mouth of Three Ways Channel are both greater than those at the entry point (Fig. 3.34). As a result, more sediment is actually flowing out of the channel than entering which, in turn, means that the channel is actually characterised by erosion, not deposition.

Like Three Ways Channel, the entry point of Beaver Dam Channel is characterised by a relatively scattered plot of [SS] versus discharge. There does, however, appear to be a more positive relationship between the two variables at the channel mouth (Fig. 3.35). In addition, discharge values are slightly lower towards the channel mouth due to the increased distance from the main body of the Slave River, the interaction of channel flow and the standing water of Great Slave Lake, and the north westerly orientation of the offing which leaves it susceptible to seiche effects driven by the predominate winds off the lake. As a result, it would appear that Beaver Dam Channel is characterised by deposition. In fact, at least three abandoned distributary channels were observed along the length of the channel during the summer field season which

Fig. 3.33

Three Ways Channel
[SS] Vs. Q



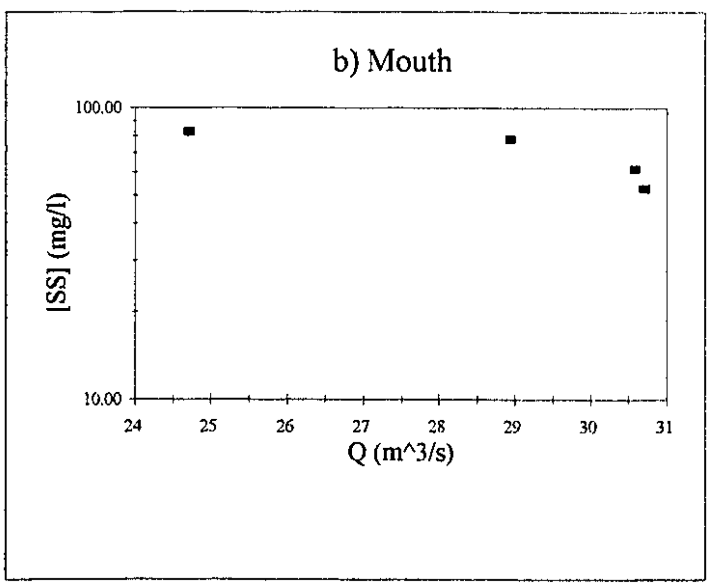


Fig. 3.34
Temporal Analysis of Mass Transport
in Three Ways Channel

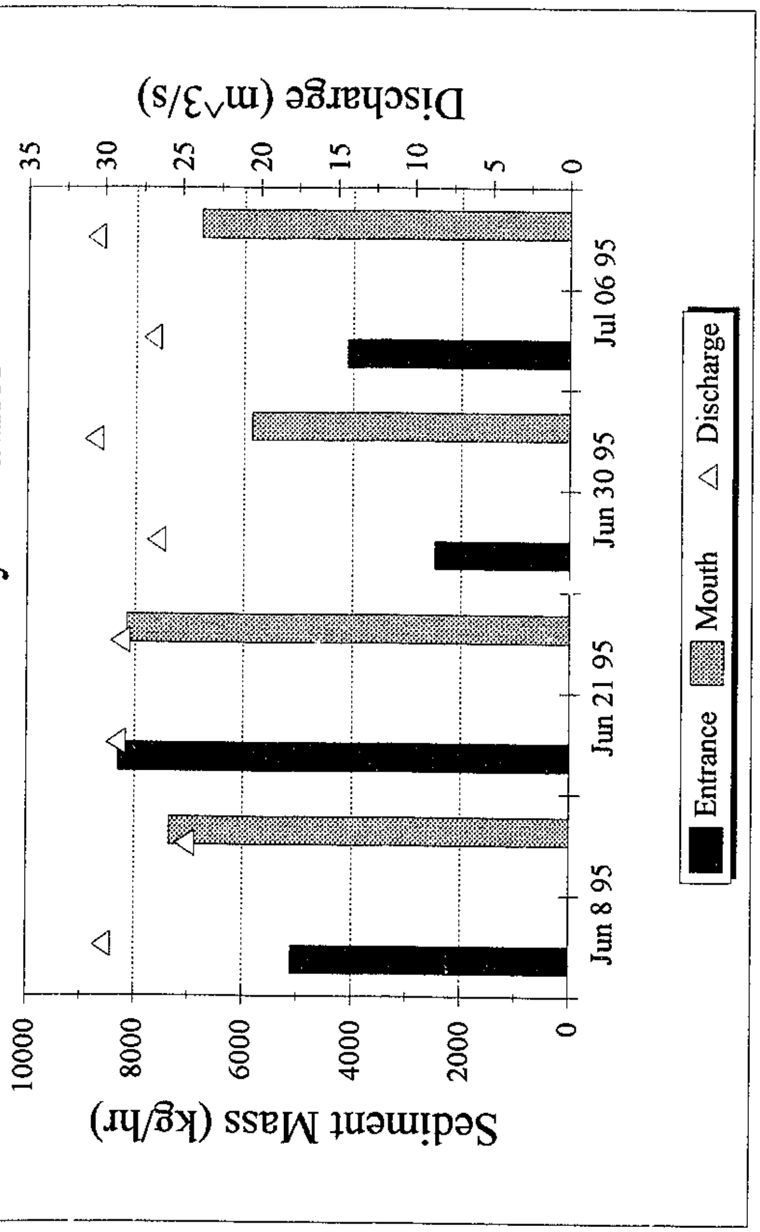
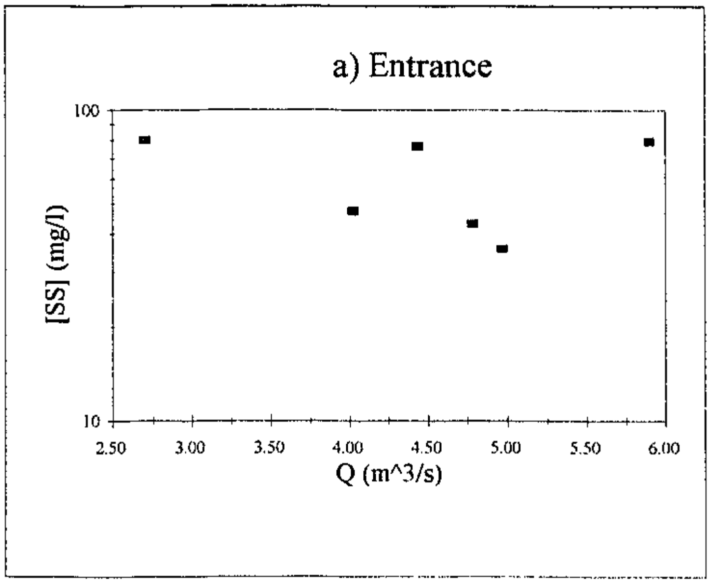
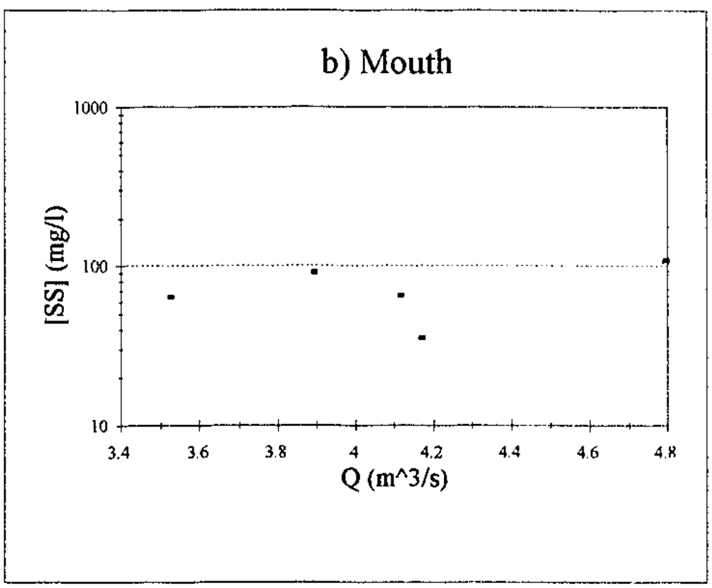


Fig. 3.35
Beaver Dam Channel
[SS] Vs. Q





indicates that active depositional processes are occurring within Beaver Dam Channel.

Temporal analysis of data gathered over the field season, however, indicates a general increase in sediment mass toward the mouth of the channel (Fig. 3.36). Consequently, Beaver Dam Channel may be more accurately defined as an erosional channel since material is being entrained by higher flows at the channel entrance and carried downstream to the mouth.

The erosional trend in both Three Ways Channel and Beaver Dam Channel may have several explanations. The former bifurcates from the upstream channel in such a way that a point bar formation is created at the entry point (Fig. 3.16). Because of this, it is possible that a large portion of the suspended load carried into Three Ways Channel is deposited at the entrance. This, in turn, means that the volume of water moving down Three Ways Channel has a strong potential to erode the banks and entrain bed material. In addition, the point bar configuration of the channel entrance may create significant turbulence in this location and, therefore, direct more of the sediment laden flows down the main channel toward Island Channel North and Island Channel South.

Channel orientation and bifurcation angle may also be responsible for the erosional trend in Beaver Dam Channel. In this case, the bifurcation angle is relatively small (Fig. 3.16); however, flows directed into Beaver Dam Channel tend to exhibit the same characteristics described by Welder (1959). Figure 3.37 shows the development of helicoidal flow in low angle bifurcations and illustrates how these flow conditions produce significant deposition in channels branching from the trunk stream. In Beaver Dam Channel, deposition at the channel entrance has not only lead to growth

Fig. 3.36
Temporal Analysis of Mass Transport
in Beaver Dam Channel

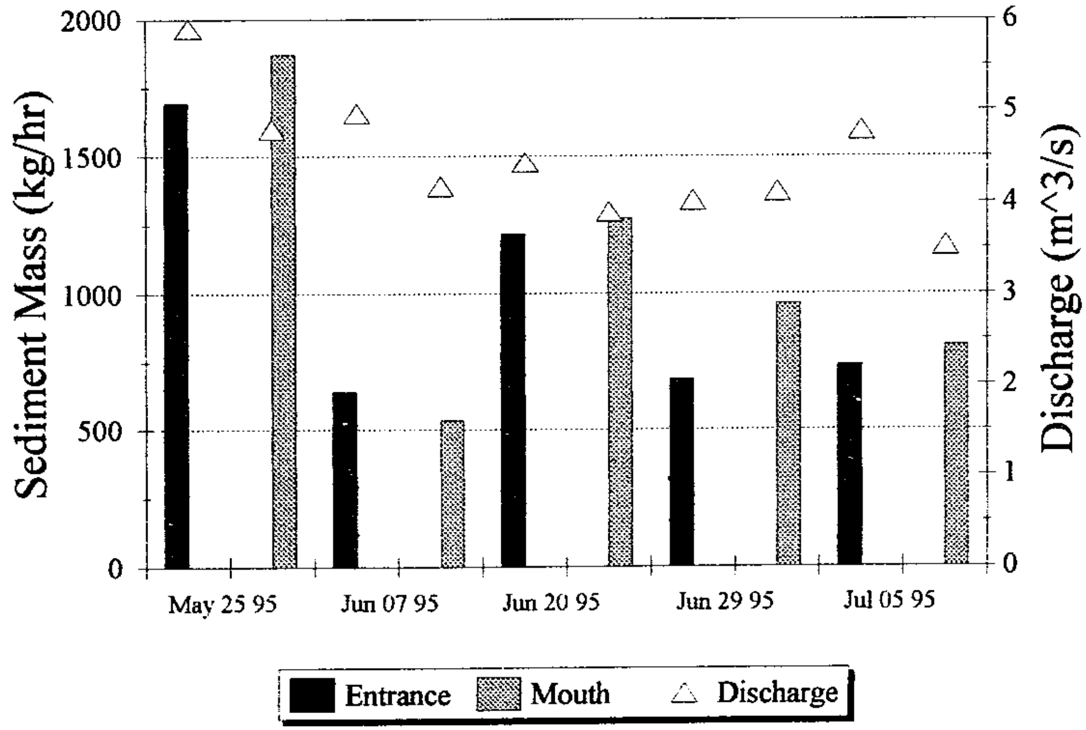
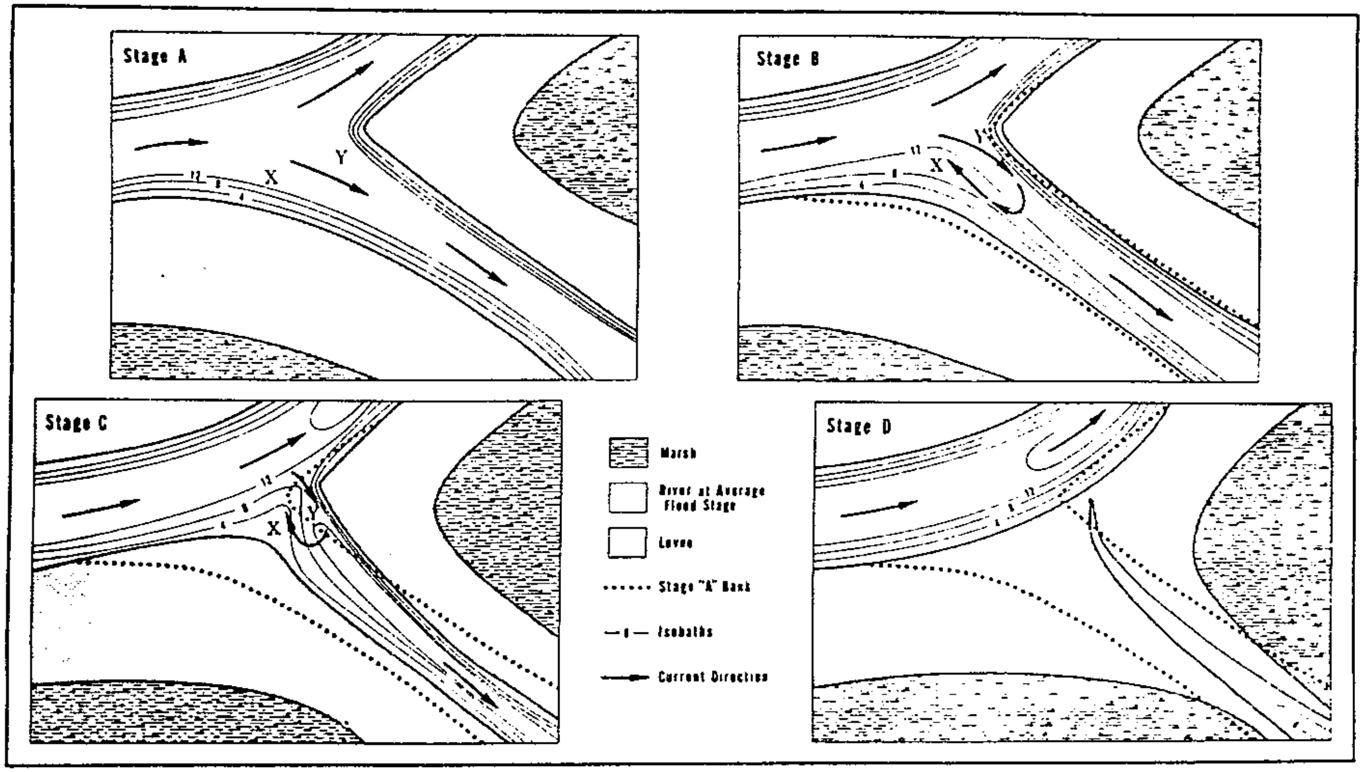


Fig. 3.37

Development of Channel Closure



Welder, 1959

of the natural levee, but has increased the carrying capacity of downstream discharges. Based on the data in Figure 3.36, it would appear that the reduced sediment load near the entry point caused by deposition enable downstream flows to entrain material from the channel proper and carry it downstream toward the mouth.

3.3.3.6. Quadruple Bifurcation Channel Characteristics

Unfortunately, the quadruple bifurcation class is represented by only two channels, both of which are part of the same distributary network. These are found in the same portion of the delta, and have a similar range of discharge and [SS]. Despite these similarities, a plot of [SS] versus discharge for the two channels seems to show the two have relatively little in common (Fig. 3.38).

At the entrance to Island Channel South, [SS] is relatively constant over the entire range of measured discharge (Fig. 3.39a); however, the channel mouth seems to exhibit the same classic power relationship between [SS] and discharge observed in the larger channels closer to the main body of the Slave River (Fig. 3.39b). According to this, peak flows in Island Channel South are carrying less sediment at the entry point than those at the mouth. An examination of sediment loading over the summer field season, however, illustrates that a greater mass is generally found at the channel entrance (Fig. 3.40). In fact, both sediment mass and discharge are higher at the entry point on all but one occasion. As a result, it would appear that deposition tends to dominate in Island Channel South because of reduced carrying capacities downstream caused by decreased discharge.

Fig. 3.38
[SS] Versus Discharge
In Quadruple Bifurcation Channels

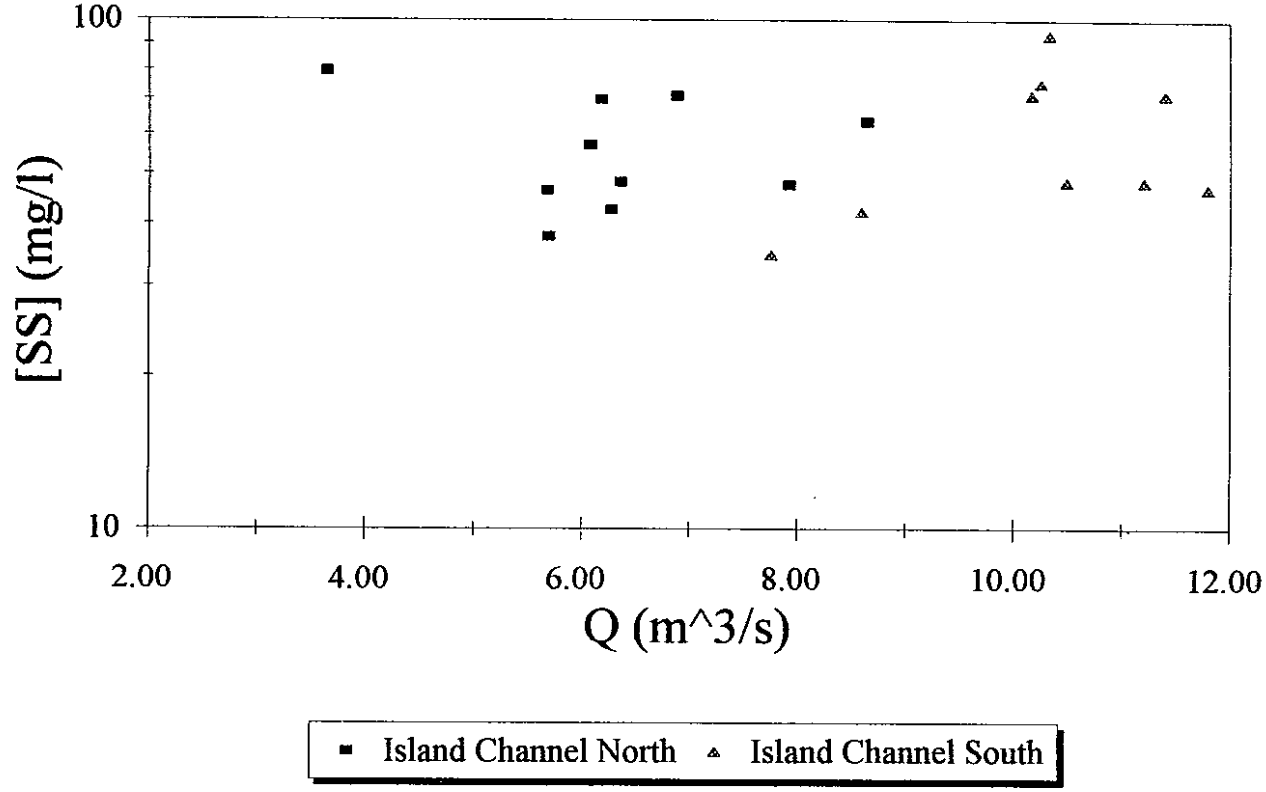
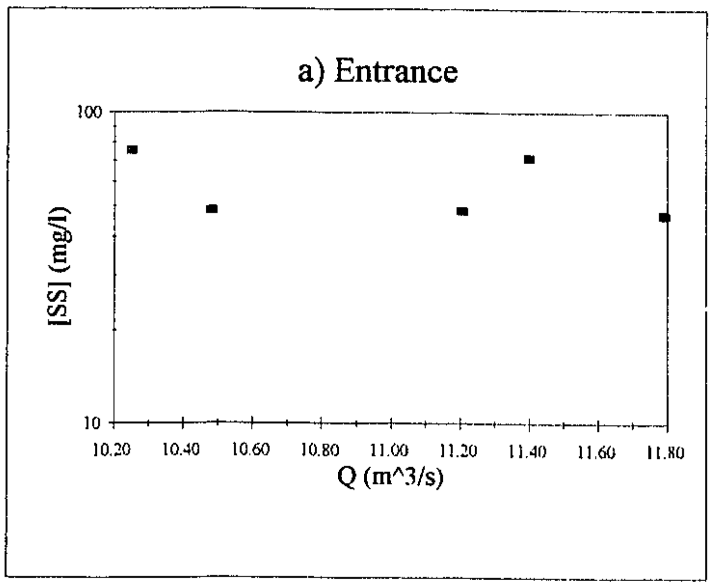
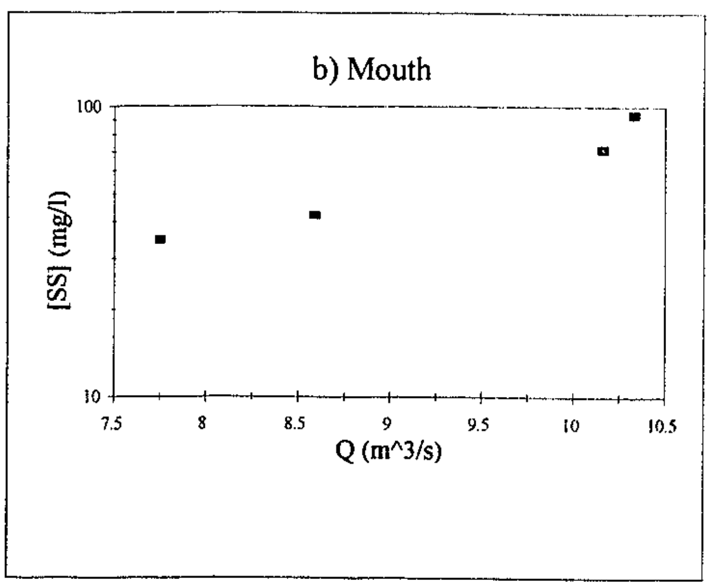


Fig. 3.39

Island Channel South
[SS] Vs. Q





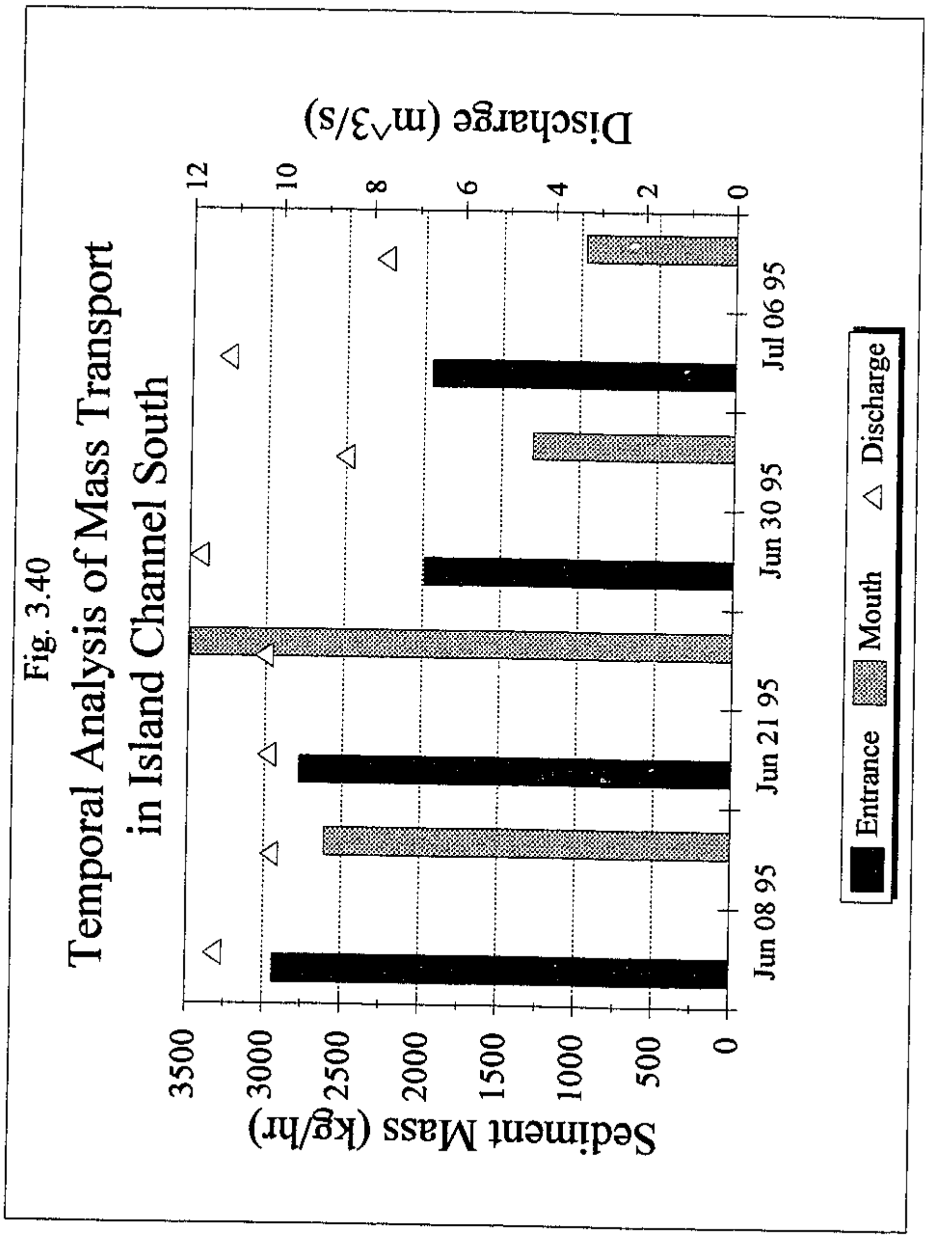


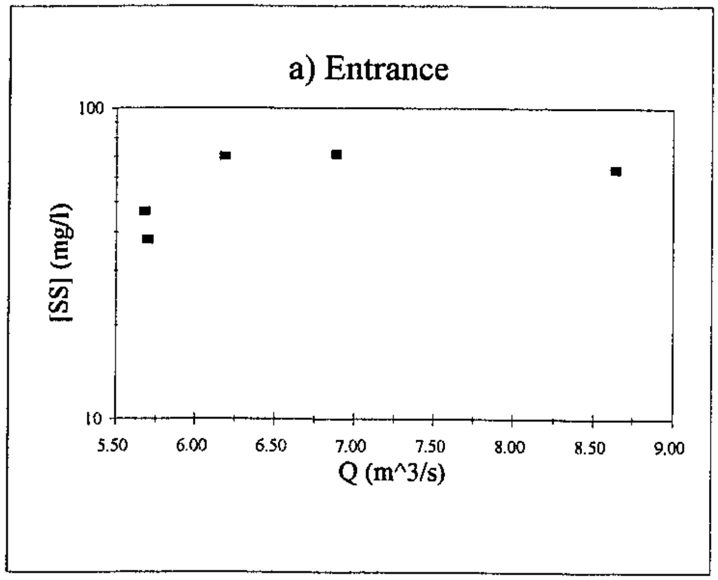
Fig. 3.40
Temporal Analysis of Mass Transport
in Island Channel South
Sediment Mass (kg/hr)
3500
3000
2500
2000
1500
1000
500
0
Discharge (m^3/s)
12
10
8
6
4
2
0
Jun 08 95
Jun 21 95
Jun 30 95
Jul 06 95
Entrance
Mouth
Discharge

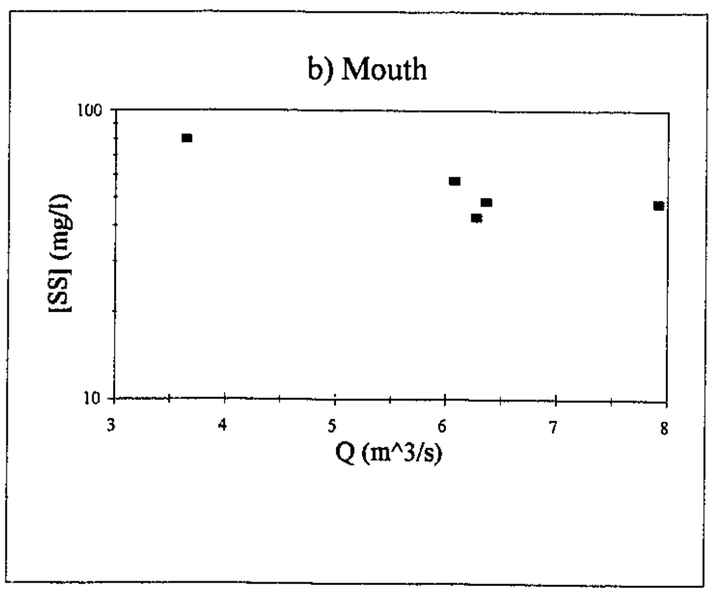
Given the general characteristics of this channel, it would appear that the massive sediment load observed at the mouth of Island Channel South is a definite anomaly. One possible explanation would be measurement error; however, the magnitude of difference in this case indicates that this is not the case. Another more reasonable explanation would be the transport of material from within the distributary itself. Although no significant erosional features were observed during this time, it is entirely possible that a section of bank material fell into the channel and was carried downstream where it was recorded as an increase in sediment.

Having examined the relationship between [SS] and discharge in Island Channel North in more detail, it would appear that this channel, like Island Channel South, is predominately depositional. In this case, the channel is characterised by a strong positive linear relationship between discharge and [SS] at the entry point and an inverse relationship at the mouth (Fig. 3.41). As a result, increased discharge through the entry point tends to carry a substantial sediment load into the channel. As this flow makes its way down the channel, however, sediment mass and concentration decrease, signifying the deposition of material along the way. Further evidence also illustrates the depositional characteristics of Island Channel South. A plot of sediment mass transport (Fig. 3.42) shows the presence of greater sediment mass at the channel entrance across the entire range of discharge observed during the summer field season. As a result, a large portion of this material must be deposited within the channel in order to produce the reduction of sediment at the mouth of Island Channel North.

Fig. 3.41

Island Channel North
[SS] Vs. Q





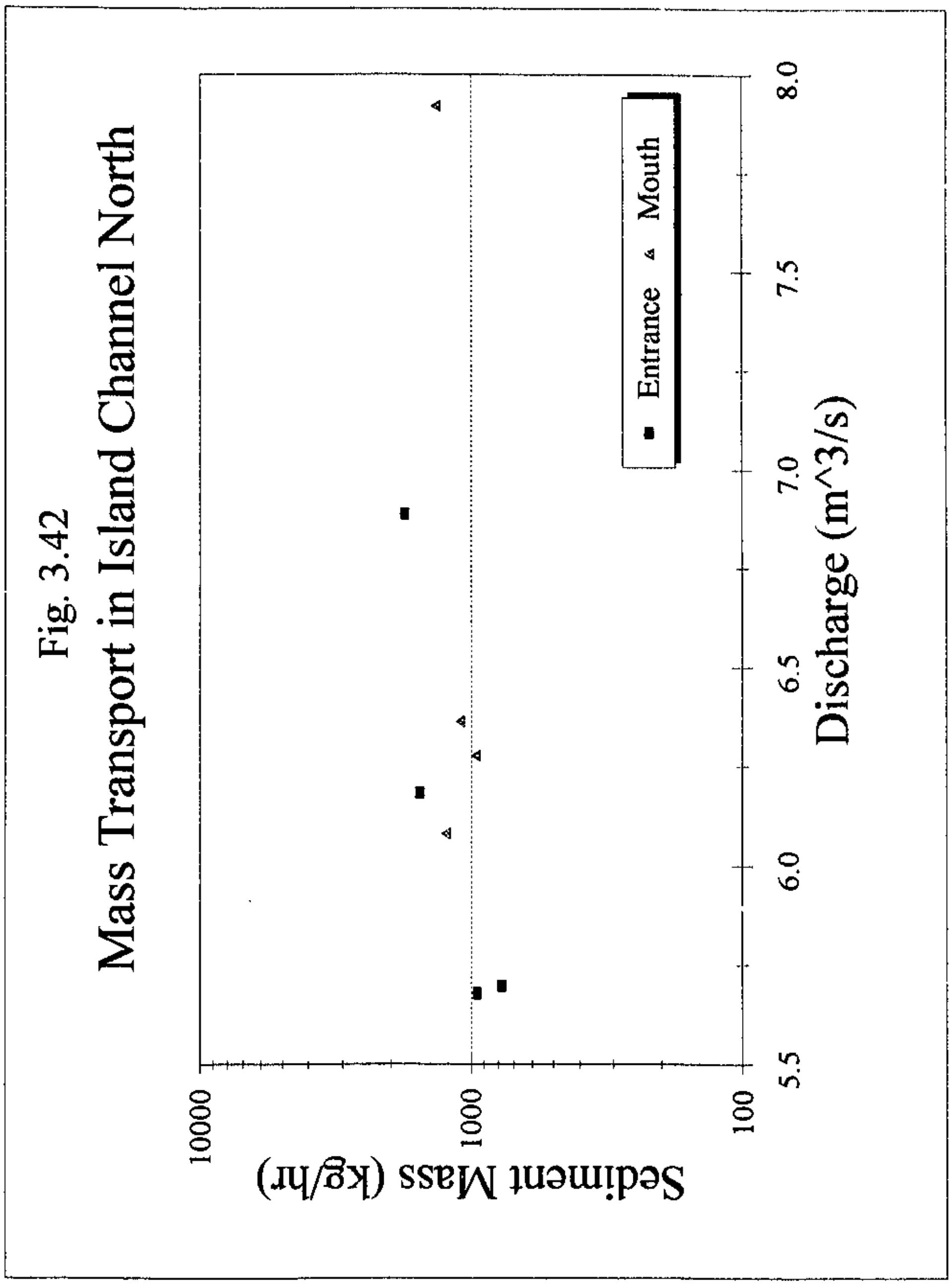


Fig. 3.42
Mass Transport in Island Channel North

3.4 CONCLUSIONS

Examination of data from field research, historical sources, and aerial photography clearly indicate that the hydrological regime of the Slave River Delta underwent considerable changes from 1946 to 1994. Using a strong relationship between discharge and channel width, it is estimated that summer flows through Old Steamboat Channel dropped from 786 m^3/s to 84 m^3/s over the 48 year period while those in Middle Channel decreased from 3582 m^3/s to 208 m^3/s. Conversely, estimates of discharge in Resdelta Channel show an increase from 1842 m^3/s to 2486 m^3/s over the same time period. The alteration of flow within these major channels has lead to changes in the distribution of flow which, in turn, have implications for deposition and erosion throughout the delta.

Examination of [SS] and discharge in various channels throughout the Slave River Delta has shown that seasonal variations in the annual hydrograph, channel bifurcation, and the processes involved with each strongly influence the relationship between these two variables which, in turn, has implications for deposition and erosion as well. During both the summer and autumn, correlation between [SS] and discharge is rather weak but tends to show some indication of a relationship. Suspended sediment concentrations are higher under low flow conditions during the fall and lower under high flow conditions due, in part, to the impacts of upstream impoundment on the Peace River. In addition, fall flows appear to be sediment limited due to the general lowering of fall water levels and available sediment sources.

The relationship between discharge and suspended sediment is more complex during the spring. The influence of breakup often leads to elevated [SS] due to thermoniche erosion, ice scoured banks, rafted deposits, and the release of bottom fast ice. In addition, ice jams often impede flow through certain channels or block them entirely, producing relatively low discharges with artificially elevated [SS].

In addition to seasonal influences, the relationship between discharge and [SS] is dependant upon the distribution of flow throughout the delta. According to the data, discharge tends to decrease as flows move away from the main body of the Slave River. In addition, the amount of variation in both discharge and [SS] values also tends to increase with increased channel bifurcation. As a result, distributaries were classified according to how many bifurcations they were away from the main body of the Slave River.

Within up to two bifurcations from the main channel, plots of discharge and [SS] are generally characterised by the strong positive relationship described by Leopold and Maddock's (1953) power function form. One channel which does not conform to this trend, however, is Old Steamboat Channel. Because of recent low water levels and the continued formation of a depositional bar across its entry point, Old Steamboat Channel exhibits an inverse relationship between discharge and [SS].

Beyond two bifurcations, discharge and [SS] tends to be inversely related, signifying a strongly sediment limited system. In addition, channels within these classifications are generally found towards the delta front and are characterized by deposition.

• CHAPTER 4.0 •

AN ASSESSMENT OF LANDFORM DEVELOPMENT WITHIN THE SLAVE RIVER DELTA, NWT DURING THE PRE- AND POST-IMPOUNDMENT PERIODS 1946 - 1994

4.1 INTRODUCTION

Formation of the Slave River Delta began approximately 10 000 years before present (BP) following the retreat of the Selwyn ice tongue (Cameron, 1922). Since that time, the delta has continued to fill in the southern arm of Great Slave Lake from the rapids at Fort Smith to its present day location at approximately 61° 15' N 113° 30' W (Fig. 4.1). Vanderburgh and Smith (1988) have estimated progradation rates of close to 20.7 m/year for the Slave River Delta; however, English *et al.* (1996) report that only about 5% of the total 8300 km^2 is currently undergoing active development.

Because of the significance of Peace River flows on the hydrologic regime of the Slave River (Fig. 4.2), there have been concerns that regulation of the Peace may have impacted on the development of the Slave River Delta. Several authors have already explored the potential impacts of impoundment on the Slave River Delta (English, 1979, 1984; Bodden, 1981b; English *et al.*, 1996) and a number of others have examined both the potential and actual impacts of Peace River regulation on the Peace-Athabasca Delta (Dirschl, 1971; Blench, 1972; Gill, 1973, 1976b; Peace-Athabasca Delta Project Group, 1972).

Fig. 4.1

Study Site

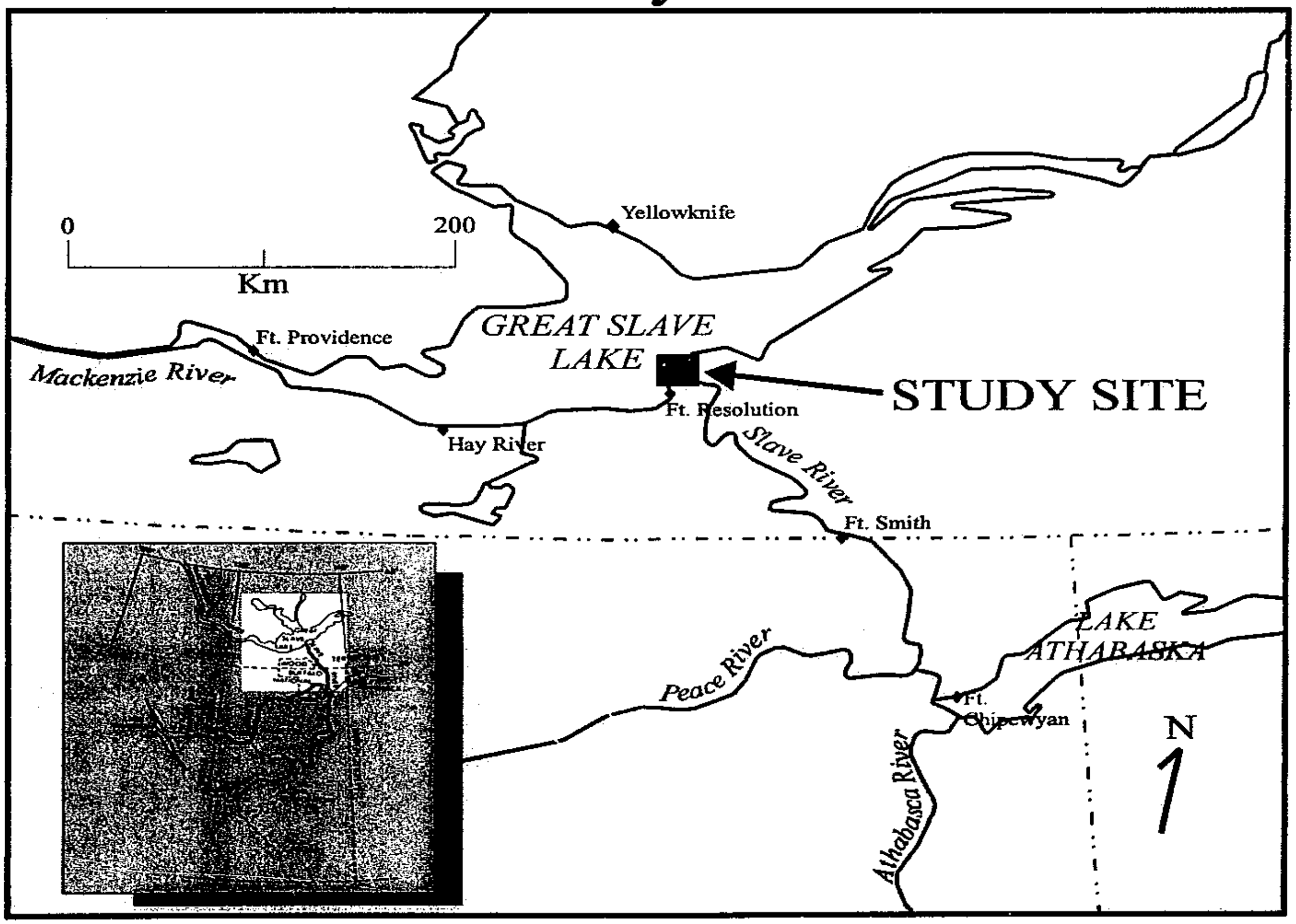
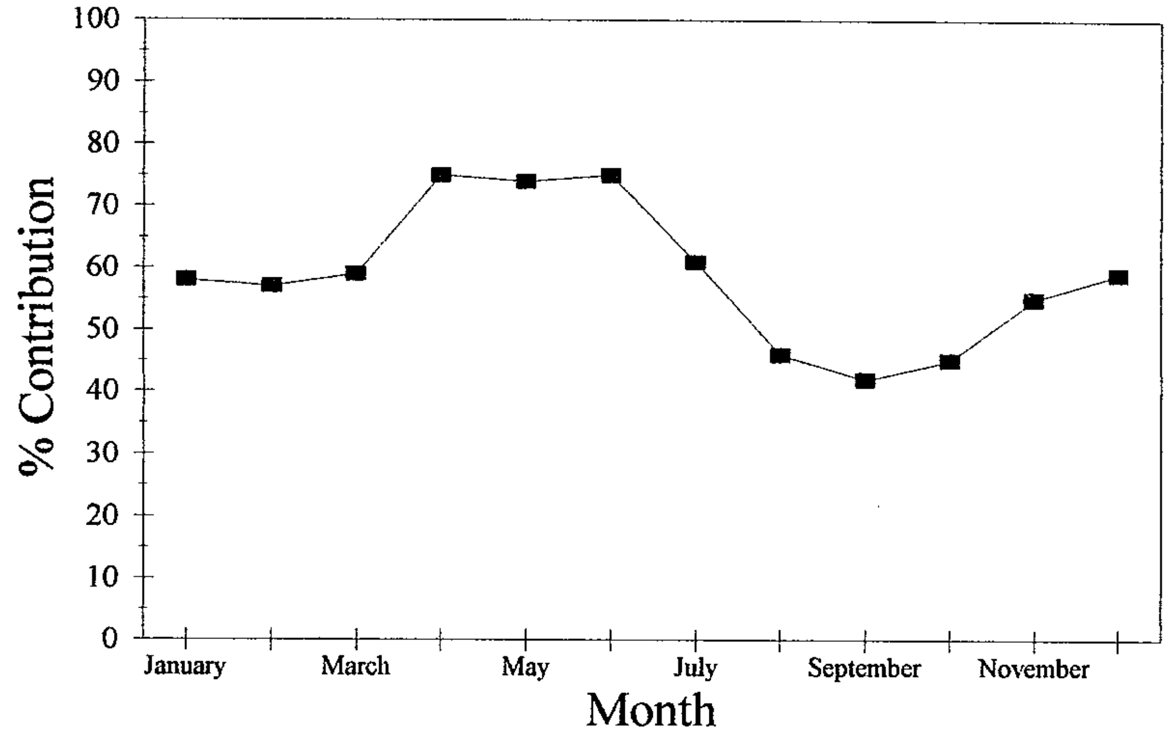


Fig. 4.2

% SLAVE RIVER FLOW FROM PEACE RIVER: PRE- AND POST-REGULATION



(English et al., 1996)

The purpose of this chapter is to identify and measure areas of morphometric change within the Slave River Delta. Four sets of aerial photographs representing the active portion of the Slave River Delta over approximately 20 year periods before and after regulation of the Peace River have been converted to digital format and are used to quantify the magnitude of change which has occurred within the subaerial portions of the delta during these time periods.

4.2 *METHODOLOGY*

4.2.1 PHOTO SELECTION

In order to assess the impact of the W.A.C. Bennett Dam on geomorphic change within the Slave River, it was imperative to examine photography taken over periods before and after the 1968 impoundment. Table 4.1 shows the dates of aerial photography available from the National Air Photograph Library for the area under study as well as their respective scales and colour schemes. Photography was chosen from 1994 because it represents the most recent data available for the area. This not only helped in the GIS analysis of landform change, but helped in the selection of field sites for the 1995 field season as well. Several sets of aerial photography were taken during the 1970's; however, only the 1977 set provides a comprehensive coverage of the entire delta at a comparable scale to that of the 1994 photography. The 1966 photography was chosen because it is the last photography of the delta prior to the 1968 completion of the Bennett Dam. Finally, the 1946 photography was chosen on the basis that it is one of the earliest sets to provide comprehensive coverage of the active delta and,

Table 4.1

Aerial Photography of the Slave River Delta

YEAR	DATE	COLOUR	SCALE
1930	August	b/w	1:12 000
1946	July	b/w	1:25 000
1954	August	b/w	1:70 000
1957	September	b/w	1:25 000
1960	July	b/w	1:40 000
1966	August	normal	1:24 000
1970	September	b/w	1:60 000
1972	August	b/w	1: 8 000
1973	July	b/w	1:25 000
1977	September	colour & false colour I.R.	1:25 000
1979	July	b/w	1:20 000
1994	June	false I.R.	1:25 000

(After Mollard, 1981)

when combined with the 1966 photography, represents a time frame for the pre-impoundment period which is comparable to that of the post-impoundment period from 1977 - 1994.

4.2.2. PHOTO REGISTRATION

Before the photographs could be converted into digital format, they had to be registered to some form of coordinate system. Since the chosen software package, TerraSoft, uses the Universal Transverse Mercator (UTM) grid as a default setting, the photos were registered to 1:50 000 National Topographic Series maps of the Slave River Delta which conform to the same system. Plastic transparencies were placed over each photograph and then the appropriate topographic sheet was imposed onto the image using a Bausch and Laumb Zoom Transfer Stereoscope. The photos were then registered by marking a series of dots at the intersection points of UTM eastings and northings onto the transparencies and labelling them accordingly.

4.2.3 DIGITIZING

Once registered, the photos were put into digital form using the GIS package TerraSoft. To do this, a template was cut to isolate the central 60% of each photo in order to eliminate those portions of the photo which were subject to parallax error and distortion. Each photo was then taped to a digitizing tablet, covered by the template, and digitized in the following manner.

A feature class table was created for each set of photography in order to provide a number of classifications for the digitized line work (Appendix C). TerraSoft map files (*.TSF) were then set up for each set of photography by defining the maximum and minimum coordinates for UTM eastings and northings. Three coordinates from the clear transparency were then used to register the photo within the spatial context defined by the map file. An appropriate feature class was then chosen from the table to represent a feature to be digitized from the photo. A digital image was created by selecting the "line string" function from the CREATE NEW FEATURES menu, running the cross hairs of the digitizing puck along the feature in the photo, and creating linked nodes by depressing a button on the puck.

Here the methodology differs slightly for the 1977 photography, for it was available only as a roll of false colour film positive. As a result, the features had to be traced onto the transparency using a light table and overhead marker. The features were then transferred to digital form in the same manner as the other photography. In this case, however, digitizing was done along the traced image instead of the original.

Once all similar features had been completed, a new feature class was chosen and the process was repeated for all of the elements in the photo which fell under this new classification. This method was used to digitize not only the boundary between land and water, but to digitize the areal extent of various vegetation assemblages as well. Finally, numeric labels were added to each individual island using the "text" function and the appropriate feature class.

4.2.4 ESTIMATE OF ERROR CALCULATIONS

Errors created from digitizing should be relatively small since the digitizing puck includes a set of 0.25 mm cross hairs which enable the user to be very precise and accurate. Given the width of these cross hairs, human error is estimated at approximately 0.5 mm. Even at the photographs' 1:25,000 scale, however, the digitized features would be within ±1.25 m of their actual location in space. As a result, only the original registration process and the tracing of 1977 photography onto transparencies could have provided any significant source of error. Great care was taken to ensure that each photo was registered as accurately as possible both from the topographic sheets and within TerraSoft. In fact, the TerraSoft program provides a measure of error during its registration process which calculates the distance between the points used to register the image and their actual position in space. During the digitizing process, no error greater than ±0.00 m was ever recorded.

Tracing the 1977 photography did provide some problem as the thickness of the pen used to transfer data to transparencies was wider than that of the fine cross hairs on the digitizing puck. To quantify the effects created by the wide line of the pen at the photo scale, a 2 km X 2 km box, a 2 km X 2 km right angled triangle, and a 2 km straight line were drawn at the same scale as the air photos using the pen. The figures were then digitized along the inside and outside edges of their borders. Areas were then calculated using the inside edges of the two closed polygons and compared to those calculated using the outside edges. For the straight line, distances between the inside and outside edges were measured at 12 random locations and used to calculate an average distance.

According to the test results (Appendix D), digitizing along the outside of the pen line added 8 ha to both the 400 ha square and the 200 ha triangle. Conversely, digitizing along the inside of the pen line resulted in a loss of 7 ha from the square and 3 ha from the triangle. In the case of the 2 km straight line, the test results show that features digitizing along the pen are within ± 12 m of the actual location.

4.2.5 ARC/INFO

Once the four sets of aerial photography had been successfully converted to digital form in TerraSoft, the resulting line work was converted to Digital Transfer Format (DXF) and copied into an Arc/Info GIS. Here the line work was edited to ensure that there were no dangling lines or open polygons and that all islands were properly labelled. The system was then instructed to link each label to its associated island and calculate the area. The results of this process were used to create spreadsheet files for each set of photography which, in turn, were used to help determine areal change within the Slave River Delta over the pre- and post-impoundment periods.

4.2.6 ADDITIONAL CALCULATIONS

Before analysing the data from the four years under study, the areas calculated with the Arc/Info GIS were adjusted to account for: 1) the fusion of islands that has occurred between 1946, 1966, 1977, and 1994 and 2) the differences in water level on the dates that each set of air photographs were taken. The fusion problem was simply solved by taking the calculated areas for each of the single islands present in the early years and combining them into a "composite" total which could then be compared to the amalgamated island of later years. Figure 4.3 shows the location of the 65 island complexes used to compare landform area over the 4 time periods.

Unfortunately, the problem of changing water levels on Great Slave Lake is not so easily solved. Historic water level records of Great Slave Lake were obtained from Water Survey of Canada (WSC) in Fort Smith and used to determine the variability of mean water levels between the four years under study (Fig. 4.4). According to this data, there is very little difference between water levels in 1977 and 1994. In fact, the 5.8 cm difference in water level would produce less change than the maximum error attributable to digitizing the 1977 photography; as a result, no changes were made to the 1977 data.

The June 14 level from 1994 was chosen as the standard baseline because of the fact that the 1994 water levels were the most recent values available at the time of study. As a result, water levels in 1946 are as much as 23 cm below baseline while those of 1966 are as much as 11 cm above.

In order to adjust the calculated areas to a standardized water level these values were placed in a cubic equation for channel levee elevation determined from cross-sectional profiles surveyed during the 1995 summer field season (Fig. 4.5). An increase or decrease in landform width due to changes in water level could then be calculated by substituting the elevation of the water level into the equation, solving for the distance, and comparing this value to that of the 1994 water levels. For example, the

Fig. 4.3

Island Complex Locations

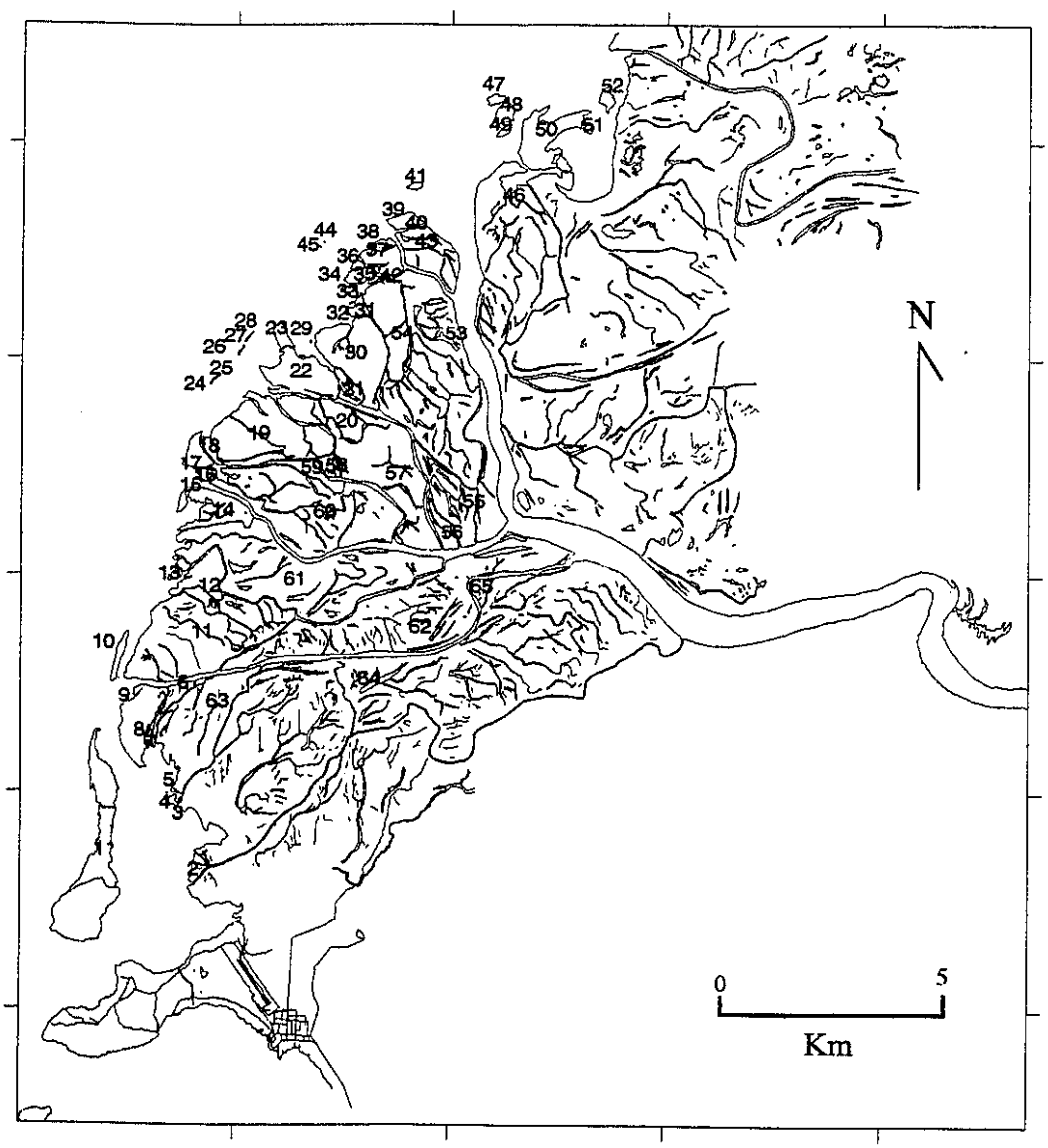


Fig. 4.4

Great Slave Lake Water Levels
Recorded at Yellowknife, NWT

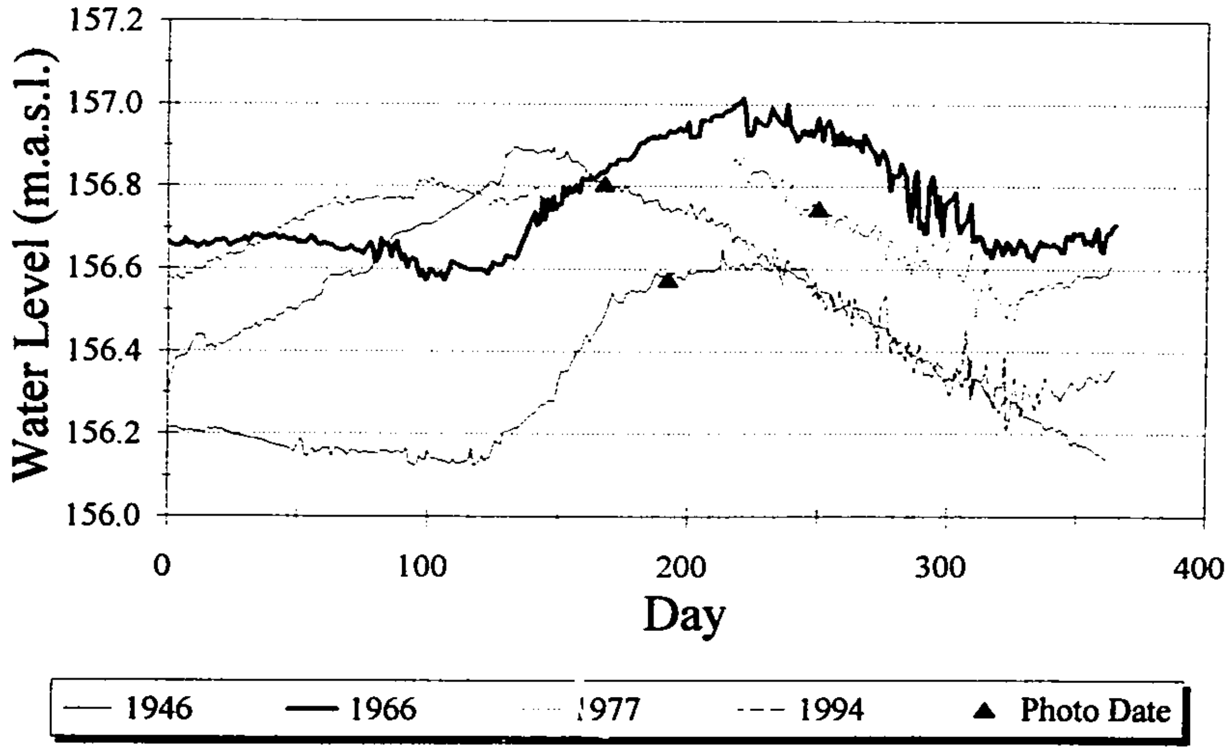
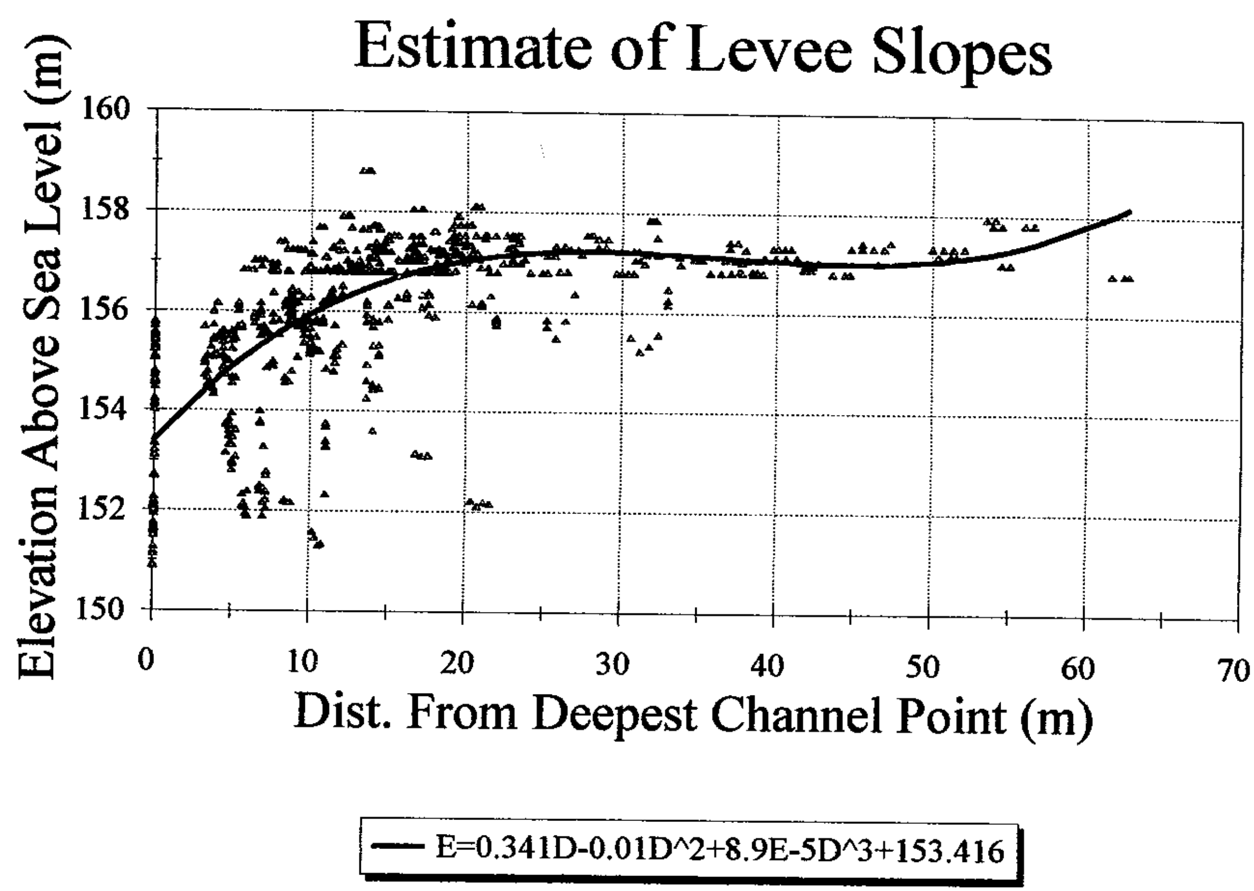


Fig. 4.5


Estimate of Levee Slopes
Elevation Above Sea Level (m)
160
158
156
154
152
150
0
10
20
30
40
50
60
70
Dist. From Deepest Channel Point (m)
E=0.341D-0.01D^2+8.9E-5D^3+153.416

156.807 m water level of the 1994 photography corresponds to a distance of 16.975 m from the deepest point in the channel while the 156.576 m water level from the 1946 photography corresponds to a distance of only 14.610 m. Consequently, 2.365 m more of the levee is exposed under the low water conditions of 1946. The change in total surface area due to variations in water level was then calculated by multiplying this distance difference by the perimeter of the island.

The use of Yellowknife water levels presented a problem due to the fact that predominate north westerly winds blowing across Great Slave Lake have the potential to build up a large seiche at the delta. Unfortunately, water level records for Fort Resolution do not exist for all the years under study and are rather limited for those dates that are on record (Fig. 4.6). A plot of Fort Resolution water levels versus Yellowknife water levels, however, indicates a strong correlation between the two (Fig. 4.7); consequently, the Yellowknife data were considered accurate enough to depict the relative water levels over the four years under study.

4.2.7 ANALYSIS

After grouping the four sets of photography into comparable units and adjusting to an analogous water level, comparisons of morphometric change were carried out. Initial comparisons were made on the total area of the subaerial delta present in each of the four years under study. Subsequent comparisons were made by: 1) isolating the outer delta islands which make up the predominate depositional environment within the Slave River Delta and 2) grouping the islands into 3 distinctive zones based on trends

Fig. 4.6

Great Slave Lake Water Levels
Recorded at Ft. Resolution, NWT

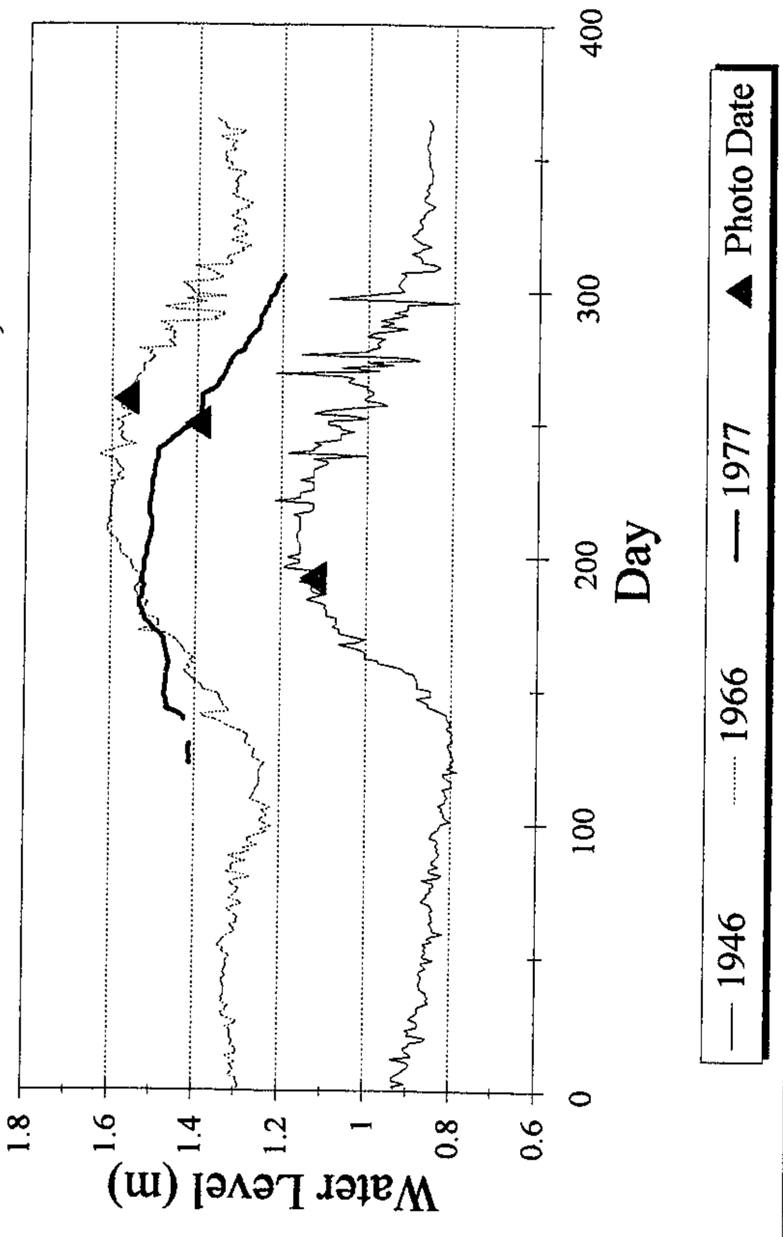
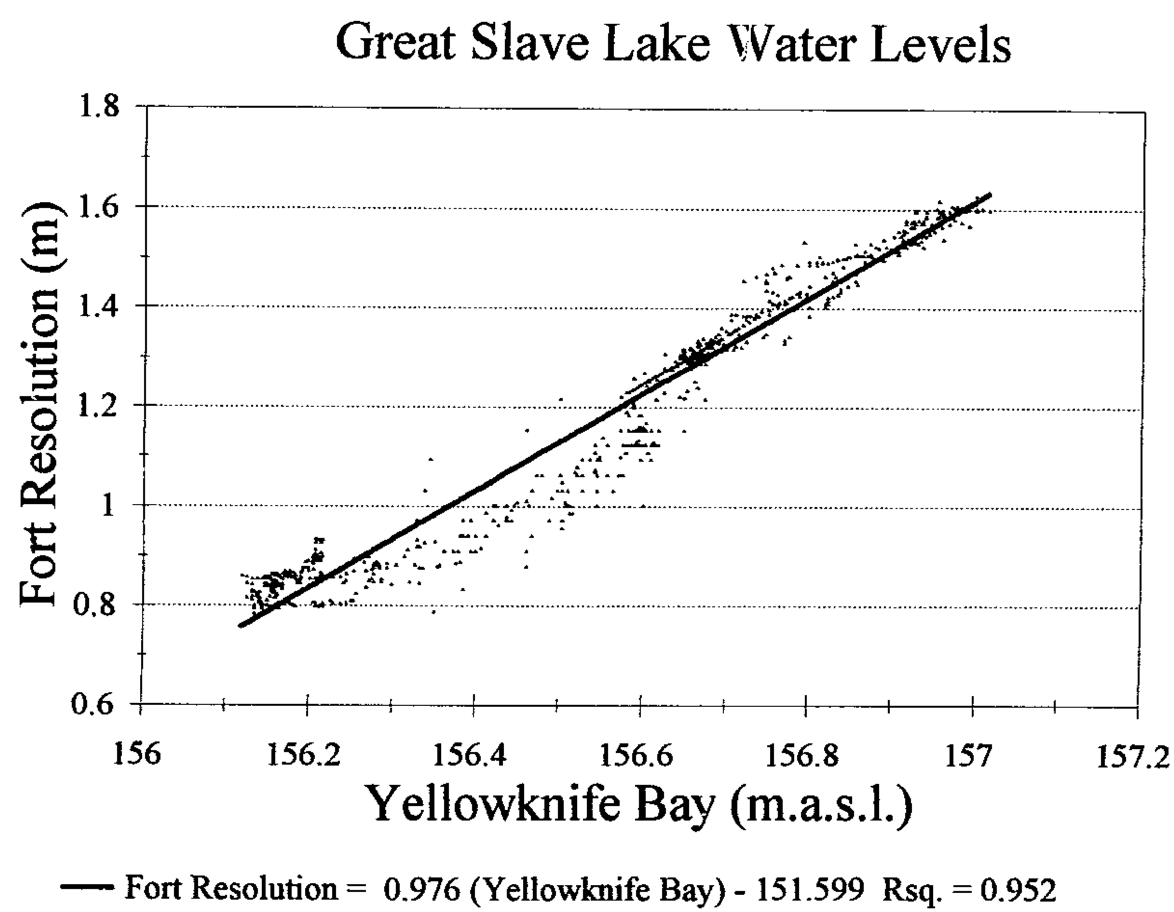


Fig. 4.7


Great Slave Lake Water Levels
Fort Resolution (m)
1.8
1.6
1.4
1.2
1
0.8
0.6
156
156.2
156.4
156.6
156.8
157
157.2
Yellowknife Bay (m.a.s.l.)
Fort Resolution = 0.976 (Yellowknife Bay) - 151.599 Rsq. = 0.952

in channel flow distribution over the 48 year period.

The channel islands were grouped into 3 regions: northwest, middle, and southwest in order to measure the relative growth or decline of these areas over the pre- and post-impoundment periods. This grouping was adopted since 1) these regions are bound by tributaries originating from the delta's three main channel complexes (Resdelta, Middle, and Old Steamboat/Nagle); 2) recent research indicates a general senescence of landform development in the southern sections of the delta while islands towards the middle and northwestern regions continue to develop (English *et al.*, 1996); and 3) residents of nearby Fort Resolution have also indicated a continual shift in the distribution of maximum flow in a north westerly direction (Beaulieau, pers. com., 1995).

4.3 DISCUSSION

4.3.1 TOTAL AREA

After the four sets of aerial photography were converted to digital format, a series of maps were produced which clearly illustrate substantial changes in the Slave River Delta over the 48 year period under study (Fig. 4.8). The first step in examining changes within the Slave River Delta is to look at changes in the total area. Table 4.2 shows the calculated area for each of the 65 island complexes over the four time periods as well as the total area for each year. The missing values in the first three columns indicate that these particular island complexes did not exist in those time periods; as a result, the table also shows the evolution of landform development within the Slave River Delta over the 48 year period.

Fig. 4.8

The Slave River Delta

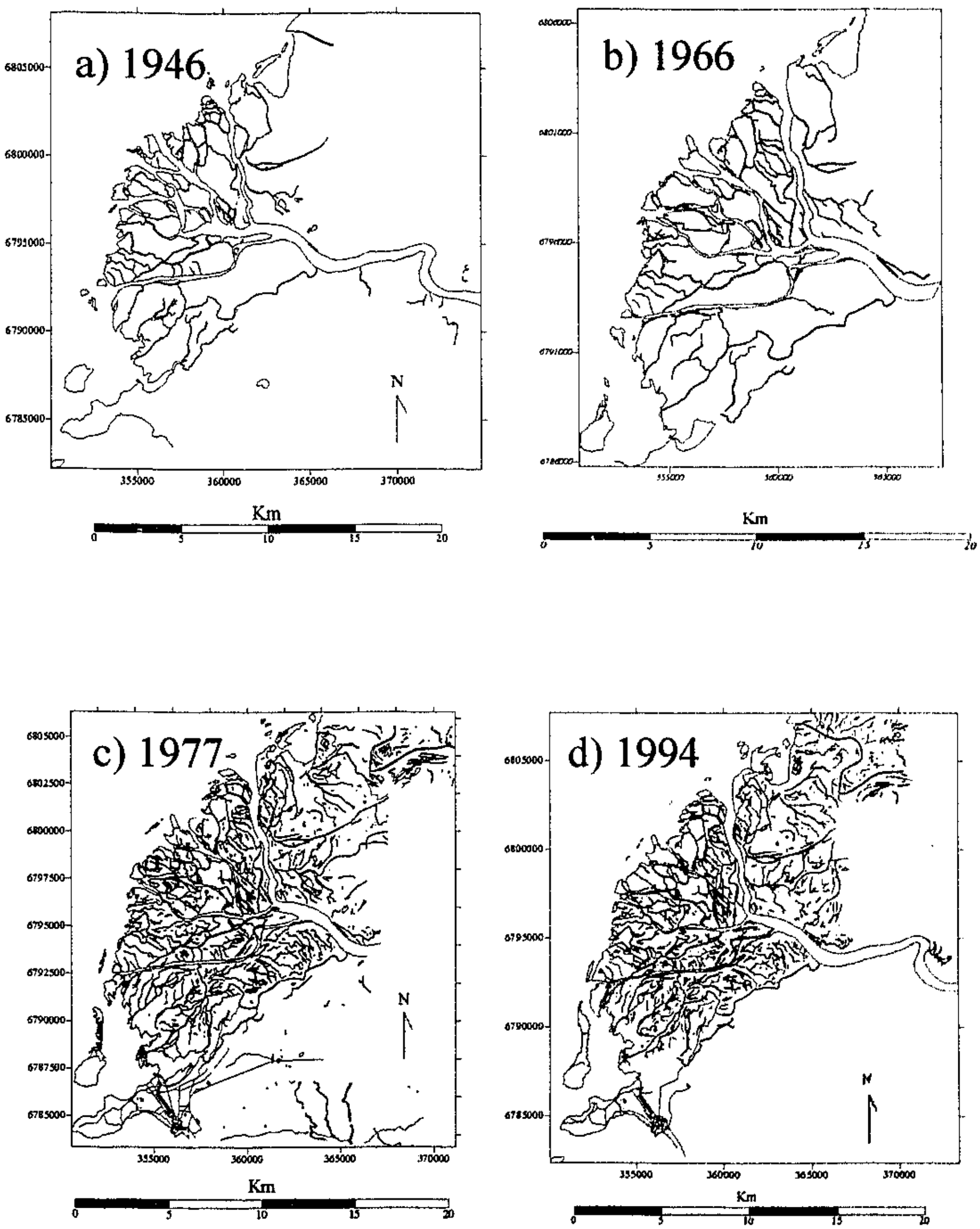


Table 4.2

Total Island Area (adjusted for GSL water levels)

ISLAND I.D. #	1946	1966	1977	1994
1	1546330.705	1905131.470	2382329.634	2886263
2	65445.783	16308.331	84643.056	148175.100
3			0.000	5638.109
4			89088.454	31553.750
5			4003.156	618.273
6		59611.972	190872.200	275029.913
7		13501.673	0.000	35703.910
8	99690.817	327492.042	732162.300	1160901.000
9	149430.393	136589.286	0.000	148.930
10			38327.320	151730.800
11	3993290.017	4253195.708	3116307.008	4913428.836
12	587728.283	664583.572	680745.600	715954.500
13	89435.413	154600.881	54412.770	123760.339
14	934174.429	943275.304	893862.100	924865.100
15			0.000	3023.820
16			45762.495	94429.130
17	574246.356	330991.451	314378.200	311613.800
18	68582.017	108396.986	102603.700	133425.200
19	2820027.452	2831931.394	2645396.300	2858432.000
20	1030596.540	512510.551	507282.100	512359.600
21		45250.313	121821.670	234348.300
22	1226332.895	1021627.263	1043554.000	1302082.000
23	488470.058	220298.178	190602.900	156164.300
24			37401.300	4806.172
25			37401.300	2701.984
26			0.000	2821.039
27			0.000	1494.563
28			2440.891	5844.258
29			0.000	1356.656
30	2080466.547	1871150.190	1810748.900	1986899.000
31	217456.734	96754.335	107513.900	145537.600
32			5852.461	4632.250
33			0.000	2637.828
34			0.000	29294.960
35			86499.071	176481.400
36			0.000	52840.650
37	209601.104	192388.794	360099.020	444949.800
38			39226.876	75784.470
39	190794.563	139282.738	21982.800	214469.000
40	407418.148	383665.606	382338.000	453131.900
41	113781.332	23783.050	56585.050	41661.390
42			0.000	19988.510
43	799025.985	802333.842	706847.747	715034.700
44			0.000	152.711
45			0.000	395.750
46	5392533.904	5218207.647	4506407.000	4911908.8
47			30858.225	71454.830
48			23033.534	159710.400
49			44907.437	49187.350
50	4104.266	434893.199	659249.900	1225239.000
51			7848.484	36119.800
52	63470.292	23272.286	92746.200	122662.400
53	2170489.349	2118630.648	1922521.000	1977521.000
54	7440392.834	7144051.078	6799971.000	6921915.000
55	606456.769	1220861.278	1234975.000	1278786.477
56	284356.870	106455.425	271087.610	350699.600
57	3227923.977	3469906.527	2932315.700	3888061.82
58		86185.306	58694.750	195262.97
59	114416.561	287655.789	285851.800	366231.000
60	3462632.706	4660891.317	4776493.000	4985698.000
61	6138511.194	6418829.227	4851774.000	6454703.000
62	6455434.297	7125044.407	6747199.861	7085894.000
63	2306922.373	2556470.650	2473701.000	2928270.000
64	25036157.985	26664040.283	23401342.580	25950485.92
65	63551.228	140527.437	175746.100	197045.400
Total (m^2):	80459680.176	84730577.435	78189816.460	90519423.068
Total (ha):	8045.968	8473.058	7818.982	9051.942

In terms of total area, measurements reveal a general growth between 1946 and 1966, followed by a fairly rapid period of decay between 1966 and 1977 (Fig. 4.9). The delta then appears to have undergone another period of growth from 1977 - 1994.

Clarification of the magnitude of change during each of these time periods is provided by Table 4.3 which summarizes the change in area between successive time periods for each island complex as well as the rate of increase or decrease. Between 1946 and 1966, the Slave River Delta grew by approximately 428 ha. This figure is quite comparable to the magnitude of development reported by Vanderburgh and Smith (1988). According to these authors, progradation of the delta has slowed to approximately 9.96 m/year since 1180 BP. Applying this figure to the active delta front which is approximately 25 km long results in a growth rate of close to 25 ha/year. As a result, development of the Slave River Delta over the 20 year period between 1946 and 1966 seems to be rather representative of the area's average natural growth.

The same cannot be said for the remaining two periods of study. In fact, during the 11 year period between 1966 and 1977 the subaerial delta was reduced by 652 ha. The difference between these time periods may be exaggerated by the fact that the 1977 values were not adjusted to reflect higher water levels at this time; however, the magnitude of this difference would be quite small because 1977 water levels are only about 5 cm above those of 1994. As a result, the general trend of areal loss between 1966 and 1977 would still be quite apparent.

The rapid erosion of this material may be the result of the

Fig. 4.9

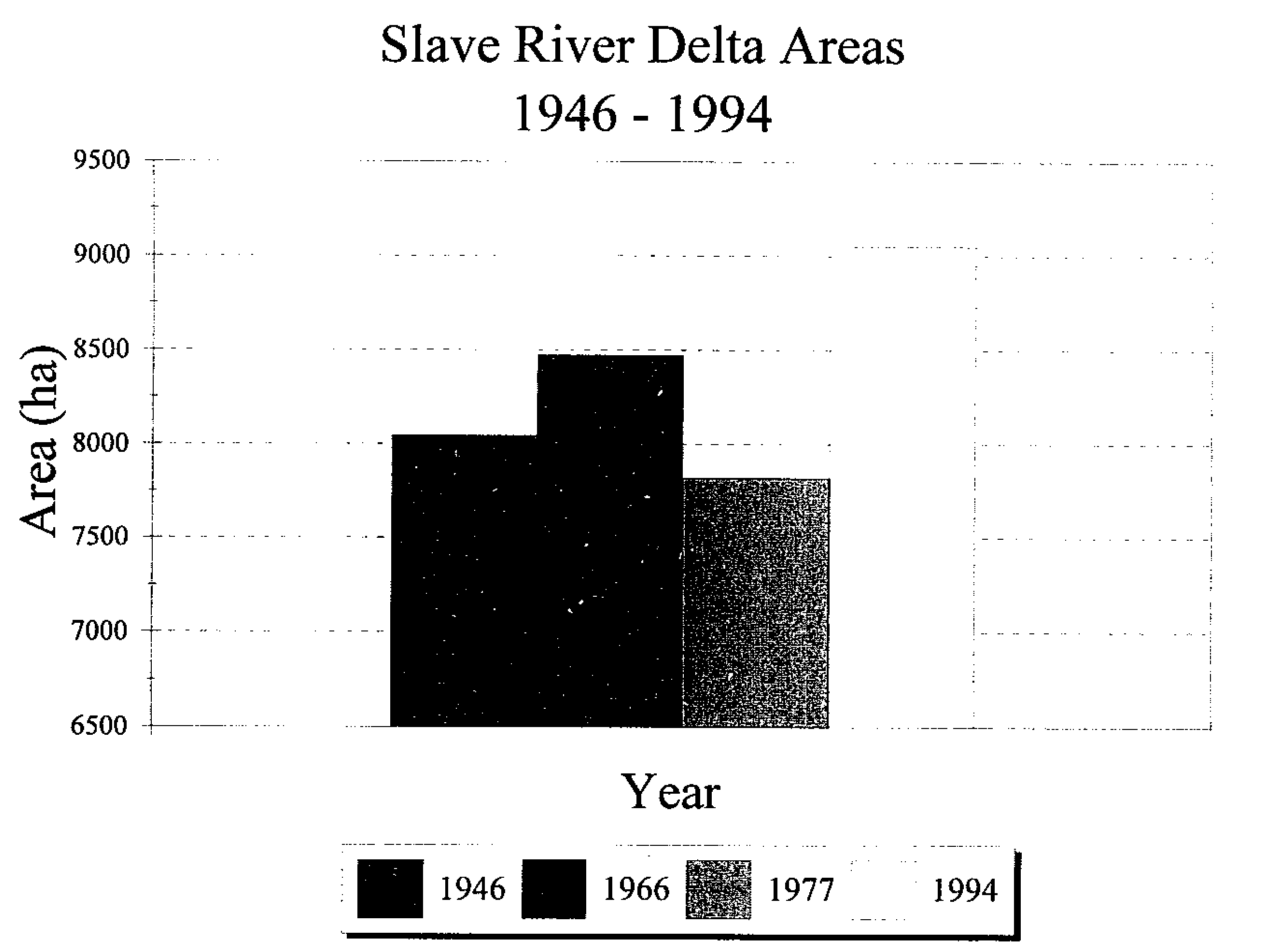

Slave River Delta Areas
1946 - 1994
Area (ha)
9500
9000
8500
8000
7500
7000
6500
Year
1946
1966
1977
1994

Table 4.3

Individual Island Area Changes (adjusted for GSL water levels)

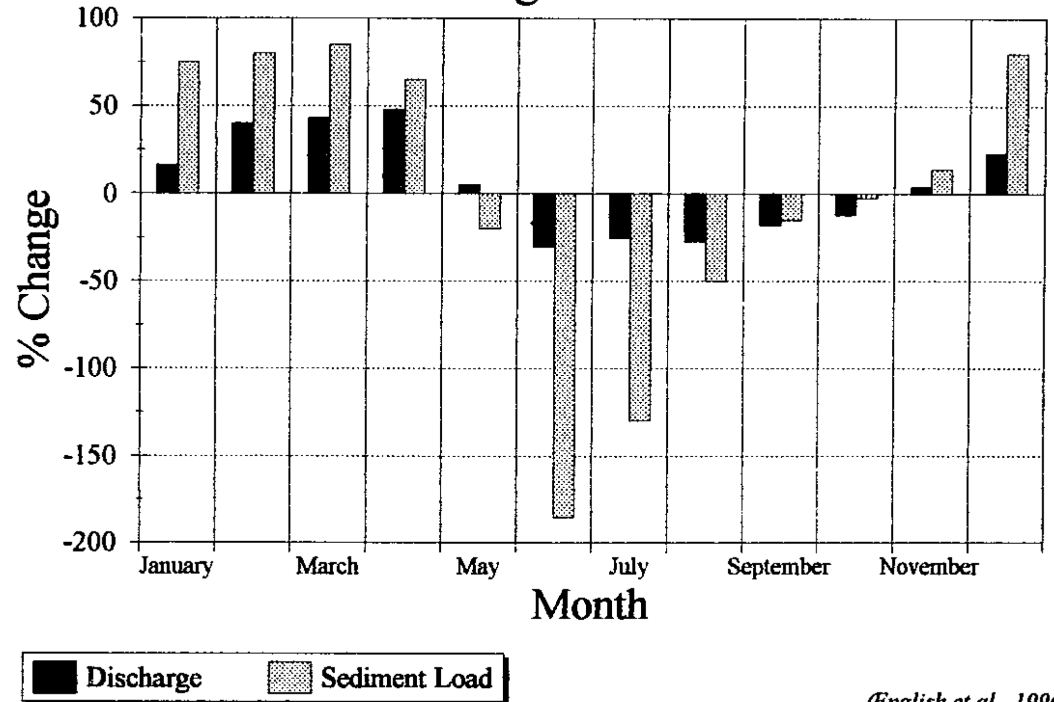
ISLAND I.D. #	PERIOD 1946 - 1966	1966 - 1977	1977 - 1994	1946 - 1994
1	358800.765	477198.164	503933.366	1339932.295
2	-49137.452	68334.725	63532.044	82729.317
3	0.000	0.000	5638.109	5638.109
4	0.000	89088.454	-57534.704	31553.750
5	0.000	4003.156	-3384.883	618.273
6	59611.972	131260.228	84157.713	275029.913
7	13501.673	-13501.673	35703.910	35703.910
8	227801.224	404670.258	428738.700	1061210.183
9	-12841.106	-136589.286	148.930	-149281.463
10	0.000	38327.320	113403.480	151730.800
11	259905.691	-1136888.700	1797121.828	920138.819
12	76855.289	16162.028	35208.900	128226.217
13	65165.469	-100188.111	69347.569	34324.926
14	9100.875	-49413.204	31003.000	-9309.329
15	0.000	0.000	3023.820	3023.820
16	0.000	45762.495	48666.635	94429.130
17	-243254.905	-16613.251	-2764.400	-262632.556
18	39814.969	-5793.286	30821.500	64843.183
19	11903.942	-186535.094	213035.700	38404.548
20	-518085.989	-5228.451	5077.500	-518236.940
21	45250.313	76571.357	112526.630	234348.300
22	-204705.632	21926.737	258528.000	75749.105
23	-268171.880	-29695.278	-34438.600	-332305.758
24	0.000	37401.300	-32595.128	4806.172
25	0.000	37401.300	-34699.316	2701.984
26	0.000	0.000	2821.039	2821.039
27	0.000	0.000	1494.563	1494.563
28	0.000	2440.891	3403.367	5844.258
29	0.000	0.000	1356.656	1356.656
30	-209316.356	-60401.290	176150.100	-93567.547
31	-120702.399	10759.565	38023.700	-71919.134
32	0.000	5852.461	-1220.211	4632.250
33	0.000	0.000	2637.828	2637.828
34	0.000	0.000	29294.960	29294.960
35	0.000	86499.071	89982.329	176481.400
36	0.000	0.000	52840.650	52840.650
37	-17212.309	167710.226	84850.780	235348.696
38	0.000	39226.876	36557.594	75784.470
39	-51511.825	-117299.938	192486.200	23674.437
40	-23752.541	-1327.606	70793.900	45713.752
41	-89998.282	32802.000	-14923.660	-72119.942
42	0.000	0.000	19988.510	19988.510
43	3307.857	-95486.095	8186.953	-83991.285
44	0.000	0.000	152.711	152.711
45	0.000	0.000	395.750	395.750
46	-174326.257	-711800.647	405501.800	-480625.104
47	0.000	30858.225	40596.605	71454.830
48	0.000	23033.534	136676.866	159710.400
49	0.000	44907.437	4279.913	49187.350
50	430788.933	224356.701	565989.100	1221134.734
51	0.000	7848.484	28271.316	36119.800
52	-40198.006	69473.914	29916.200	59192.108
53	-51858.701	-196109.648	55000.000	-192968.349
54	-296341.756	-344080.078	121944.000	-518477.834
55	614404.509	14113.722	43811.477	672329.708
56	-177901.445	164632.185	79611.990	66342.730
57	241982.550	-537590.827	955746.120	660137.843
58	86185.306	-27490.556	136568.220	195262.970
59	173239.228	-1803.989	80379.200	251814.439
60	1198258.611	115601.683	209205.000	1523065.294
61	280318.033	-1567055.227	1602929.000	316191.806
62	669610.110	-377844.546	338694.139	630459.703
63	249548.276	-82769.650	454569.000	621347.627
64	1627882.298	-3262697.703	2549143.340	914327.935
65	76976.209	35218.663	21299.300	133494.172
Total (m^2):	4270897.260	-6540760.975	12329606.608	10059742.892
Total (ha):	427.090	-654.076	1232.961	1005.974
Rate (ha/yr)	21.354	-59.461	72.527	20.958

construction of the W.A.C. Bennett Dam which took place over this same time period. With the reduction of flows on the Slave River caused by filling of the Williston Reservoir (Fig. 4.10), sediment transport to the delta front would have been reduced as well. In addition, the erosional potential of waves and longshore drift caused by prevailing north westerly winds would have still persisted despite the lack of sediment availability. As a result, the balance between sediment input and sediment removal outlined by Galloway (1975) could have shifted in favour of the latter, thrusting the delta into a deconstructional phase of development.

Over the next 17 years, the Slave River Delta quickly rebounded, depositing approximately 1231 ha of sediment between 1977 and 1994. In this case, ignoring the effects of water level differences on the 1977 values produces a slightly exaggerated growth; however, the magnitude of this error has already been mentioned and is considered to be rather insignificant.

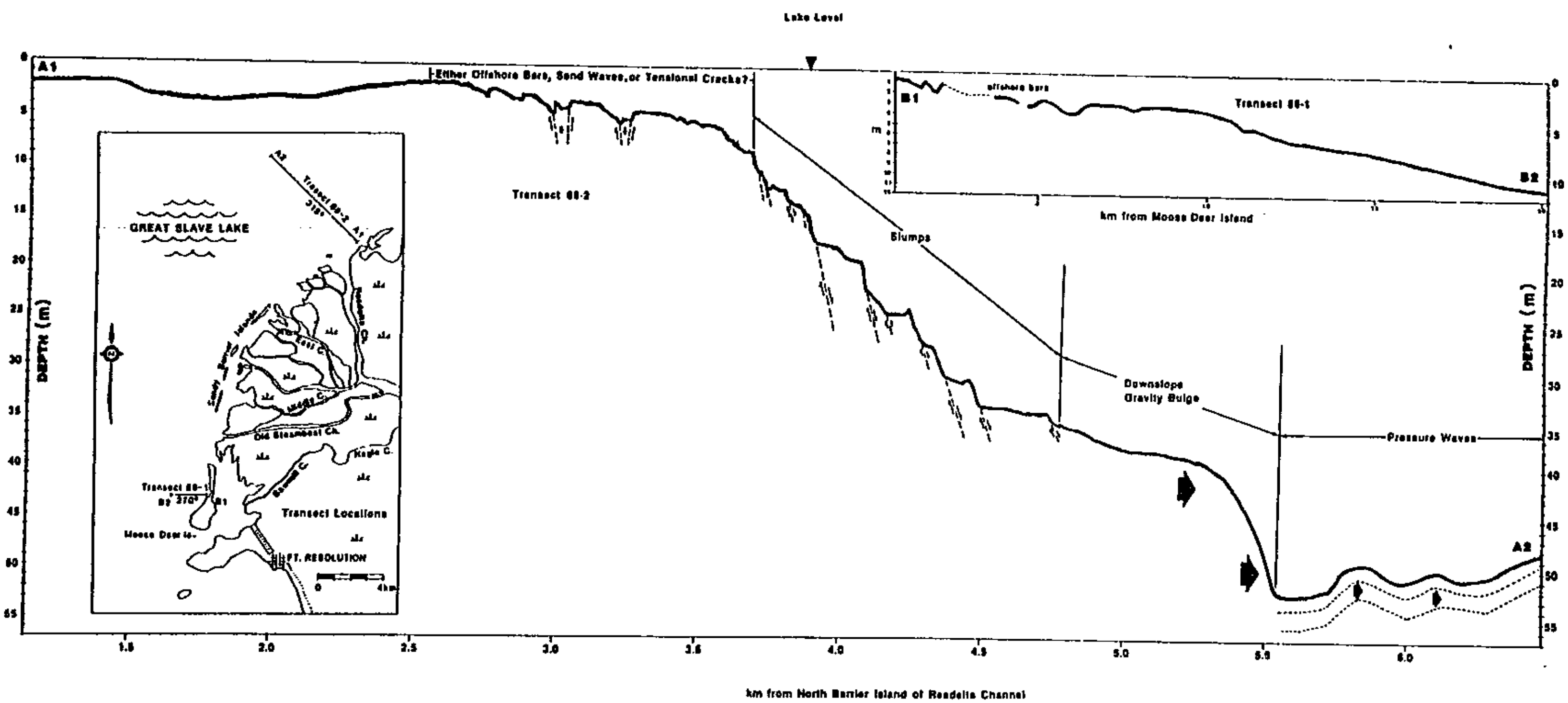
According to these results, the subaerial delta has grown more rapidly in the post-impoundment period despite the reduction in post-regulation discharge and sediment load in the Slave River. The topography of the Slave River Delta offers one possible explanation for this growth, for Vanderburgh and Smith (1988) have illustrated the fact that the subaqueous delta front extends anywhere from 2 - 4 km at depths less than 10 m. In fact, a relatively flat platform extends for almost 3.5 km from the mouth of Resdelta Channel at a depth of less than 5 m (Fig. 4.11). As a result, the deposition of relatively little new material could produce a more notable growth of the subaerial delta than an equal amount of material in deeper waters.

Fig. 4.10 Change in Pre/Post Slave River Discharge and Sediment Load



(English et al., 1996)

Fig. 4.11
Subaqueous Delta-Front Morphology



(Vanderburgh and Smith, 1988)

Water levels in Great Slave Lake may provide another explanation for the rapid growth of the Slave River Delta during the post-impoundment period. According to the records, lake levels have decreased considerably during the spring and fall periods (Fig. 4.12) and, as a result, may reduce the potential for erosional impacts on sediment deposited on the outer portions of the delta. Perhaps the best explanation, however, lies in the fact that most of the growth seems to be occurring along the edge of the outer delta region, especially in the shallow protected estuaries of Nagle Bay and Jackfish Bay in the outer delta region (Fig. 4.13).

4.3.2 THE OUTER DELTA

In general, the growth of a delta occurs due to the reduction of river energy as it enters a larger standing body of water. As a result, most of the active deposition within a deltaic environment occurs at the delta front in the outer portion of the delta. In this region, the loss of energy caused by lower flows reduce the carrying capacity of the channel which, in turn, leads to the deposition of sediment. As this process continues, progradation of the delta front occurs as sedimentary material is deposited at channel offings in the form of crescent shaped features or cleavage bars (Russell, 1967). Cleavage bar development has also been reported as a significant depositional process in the Laiture and Kvikkjokk deltas by Axelsson (1967) and Dahlskog *et al.* (1972) respectively. According to English (1984), cleavage bar development is the primary process of deposition within the outer delta. Because of the significance of deposition within the outer delta, it is important to examine changes within

Fig. 4.12
Seasonal Water Levels
Great Slave Lake, NWT

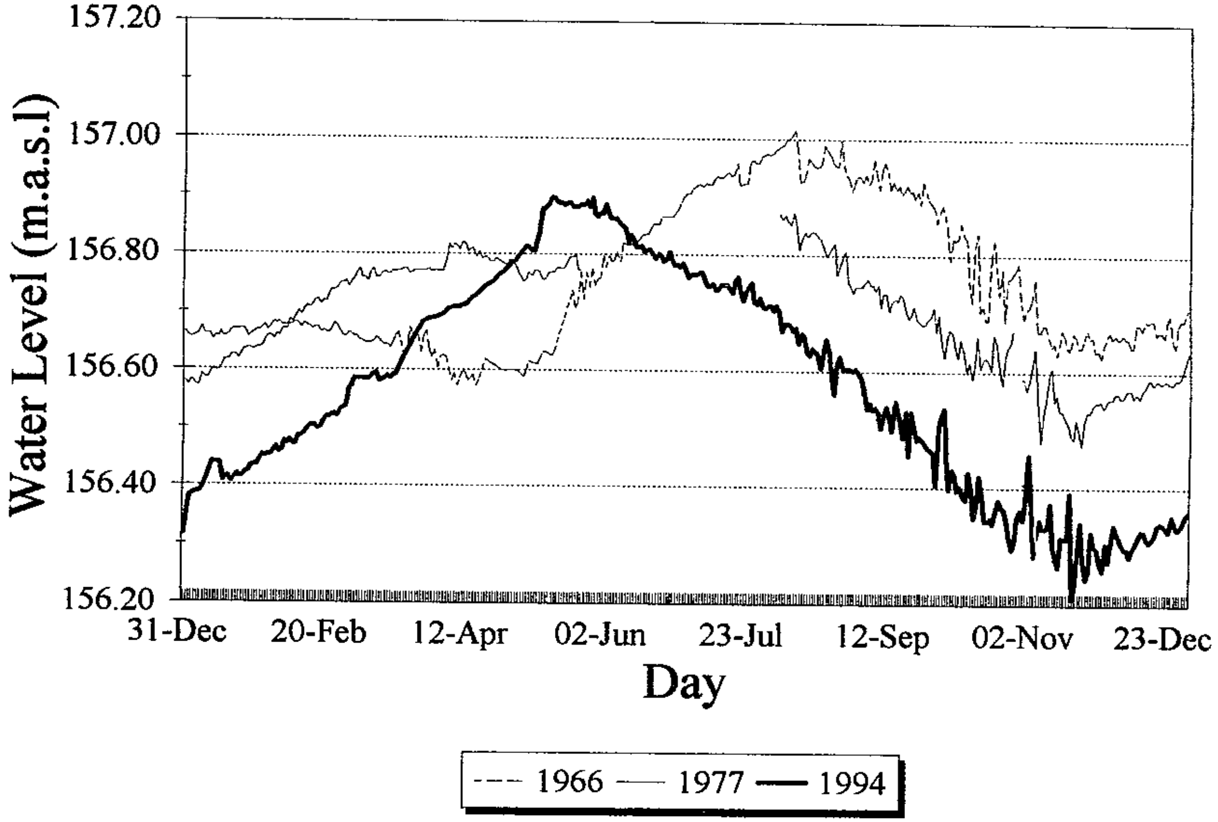
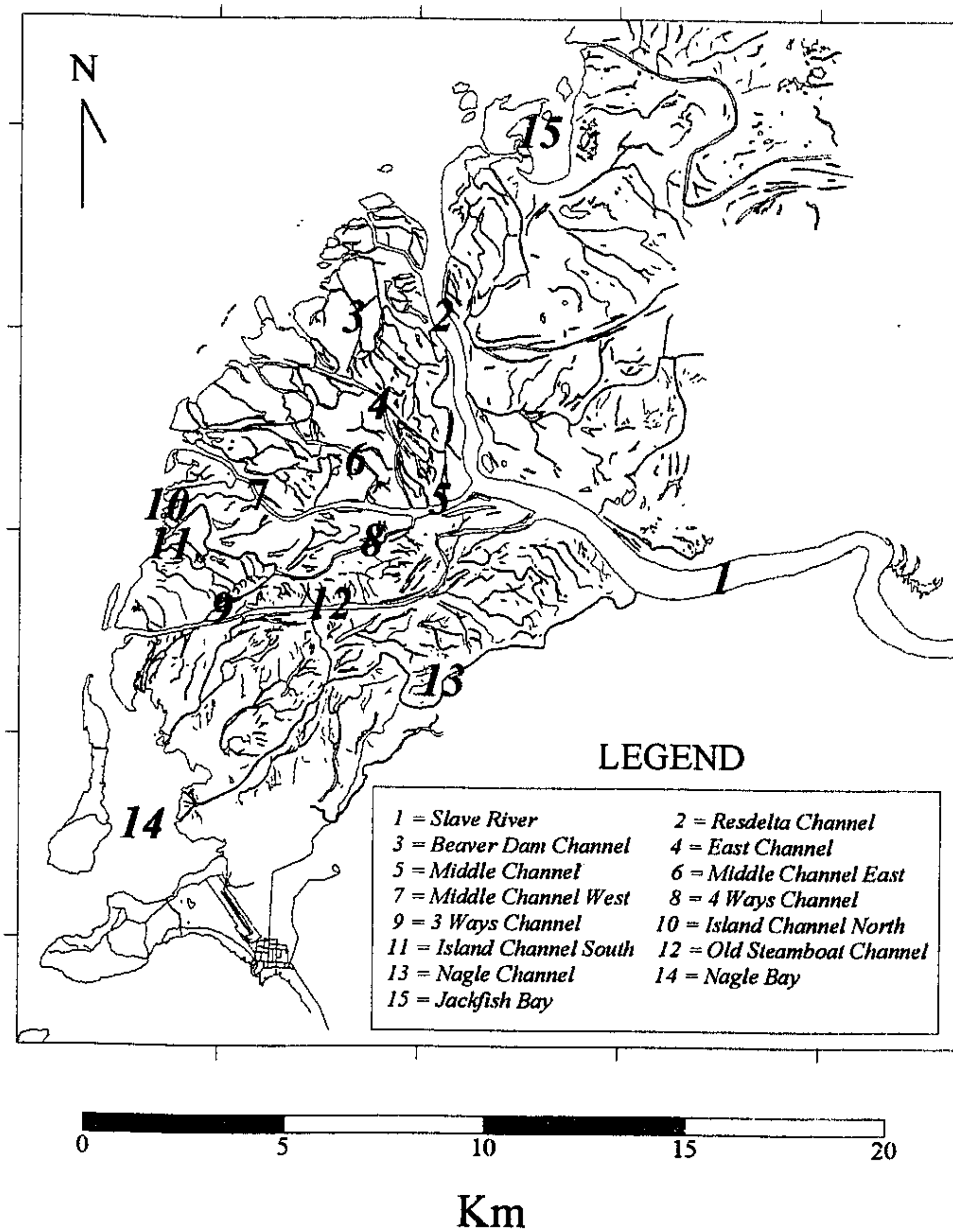


Fig. 4.13
Major Features of the Slave River Delta



this region using data from the chosen time periods.

In order to calculate the total area of the subaerial delta within the outer region of the Slave River Delta, the area was delineated as shown in Figure 4.14 based loosely upon English's (1984) classification. As a result, only those islands which fell on the Great Slave Lake side of this division were considered.

The total area of the subaerial delta for each of the four years of study, given in Fig. 4.15 and Table 4.4, illustrates how these areas changed over the 48 year period. Similar to the total area of the entire delta, the outer region underwent a period of growth between 1946 and 1966, followed by a short deconstructional phase between 1966 and 1977 which, in turn, was followed by another period of growth from 1977 to 1994. What is interesting to note, however, is the proportion of the delta's total change occurring in the outer delta (Table 4.4). Between 1946 and 1966, the 103.62 ha growth in the outer region represented close to 25% of the 427.09 ha increase which occurred over the entire delta. Between 1966 and 1977 the delta lost 651.692 ha; however, only 7.4% of this came from islands in the outer delta. Finally, in the 17 year period from 1977 to 1994, approximately 50% of the 1233 ha added to the delta came from growth in the outer region.

The contribution of the outer delta during periods of overall growth is not surprising since progradation of the active delta generally occurs at channel offings in the outer delta; however, it is interesting to see that this region suffered such small losses during the deconstructional phase between 1966 and 1977. The reason for this lies in the fact that continued sediment supply to the central portions of the outer delta has

Fig. 4.14

Outer Delta Region
Slave River Delta, NWT

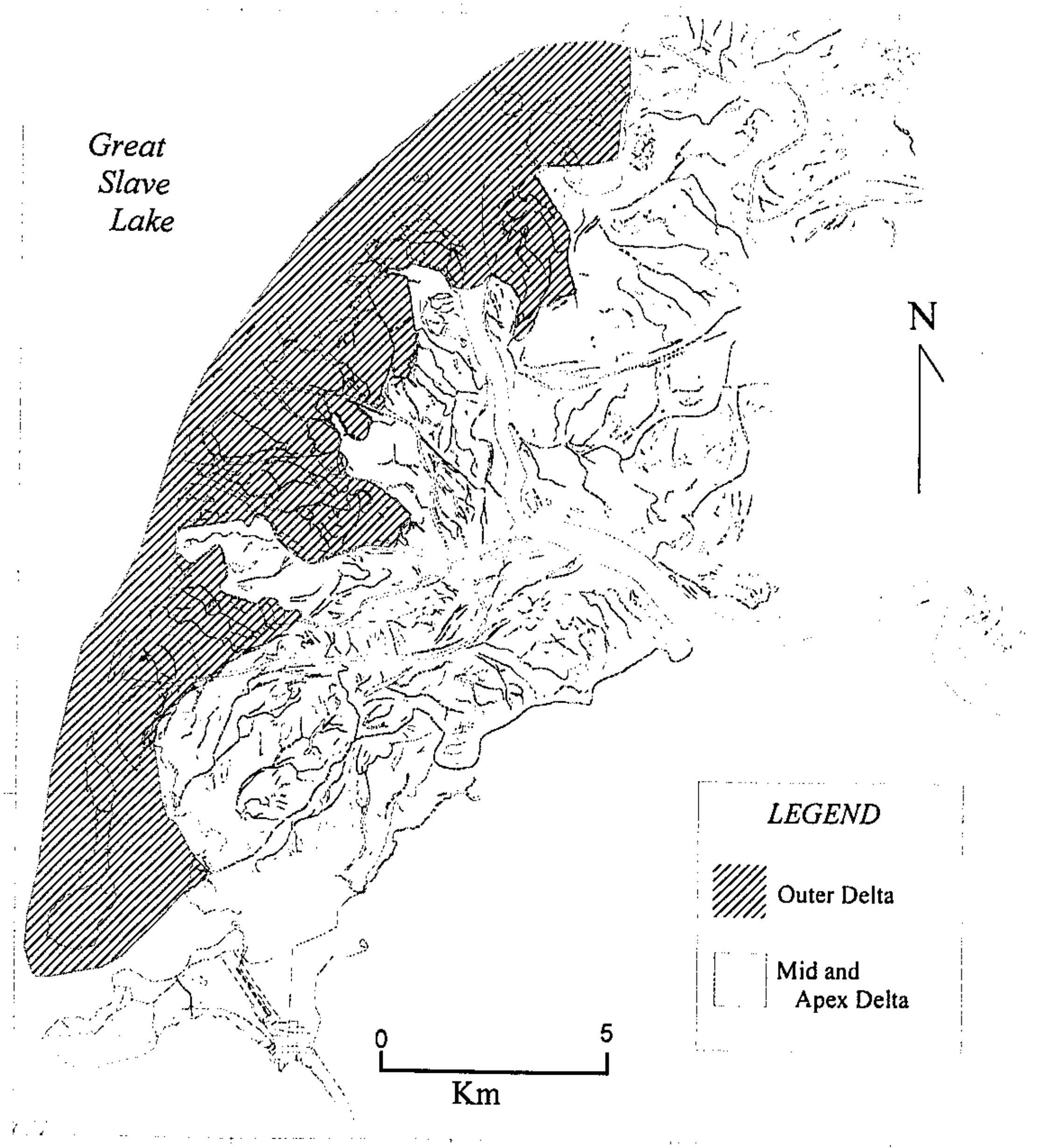


Fig. 4.15

Outer Delta Island Areas

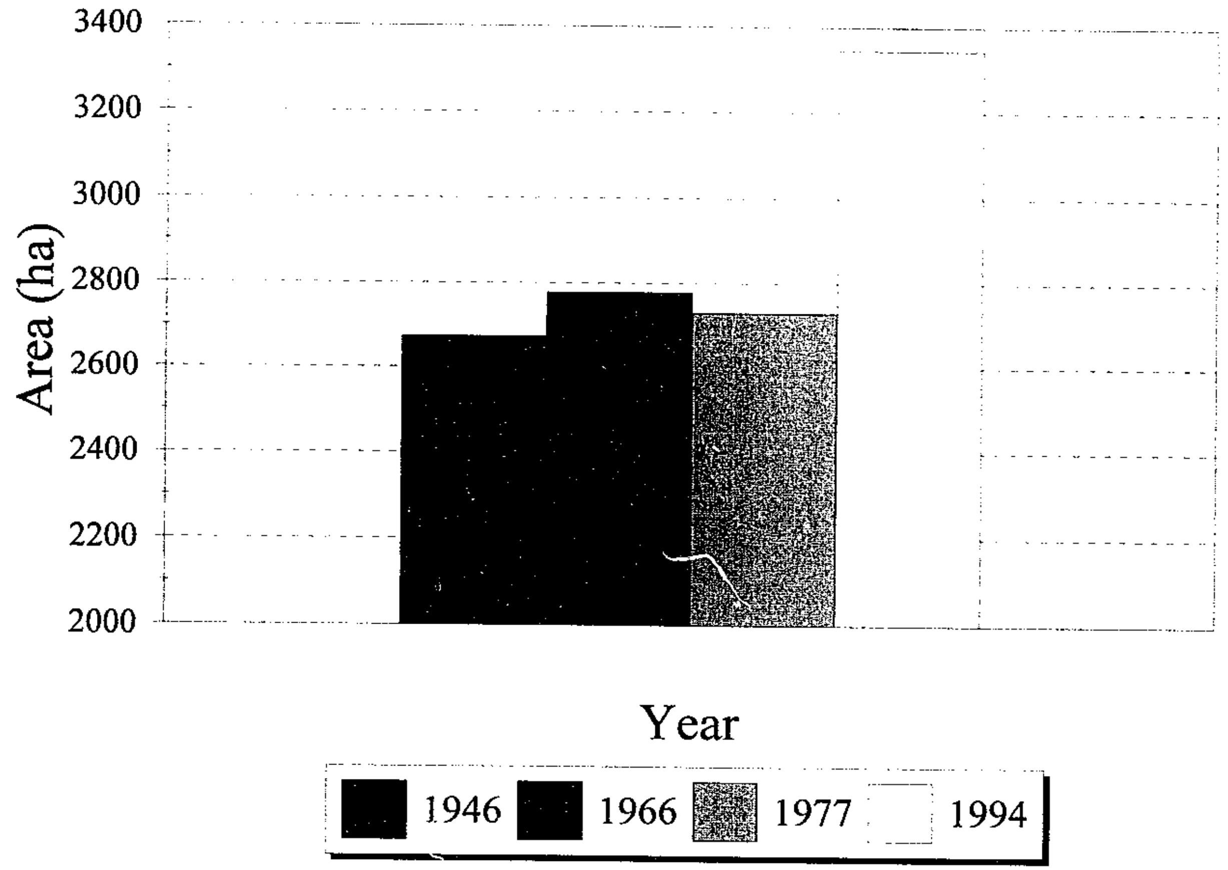


Table 4.4

Outer Island Area Change
(adjusted for GSL water levels)

	Period			
	1946 - 1966	1966 - 1977	1977 - 1994	1946 - 1994
Outer Change (m^2)	1036277.178	-479669.477	6162139.720	6718747.421
Total Change (m^2)	4270897.260	-6540760.975	12329606.608	10059742.892
Outer %	24.264	7.334	49.978	66.788

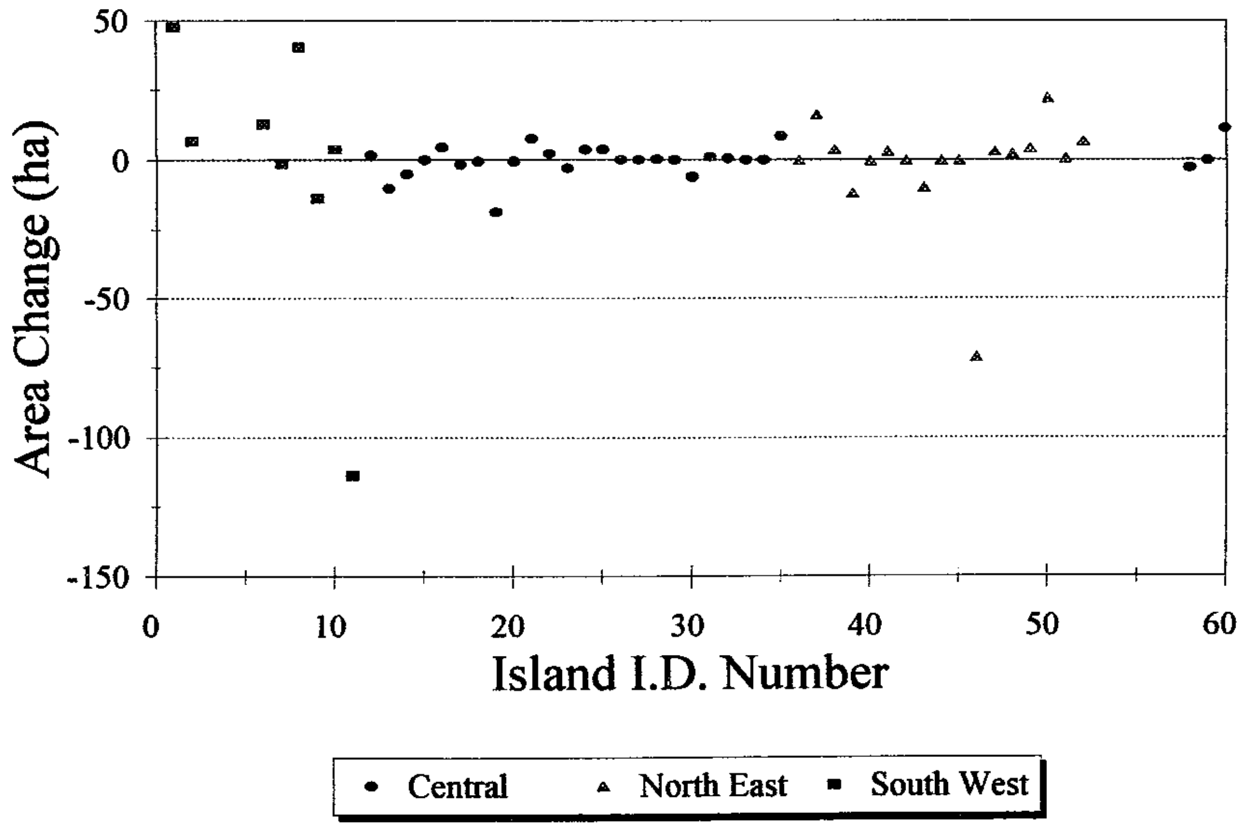
remained in relative equilibrium with the loss of material due to wave erosion and longshore drift; as a result, depositional features in this location changed very little (Fig. 4.16). In addition, several islands experienced growth during this time due to the deposition of sedimentary material in quiet, sheltered estuaries towards both the south western and north eastern limits of the outer delta region around islands 1-10 and 57-64 (Table 4.3). In these areas sediment laden flows not only enter relatively calm water, but are protected from the erosional impact of wave action by previously built deposits. Conversely, the islands in the central portions of the outer delta seem to have exhibited little growth or, in some cases, have experienced erosion. A similar trend can be observed in the development of the whole delta over the entire 48 year period between 1946 and 1994 (Fig. 4.17). As a result, the South West, Central, and North East regions seem to provide a natural division for further examination of development within the Slave River Delta.

4.3.3 REGIONAL EXAMINATION

In order to divide the Slave River Delta into South Western, Central, and North Eastern regions, boundaries were drawn in accordance with the natural distribution of landform development over the 48 year period of study (Fig. 4.18). Having grouped the appropriate island complexes, the total landmass was calculated for each region as well as the magnitude of change in each region over the 1946-1966, 1966-1977, and 1977-1994 time periods (Fig. 4.19 and 4.20).

Fig. 4.16

Regional Change in the Outer Delta



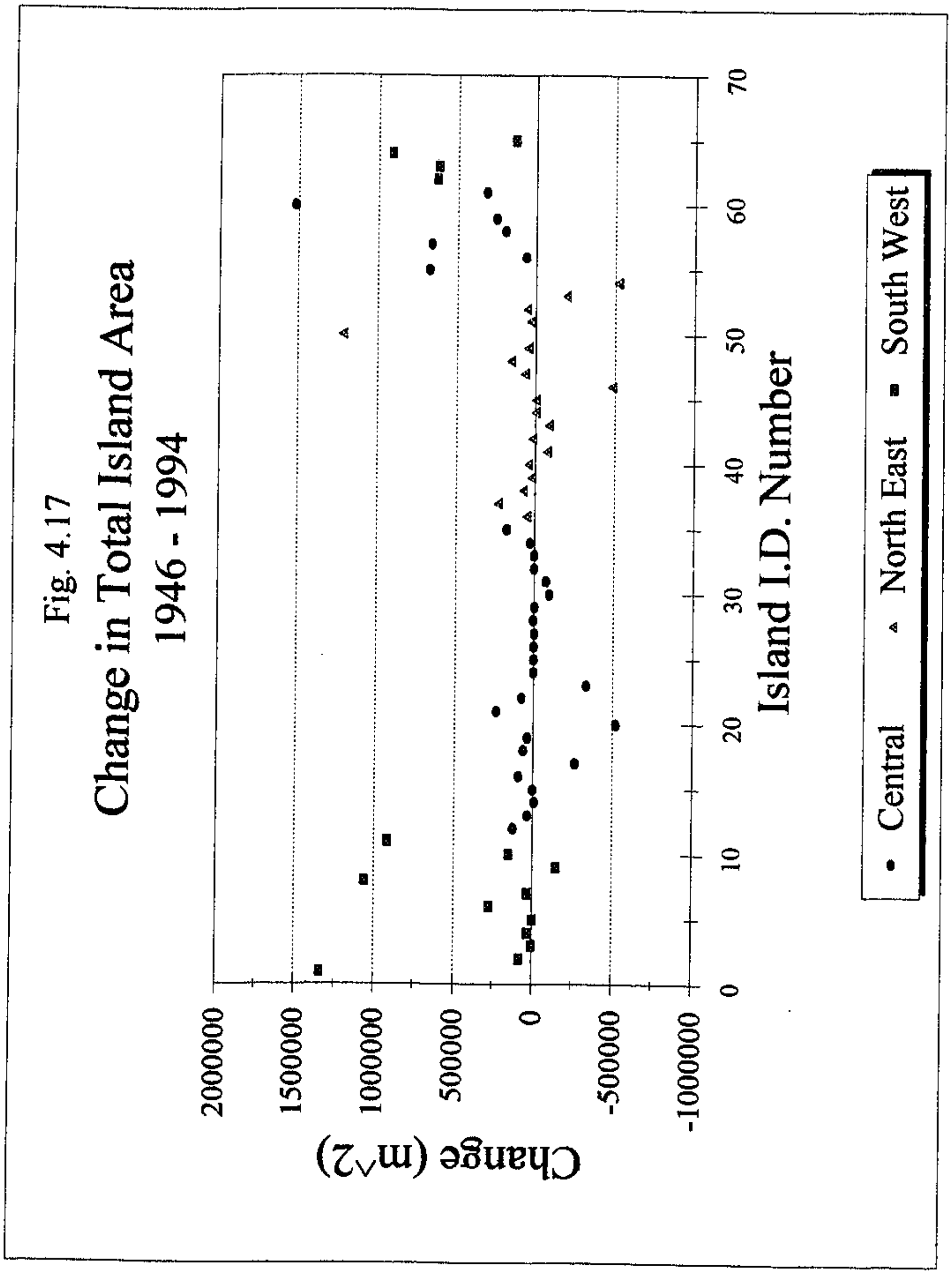


Fig. 4.17
Change in Total Island Area
1946 - 1994
Change (m^2)
2000000
1500000
1000000
500000
0
-500000
-1000000
0
10
20
30
40
50
60
70
Island I.D. Number
Central
North East
South West

Fig. 4.18
Regional Boundaries

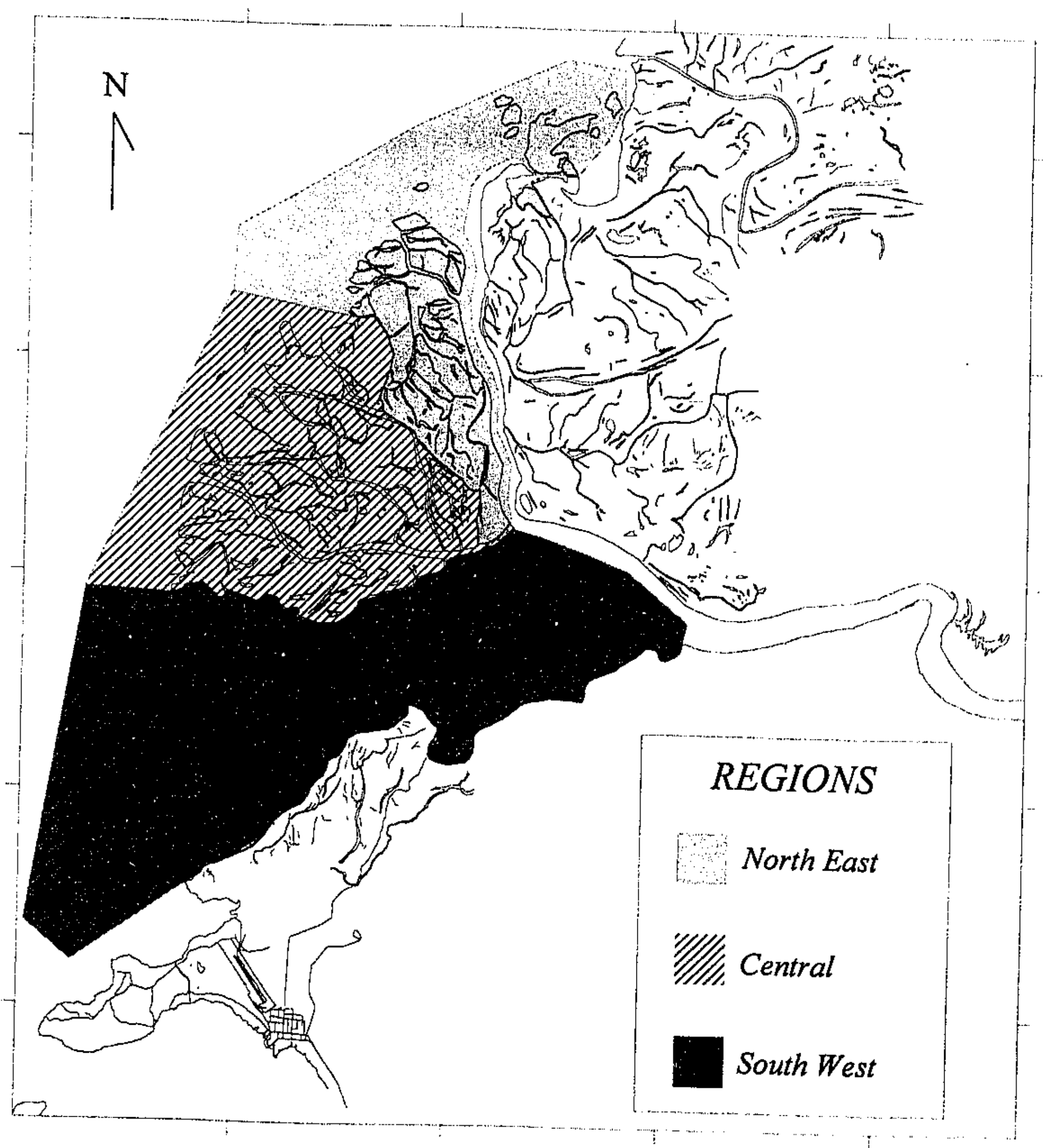
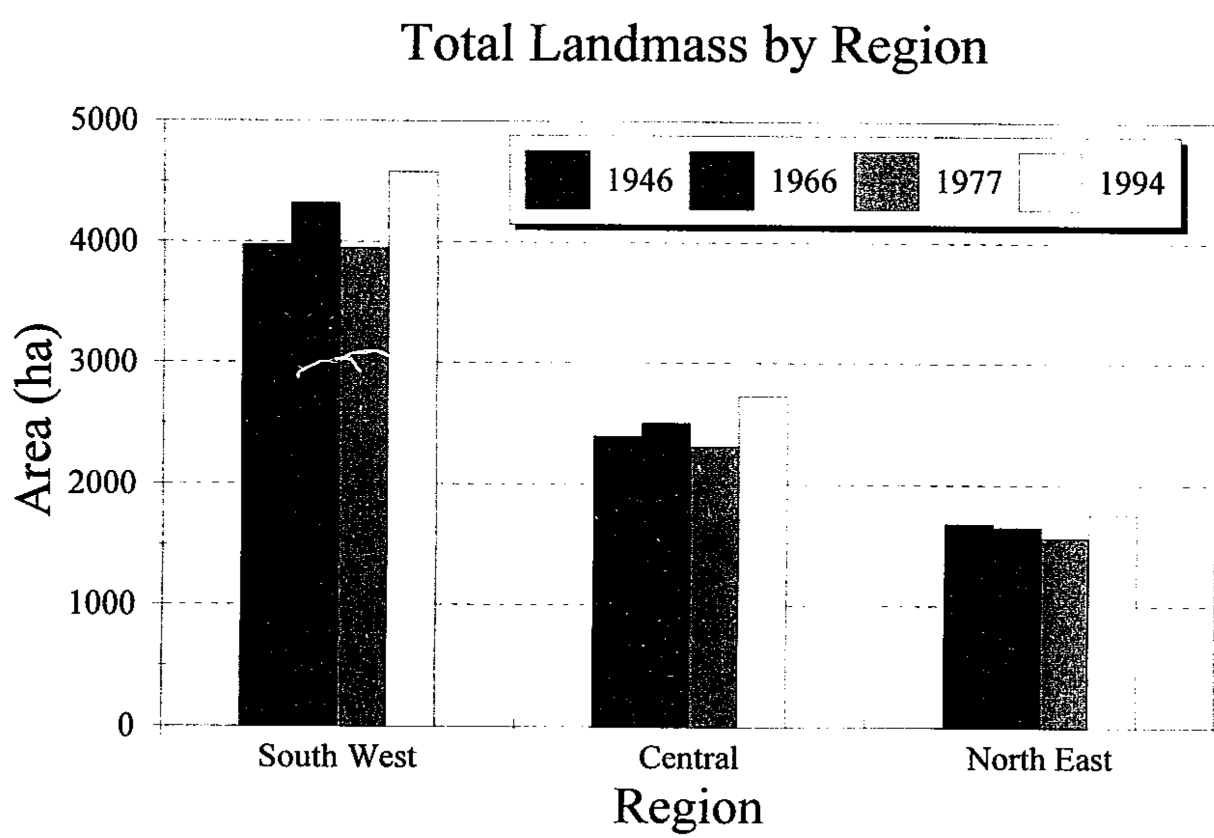


Fig. 4.19


Total Landmass by Region
1946
1966
1977
1994
5000
4000
3000
2000
1000
0
Area (ha)
South West
Central
North East
Region

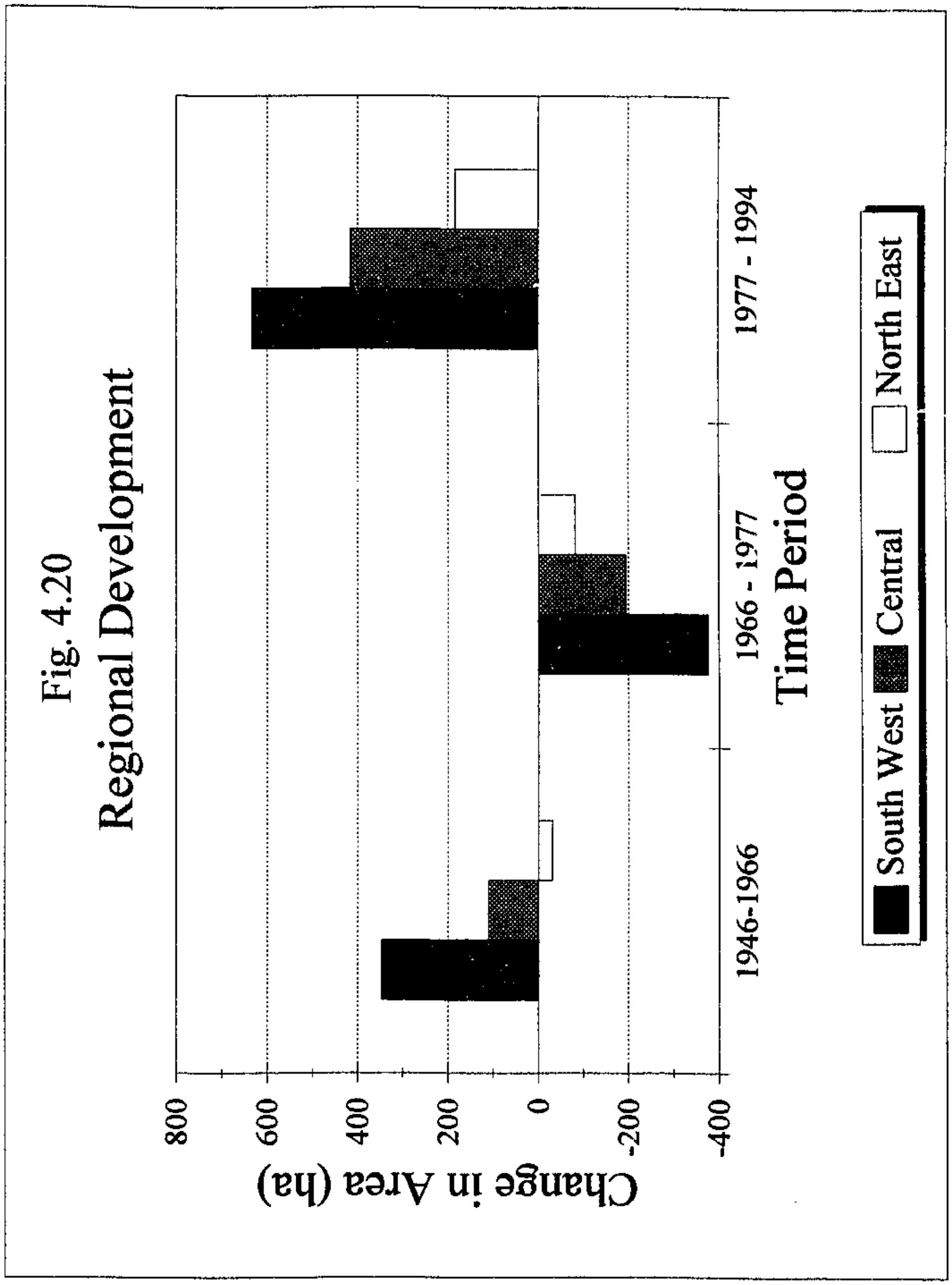


Fig. 4.20
Regional Development

4.3.3.1 North East Region

Despite the fact that Resdelta Channel has always been one of the most important distributaries of the Slave River Delta, the North East region has changed the least over the 48 year period of study. Between 1946 and 1966, islands in this region grew by less than 25 ha; in fact, given the accuracy of water level adjustments, it could be argued that the North East region remained virtually unchanged over this 20 year time period. This is probably due to the fact that both Middle Channel and Old Steamboat were still relatively large channels at this time; thus, they drew off a substantial proportion of the Slave River flow. In addition, the mouth of Resdelta Channel is quite open to the effects of wave action and longshore drift created by prevailing north westerly winds; as a result, sediment laden flows are directed eastward into the still waters of Jackfish Bay. Finally, because both Middle Channel and Old Steamboat Channel were notably larger than Resdelta Channel, their higher discharges would also carry more of the large grained material required for subaerial development of the delta front. As a result, most of the finer grained material transported within Resdelta Channel would be carried out into Great Slave Lake or the adjacent Jackfish Bay area where it would have been incorporated by the development of subaqueous deposits.

From 1966 to 1977, the North Eastern region underwent a deconstructional phase much like that experienced by the rest of the Slave River Delta. What is interesting to note, however, is that losses in this region were notably less than those in the other two regions. Perhaps the most important reason for this is the fact that Resdelta Channel had become the largest distributary in the delta by 1977. As a result, the reduction of flows caused by upstream impoundment may have had less impact on Resdelta Channel because it would still be carrying the highest proportion of Slave River flow. This, in turn, would mean that although sediment supply to the mouth of Resdelta Channel may have been reduced during the completion of the Bennett Dam, it would not have been reduced as much as it was in the remaining channels.

An interesting feature of the North East region is the relatively small subaerial growth in the post-impoundment period. Despite the fact that Resdelta now carries as much as 80 - 90% of the total Slave River discharge, growth in the North East region accounts for only 32% of the total increase in the outer delta. One of the best explanations for this may lie in the effects of river regulation. According to English (1979, 1984), upstream impoundment can often shift the particle size distribution of suspended sediment in downstream channels toward the finer end of the spectrum. Calculations by English *et al.* (1996) indicate that reduced flows during the ice free period have lead to a 33% reduction in the sediment load within the Slave River and may have also reduced the capacity of the river to carry coarser sediment. In fact, English *et al.* (1996) found that approximately 90% of the material transported by the Slave River at Fitzgerald is finer than 63μm. Because of this, less sediment arrives at the mouth of the Resdelta Channel and that which does remains in suspension well out into Great Slave Lake due to the fact that it is much too fine to settle out earlier.

4.3.3.2 Central Region

Similar to the North Eastern region, islands in the central portions of the delta have undergone relatively little change over the 48 year period. Between 1946 and 1966, the area grew by approximately 100 ha, undoubtedly due to the strong supply of sediment delivered by the large distributaries of Middle Channel. Interestingly, most of the deposition during this period occurred within the central portions of the delta, narrowing the major distributaries like Middle Channel, East Channel, Middle Channel East, and Middle Channel West in addition to abandoning several smaller channels.

During the 11 year period between 1966 and 1977, reduced peak flows during the ice free period caused by upstream impoundment meant that less water was available for sediment transport through the Central region. Because the outer portions of the delta still faced constant erosion by waves and longshore drift during this period of reduced sediment supply, approximately 200 ha of material was eroded from the Central region during the construction of the W.A.C. Bennett Dam. In addition, the central portion of the delta is also characterised by relatively high levees which tend to contain channel flow and experience growth only during significant flood events. As a result, there is already a reduced potential for subaerial growth in this region due to channel morphology.

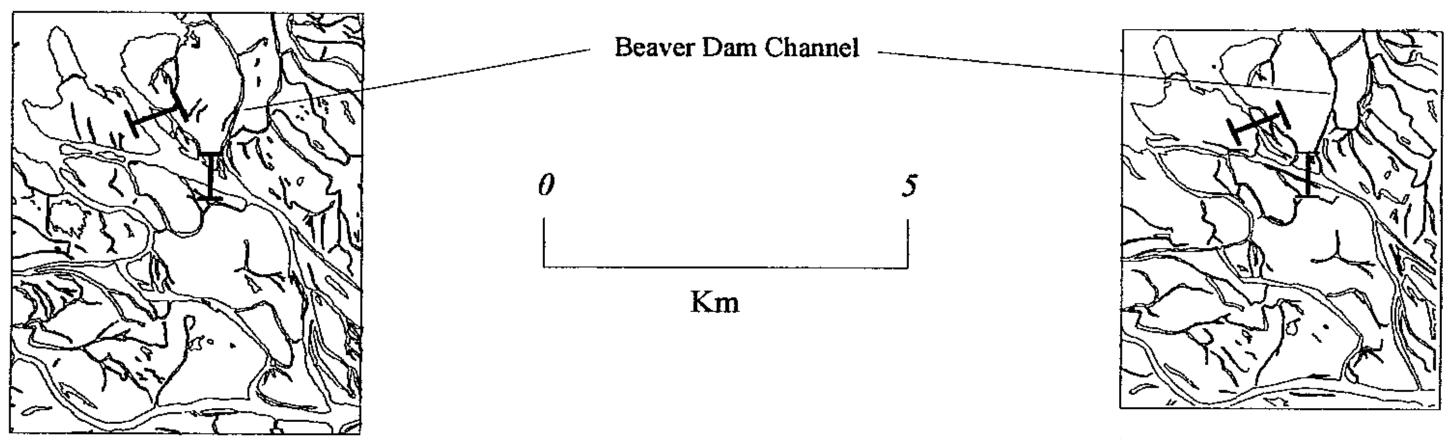
From 1977 to 1994, the Central region rebounded from the losses incurred by regulation, increasing in size by approximately 400 ha. Despite the obvious growth of several cleavage bar islands, however, most of the outer delta appears to have remained relatively unchanged during this 17 year period. As a result, it would seem that the majority of landform change in this region has occurred due to channel abandonment and the narrowing of active channels and not to the expansion of cleavage bar islands. A definite case in point would be East Channel, for it has narrowed by more than 60% near the entrance to Beaver Dam Channel and more than 87% to the north of the cleavage bar island formation at its mouth (Fig. 4.21). Similar trends can be observed along both Middle Channel East and Four Ways Channel and are presumably the result of reduced flows in the post-impoundment period and the partial abandonment of Middle Channel due to the diversion of flows through alternate channels. Because of the considerable drop in discharge through the central portions of the delta, the carrying capacity is lowered; consequently, the potential for in-channel deposition increases considerably.

4.3.3.3 South West Region

Of all three regions, it would appear that the South West region has undergone the most dramatic shifts in landform area over the 48 year period of study. Between 1946 and 1966, the region grew by more than 300 ha, most of which can be attributed to the formation of the bar feature to the north of Moose Deer Island and the evolution of a relatively large island off the mouth of Old Steamboat Channel (Fig. 4.22). As Vanderburgh and Smith (1988) have shown, this area is characterised by a fairly shallow platform which extends up to 2 km into Great Slave Lake. As a result, discharge from Nagle Channel, Whiteman's Channel and Old Steamboat Channel enters an almost idyllic depositional environment which is now, for the most part, less than 5 m in depth. The continued growth of the bar formation north of Moose Deer Island has

Fig. 4.21

East Channel Region

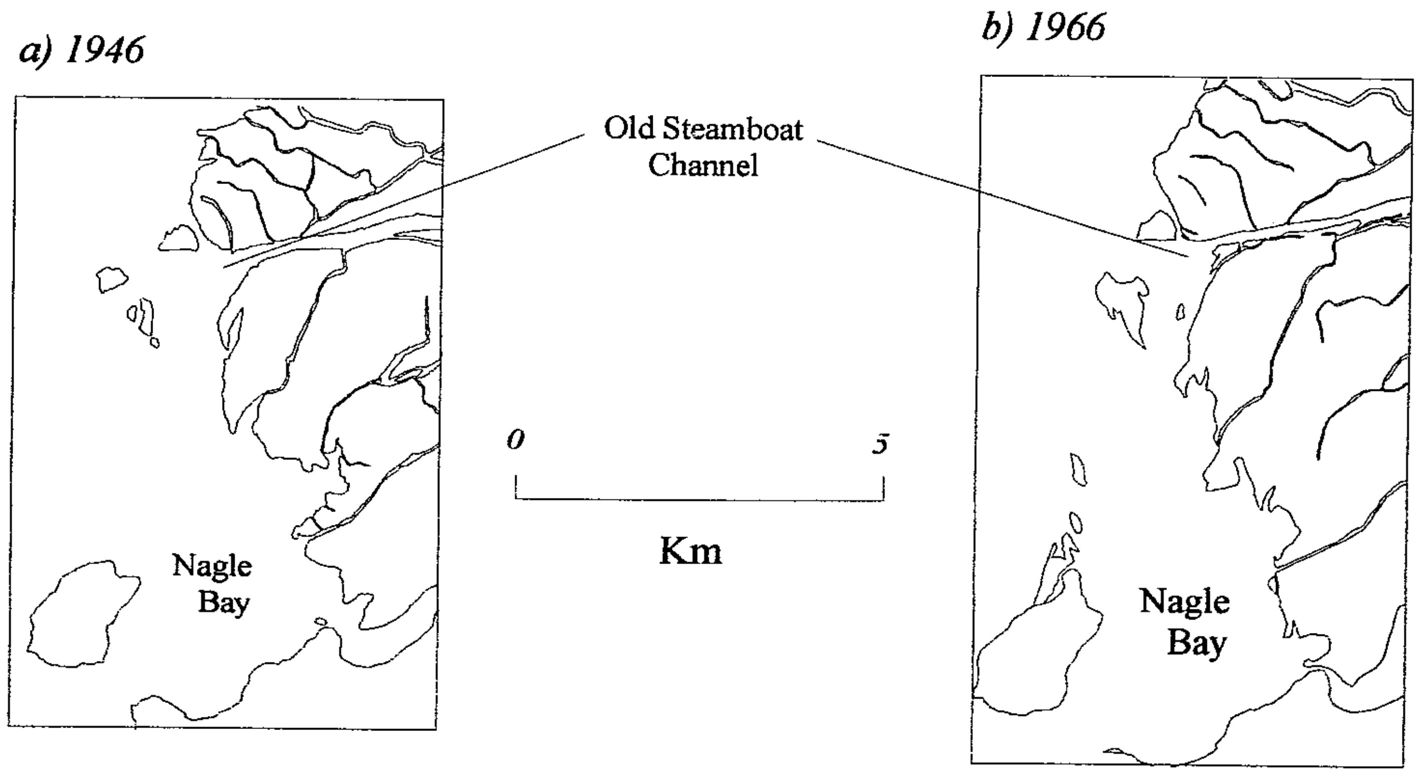


a) 1977

b) 1994

Fig. 4.22

Nagle Bay Region



continued to add protection to Nagle Bay and this, combined with the calm nature and shallow depth of the area, is probably the main factor in the growth of this region over the 1946-1966 and 1977-1994 periods.

The most striking point about the figures from this region is the dramatic loss of almost 400 ha between 1966 and 1977. Like the other regions, this area would have been impacted by the reduction of Slave River flows caused by the construction of the W.A.C. Bennett Dam in 1968. In addition, the development of a bar formation across the entrance of Old Steamboat Channel has further reduced the amount of water and sediment reaching the outer delta in this area. Despite these factors, the magnitude of change over this 11 year period seems suspiciously large, especially considering the fact that newly formed islands are clearly visible on the 1977 map. Because of this, it would appear that there is some error in measurement during this time period.

The first source of error may be attributable to the adjustment of areal totals based on differences in water level. It could be argued that some of the shallowest depths in the delta are found in the South West region, especially around Nagle Bay. Because water levels were higher in 1977 than in 1994, additional area would be added to the 1977 totals if the differences were taken into account. It would appear, however, that the areal change which would result from a 5 cm change in water levels would not have large impact on the differences between 1966 and 1977.

A second source of error, and one that seems to offer a more acceptable explanation for the magnitude of difference between the 1966 and 1977 totals, is the presence of several lakes and inactive channels on the 1977 map which do not appear on the 1966 map. By adding these features to the 1977 map, their area would be subtracted from the polygon which surrounds them. In other words, the area of island #64 in 1977 (Fig. 4.3) would not include the area calculated for each abandoned channel or lake. On the other hand, because these features are not present on the 1966 map, the area of island #64 would **include** the area lost on the 1977 map. In fact, close examination of the Individual Island Area Changes between 1966 and 1977 (Table 4.3) reveals that island #64 is responsible for 326.27 ha of the total losses in this region. As a result, it would appear safe to assume that the magnitude of area loss between 1966 and 1977 has been artificially increased by the inclusion of lakes and rivers in the calculation of areas for 1966 which have been excluded from the 1977 calculations.

Fortunately, the impact of this error is basically limited to the South West region since it is the only one which includes a landform as large as island #64 which is covered by closed lakes and abandoned channels. Despite the implications such an error has for the assessment of change within the South West region between 1966 and 1977, there is still a strong indication that this region, like the other two, underwent a notable deconstructional period during this 11 year period.

4.4 CONCLUSIONS

After examining digital images of the Slave River Delta created from 1946, 1966, 1977 and 1994 aerial photography, several areas of substantial subaerial growth have been identified. Spatial analysis indicates that the outer delta made up more than 25% of the overall growth of the delta between 1946 and 1966 and over 50% of the growth between 1977 and 1994. In addition, the outer delta lost only 48 ha during the deconstructional period between 1966 to 1977 despite the fact that more than 650 ha were eroded from the entire delta.

A regional study of deposition within the Slave River Delta seems to indicate that most of this growth is occurring in the quiet sheltered environments of Nagle Bay and Jackfish Bay. Deposition in these areas is the result of discharge into relatively shallow water where previous deposits shelter the flow from the erosive effects of waves and longshore drift. In addition, Jackfish Bay is fed by waters from the mouth of Resdelta Channel which has increased in width substantially over the post-impoundment period. As a result, it not only carries a larger proportion of the total flow from the Slave River, but a larger proportion of the sediment load as well. Ironically however, growth rates at the mouth of Resdelta Channel in the North Eastern region of the delta are relatively low due to the fact that the Slave River now carries a smaller grain size fraction since regulation. As a result, most of this material is carried out into the deeper portions of Great Slave Lake by the increased discharge of Resdelta Channel.

Conversely, deposition in the central portions of the delta appears to be the result of a decrease in discharge caused by reduced flows in the Slave River and the partial abandonment of Middle Channel. This reduction has, in turn, effectively reduced the ability of channels within this region to transport sediment. As a result, in-channel deposition appears to be leading to the narrowing and abandonment of active channels.

Based on the results of this study, it would appear that, while individual island complexes may be experiencing erosion, subaerial growth within the Slave River Delta is continuing at a rate equal to, or greater than that of the pre-impoundment period. During construction of the W.A.C. Bennett Dam, reduced flows on the Slave River contributed to the loss of approximately 652 ha within the delta between 1966 and 1977; however, depositional rates have increased considerably in the post-impoundment period. In fact, the addition of approximately 1231 ha between 1977 and 1994 is almost 3 times that of the 428 ha added between 1946 and 1966. Consequently, it seems that regulation of the Peace River has had only a minimal effect on overall change in the subaerial delta during the 48 year period from 1946 to 1994.

• CHAPTER 5.0 •

CONCLUSIONS

5.1 SUMMARY

From the outset, the purpose of this project was to identify areas of hydrological and morphometric change within the Slave River Delta, examine the variables which influence such changes, and attempt to assess how these variables have been influenced by changes in river run-off regime due to upstream impoundment over a 48 year period between 1946 and 1994. Through the use of data gathered from field research, historical sources, and aerial photography, a very strong relationship between channel width and discharge was identified. Subsequent application of this relationship has illustrated that the flow regime of the Slave River Delta has been altered by the rapid growth of Resdelta Channel and resultant decline of the remaining channels. These changes have lead to a substantial increase in the proportion of flow directed through Resdelta Channel and appear to be the direct consequence of a general increase in the overall length of Middle Channel, Old Steamboat Channel, and Nagle Channel. Increased lengths in these distributaries has lead to a reduction in channel gradient which has, in turn, resulted in decreased flow and may be responsible for the eventual abandonment of these channels.

As a result of changes in the distribution of flow throughout the delta, subaerial growth has become more predominate in the shallower waters of Jackfish Bay, an area fed by flows from the mouth of Resdelta Channel and protected by several off-shore bar formations. What is interesting to note, however, is the fact that deposition in this region has not increased proportionally with the increased discharge in Resdelta Channel. This would appear to be the result of changes in the particle size distribution of sediment carried within the main body of the Slave itself which has shifted toward the fines in the post-impoundment period.

While it appears that these changes may be part of the natural progression of the deltaic environment, distinct differences in the pre- and post-impoundment periods seem to suggest that regulation may also play a role. According to the available data, continued growth in the pre-impoundment period was followed by a rapid deconstructional phase between 1966 and 1977 when reduced flows due to the completion of the W.A.C. Bennett dam appear to have contributed to the loss of approximately 652 ha of the subaerial delta during the dam's construction. Since that time however, subaerial growth within the Slave River Delta has increased substantially. In fact, it appears that the subaerial portion of the delta is increasing at a rate close to three times that of the pre-impoundment period.

Close examination of the spatial distribution of subaerial growth within the Slave River Delta indicates that most of this growth has been occurring along the outer portions of the delta, especially in the quiet, sheltered estuaries of Nagle Bay and Jackfish Bay. In these locations, past deposition has built up extensive deposits which extend as far as 4 km into Great Slave Lake at depths of little more than 3 - 5 m. In addition, these areas tend to be protected from the erosive actions of waves and longshore drift by the development of off-shore bars.

Recent evidence also suggests that a considerable portion of this growth may be due to the fact that fall sediment loads in the Slave River have increased by approximately 25% in the post-impoundment period. Because fall concentrations of suspended sediment are now higher under low flow conditions during the fall, deposition rates should be relatively high due to the abundance of sediment in a low energy environment.

Analysis indicates that the relationship between discharge and [SS] is not only dependant upon seasonal influences, but the distribution of flow throughout the delta as well. Having classified the distributaries according to how many bifurcations they are away from the main body of the Slave River, it is apparent that plots of [SS] versus discharge for channels up to two bifurcations are generally characterised by the classic linear relationship outlined by Leopold and Maddock (1953). In channels beyond this, discharge and [SS] tend to be inversely related, signifying a strongly sediment limited system characterised by deposition.

5.2 SUGGESTIONS FOR FUTURE RESEARCH

Constraints on time, space, and financial support have made it impossible to address all of the research questions that were raised during the development of this thesis. As a result, there are a number of potential research ideas which, if explored further, may improve our understanding of past, present, and future processes in the Slave River Delta.

It is strongly recommended that both discharge and suspended sediment continue to be monitored within various channels of the Slave River Delta in order to increase the quantity and quality of available data. It is also suggested that these samples be carried out during various stages of the annual hydrograph since doing so would enable future researchers to develop a stronger understanding of the influence of seasonal variations on the relationship between [SS] and discharge in the deltaic environment.

In addition to water quantity, continued sampling in the delta would provide an excellent opportunity to gather information on water quality as well. By examining both the input and distribution nutrients and contaminants, conclusions could be drawn on the current ecological status of the delta as well as its potential to remain as a viable habitat in the future.

In terms of deposition, most of the grain size data collected from soil pits and suspended sediment samples over the summer field season were not addressed in this thesis. While some work has been done on these samples, it is felt that future analysis may provide some insight into the depositional structure of the delta and how this has varied over space and time.

Significant advances in the understanding of deposition within the Slave River Delta could also be achieved by combining this information with a closer examination of those processes which directly influence the transportation and deposition of sedimentary material. It is therefore recommended that research be conducted on the mechanisms of cleavage bar growth, point bar development, wind and wave erosion, longshore drift, and the seiche effect.

Finally, one of the key issues raised during this study has been the impact of flow regime on channel closure. While several possible explanations were suggested, a more intensive investigation of the mechanics of this phenomenon might provide a more definitive explanation for the abandonment of certain channels within the Slave River Delta. In addition, a more comprehensive understanding of these processes may allow individuals to predict the life span of specific distributaries and how their evolution will influence the hydrologic regime of the delta as a whole.

APPENDIX A: Water Survey Data

Date	Site	Bifurcation Class	Season	Discharge (m^3/s)	Avg. [ss] (mg/l)	Corrected [ss] (mg/l)
jul 06 95	3 ways entrance	3	su	26.921	42.328	42.328
jun 02 95	3 ways entrance	3	sp	25.688	319.149	53.665
jun 08 95	3 ways entrance	3	sp	30.066	280.749	47.208
jun 21 95	3 ways entrance	3	sp	29.167	78.947	78.947
jun 30 95	3 ways entrance	3	sp	26.638	25.907	25.907
jul 06 95	3 ways mouth	3	su	30.589	61.644	61.644
jun 08 95	3 ways mouth	3	sp	24.710	491.228	82.600
jun 21 95	3 ways mouth	3	sp	28.943	78.125	78.125
jun 30 95	3 ways mouth	3	sp	30.716	52.910	52.910
sep 14 95	4 ways @ 3 ways	2	f	37.097	93.750	93.750
jul 06 95	4 ways entrance	2	su	47.330	73.913	73.913
jun 02 95	4 ways entrance	2	sp	40.057	215.070	36.164
jun 21 95	4 ways entrance	2	sp	37.092	76.087	76.087
jun 30 95	4 ways entrance	2	sp	28.833	63.158	63.158
sep 14 95	4 ways entrance	2	f	37.799	108.536	108.536
aug 15 79	4 ways w.s.c.	2	su	77.600	127.000	127.000
aug 16 78	4 ways w.s.c.	2	su	64.800	56.000	56.000
aug 20 80	4 ways w.s.c.	2	su	54.300	73.000	73.000
jul 03 79	4 ways w.s.c.	2	su	112.000	528.000	528.000
may 14 80	4 ways w.s.c.	2	sp	51.800	122.000	122.000
oct 04 79	4 ways w.s.c.	2	f	63.400	107.000	107.000
oct 07 80	4 ways w.s.c.	2	f	52.200	139.000	139.000
sep 20 78	4 ways w.s.c.	2	f	66.300	88.000	88.000
jul 05 95	beaver dam entrance	3	su	4.782	42.857	42.857
jun 07 95	beaver dam entrance	3	sp	4.970	212.019	35.651
jun 20 95	beaver dam entrance	3	sp	4.435	76.190	76.190
jun 29 95	beaver dam entrance	3	sp	4.024	47.297	47.297
may 25 95	beaver dam entrance	3	sp	5.900	473.389	79.600
sep 14 95	beaver dam entrance real	3	f	2.704	80.000	80.000
jul 05 95	beaver dam mouth	3	su	3.526	63.736	63.736
jun 07 95	beaver dam mouth	3	sp	4.171	211.694	35.596
jun 20 95	beaver dam mouth	3	sp	3.895	90.909	90.909
jun 29 95	beaver dam mouth	3	sp	4.119	64.935	64.935
may 25 95	beaver dam mouth	3	sp	4.797	643.853	108.264
aug 15 79	east channel	2	su	74.800	102.000	102.000
aug 16 78	east channel	2	su	36.000	40.000	40.000
aug 20 80	east channel	2	su	33.900	54.000	54.000
jul 04 79	east channel	2	su	111.000	354.000	354.000
jul 05 95	east channel	2	su	17.200	85.714	85.714
jun 07 95	east channel	2	sp	14.433	938.342	157.782
jun 20 95	east channel	2	sp	15.928	94.937	94.937
jun 29 95	east channel	2	sp	15.386	76.389	76.389
may 14 80	east channel	2	sp	40.500	105.000	105.000
oct 04 79	east channel	2	f	50.700	85.000	85.000
oct 08 80	east channel	2	f	33.700	113.000	113.000
sep 13 95	east channel	2	f	12.028	99.127	99.127
sep 21 78	east channel	2	f	47.900	96.000	96.000
jul 05 95	east channel "mouth"	2	su	33.130	62.500	62.500
jun 07 95	east channel "mouth"	2	sp	31.335	631.579	106.200
jun 20 95	east channel "mouth"	2	sp	29.707	73.333	73.333
jun 29 95	east channel "mouth"	2	sp	31.816	50.314	50.314
sep 14 95	east channel real mouth	2	f	16.092	81.633	81.633
jul 06 95	island north entrance	4	su	5.681	46.429	46.429
jun 02 95	island north entrance	4	sp	8.641	377.806	63.528
jun 08 95	island north entrance	4	sp	6.888	422.546	71.051
jun 21 95	island north entrance	4	sp	6.183	69.892	69.892
jun 30 95	island north entrance	4	sp	5.698	37.634	37.634
jul 06 95	island north mouth	4	su	6.363	48.148	48.148
jun 08 95	island north mouth	4	sp	7.919	282.941	47.577
jun 21 95	island north mouth	4	sp	6.081	56.995	56.995
jun 30 95	island north mouth	4	sp	6.276	42.553	42.553
sep 14 95	island north mouth	4	f	3.647	79.437	79.437

sp = spring; s = summer; f = fall
w.s.c. = water survey of canada site

APPENDIX A (con't): Water Survey Data

Date	Site	Bifurcation Class	Season	Discharge (m^3/s)	Avg. [ss] (mg/l)	Corrected [ss] (mg/l)
jul 06 95	island south entrance	4	su	11.208	48.276	48.276
jun 02 95	island south entrance	4	sp	10.484	287.030	48.264
jun 08 95	island south entrance	4	sp	11.401	425.532	71.553
jun 21 95	island south entrance	4	sp	10.252	75.269	75.269
jun 30 95	island south entrance	4	sp	11.792	46.875	46.875
jul 06 95	island south mouth	4	su	7.751	34.722	34.722
jun 08 95	island south mouth	4	sp	10.164	424.412	71.365
jun 21 95	island south mouth	4	sp	10.332	93.750	93.750
jun 30 95	island south mouth	4	sp	8.592	42.105	42.105
aug 15 79	middle channel east (07)	3	su	52.400	123.000	123.000
aug 16 78	middle channel east (07)	3	su	32.800	47.000	47.000
aug 20 80	middle channel east (07)	3	su	25.400	52.000	52.000
jul 04 79	middle channel east (07)	3	su	83.000	401.000	401.000
may 14 80	middle channel east (07)	3	sp	32.700	123.000	123.000
oct 04 79	middle channel east (07)	3	f	41.300	99.000	99.000
oct 08 80	middle channel east (07)	3	f	30.000	134.000	134.000
sep 21 78	middle channel east (07)	3	f	40.200	105.000	105.000
sep 13 95	middle channel entrance	1	f	187.177	92.529	92.529
aug 14 79	middle channel west (06)	3	su	229.000	154.000	154.000
aug 16 78	middle channel west (06)	3	su	192.000	70.000	70.000
aug 19 80	middle channel west (06)	3	su	134.000	79.000	79.000
jul 04 79	middle channel west (06)	3	su	329.000	509.000	509.000
may 13 80	middle channel west (06)	3	sp	149.000	152.000	152.000
oct 03 79	middle channel west (06)	3	f	180.000	110.000	110.000
oct 08 80	middle channel west (06)	3	f	179.000	177.000	177.000
sep 13 95	middle channel west (06)	3	f	140.403	80.000	80.000
sep 20 78	middle channel west (06)	3	f	210.000	117.000	117.000
aug 09 78	nagle channel	1	su	16.600	83.000	83.000
aug 20 80	nagle channel	1	su	14.200	73.000	73.000
jul 03 79	nagle channel	1	su	32.200	539.000	539.000
may 15 80	nagle channel	1	sp	9.600	94.000	94.000
oct 03 79	nagle channel	1	f	15.300	104.000	104.000
oct 07 80	nagle channel	1	f	12.700	162.000	162.000
sep 21 78	nagle channel	1	f	15.500	122.000	122.000
jul 02 95	nagle channel campsite	1	su	9.572	57.292	57.292
aug 10 78	resdelta channel	0	su	2945.000	103.000	103.000
aug 14 79	resdelta channel	0	su	3940.000	179.000	179.000
aug 19 80	resdelta channel	0	su	2650.000	79.000	79.000
jul 04 79	resdelta channel	0	su	5300.000	579.000	579.000
may 13 80	resdelta channel	0	sp	2550.000	152.000	152.000
oct 03 79	resdelta channel	0	f	3430.000	165.000	165.000
sep 12 95	resdelta channel	0	f	2742.488	97.923	97.923
sep 19 78	resdelta channel	0	f	3480.000	115.000	115.000
sep 12 95	slave river	0	f	3040.269	101.250	101.250
jul 05 95	steamboat "entrance"	1	su	36.770	59.829	59.829
jun 01 95	steamboat "entrance"	1	sp	28.960	358.740	60.322
jun 22 95	steamboat "entrance"	1	sp	34.680	112.821	112.821
jun 29 95	steamboat "entrance"	1	sp	32.350	60.606	60.606
sep 15 95	steamboat "entrance"	1	f	24.200	94.595	94.595
aug 15 78	steamboat camp	1	su	53.000	50.000	50.000
aug 15 79	steamboat camp	1	su	68.300	97.000	97.000
aug 20 80	steamboat camp	1	su	45.900	62.000	62.000
jul 14 79	steamboat camp	1	su	106.000	336.000	336.000
may 14 80	steamboat camp	1	sp	36.100	100.000	100.000
oct 05 79	steamboat camp	1	f	49.600	78.000	78.000
oct 07 80	steamboat camp	1	f	67.300	110.000	110.000
sep 20 78	steamboat camp	1	f	56.600	68.000	68.000
jul 05 95	v north	2	su	4.149	33.333	33.333
jun 07 95	v north	2	sp	4.749	840.690	141.362
jun 20 95	v north	2	sp	3.411	67.568	67.568
jun 29 95	v north	2	sp	3.472	40.541	40.541
jul 05 95	v south	2	su	9.914	52.356	52.356
jun 07 95	v south	2	sp	10.945	924.951	155.531
jun 20 95	v south	2	sp	11.375	79.268	79.268
jun 29 95	v south	2	sp	8.146	60.811	60.811
jul 07 95	whiteman's entrance	3	su	2.142	34.014	34.014
jun 12 95	whiteman's entrance	3	sp	4.167	423.292	71.177
jun 28 95	whiteman's entrance	3	sp	2.879	52.083	52.083
may 14 80	whiteman's entrance	3	sp	4.660	100.000	100.000
may 31 95	whiteman's entrance	3	sp	5.078	431.109	72.491
oct 04 79	whiteman's entrance	3	f	11.800	78.000	78.000
jul 07 95	whiteman's mouth	3	su	2.636	21.429	21.429
jun 12 95	whiteman's mouth	3	sp	3.494	295.390	49.670
jun 28 95	whiteman's mouth	3	sp	2.829	46.875	46.875
may 31 95	whiteman's mouth	3	sp	5.661	429.222	72.174
jul 07 95	whiteman's pt. bar	3	su	3.305	27.027	27.027
jun 12 95	whiteman's pt. bar	3	sp	3.042	279.986	47.080
jun 28 95	whiteman's pt. bar	3	sp	3.058	42.328	42.328

sp = spring; s = summer; f = fall
w.s.c. = water survey of canada site

APPENDIX B: Laurel Creek [SS] Analysis

Test #	1 (low flow)			2 (high flow)	
Method	Field	Lab		Field	Lab
Plate Mass (g)	13.200			12.800	
Plate + Sed. (g)	13.400			13.000	
Sed. Mass (g)	0.200			0.200	
Sed. Mass (mg)	200.000			200.000	
Filter Mass		0.148			0.150
Filter + Sed		0.160			0.184
Sed. Mass (g)		0.012			0.034
Sed. Mass (mg)		12.000			34.000
Water Volume (ml)	515.000	234.000		290.000	242.000
Water Volume (l)	0.515	0.234		0.290	0.242
[SS] (mg/l)	388.350	51.282		689.655	140.496
Difference (mg/l)	337.067			549.159	

Difference/Lab X 100% = 657.282% 390.872%

Average = 524.077%

APPENDIX C: Re-Assessment of [SS] Adjustment Value

Test #	Plate				Filter				Difference	Difference/Lab X 100%
	Before (g)	After (g)	Volume (l)	[SS] (mg/l)	Before (g)	After (g)	Volume (l)	[SS] (mg/l)	(Plate - Filter) (mg/l)	
1	13.20	13.40	0.515	388.35	0.148	0.160	0.234	51.282	337.07	657.28%
2	12.80	13.00	0.290	689.66	0.150	0.184	0.242	140.496	549.16	390.87%
3	12.60	12.70	0.246	406.50	0.150	0.159	0.107	84.112	322.39	383.29%
5	12.90	13.50	0.394	1522.84	0.148	0.148	0.130	0.000	1522.84	N/A
6	12.90	13.00	0.202	495.05	0.149	0.183	0.130	261.538	233.51	89.28%
7	12.90	13.00	0.354	282.49	0.147	0.159	0.178	67.416	215.07	319.02%
8	13.10	13.60	0.204	2450.98	0.148	0.431	0.122	2319.672	131.31	5.66%
9	13.40	13.60	0.361	554.02	0.150	0.159	0.120	75.000	479.02	638.69%
10	13.10	13.30	0.234	854.70	0.149	0.214	0.087	747.126	107.57	14.40%
									AVG:	312.31%
									ORIGINAL:	524.08%

Adjustment Values (Plate (X) = Filter Therefore: X = Filter/Plate)

Test	1	2	3	4	5	6	7	8	9
Filter/Plate	0.1321	0.2037	0.2069	0.0000	0.5283	0.2387	0.9464	0.1354	0.8741
AVG:	**0.3628**								

Original Value 0.1679

APPENDIX D: TerraSoft Feature Class Table

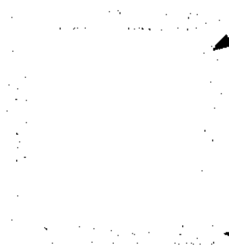
#	Feature	Clr	LT	Thk	Pattern	mm	Sh	mm	Fnt	Slnt	Prio	Comment
1	ALDER_46	4	1	1		1.00	1	1.00	1	0	50.00	
2	ALDER_66	4	1	1		1.00	1	1.00	1	0	50.00	
3	ALDER_77	4	1	1		1.00	1	1.00	1	0	50.00	
4	ALDER_94	4	1	1		1.00	1	1.00	1	0	50.00	
5	ALD_SAL_46	18	1	1		1.00	1	1.00	1	0	50.00	
6	ALD_SAL_66	18	1	1		1.00	1	1.00	1	0	50.00	
7	ALD_SAL_77	18	1	1		1.00	1	1.00	1	0	50.00	
8	ALD_SAL_94	18	1	1		1.00	1	1.00	1	0	50.00	
9	AQUA_46	9	1	1		1.00	1	1.00	1	0	50.00	
10	AQUA_66	9	1	1		1.00	1	1.00	1	0	50.00	
11	AQUA_77	9	1	1		1.00	1	1.00	1	0	50.00	
12	AQUA_94	9	1	1		1.00	1	1.00	1	0	50.00	
13	A_LAB_66	1	1	1		1.00	1	1.00	1	0	50.00	
14	BC_46	11	1	1		1.00	1	1.00	1	0	50.00	
15	BC_66	4	1	1		1.00	1	1.00	1	0	50.00	
16	BLACK_CLSD	1	1	1		1.00	1	1.00	1	0	50.00	
17	BLACK_OPEN	1	1	1		1.00	1	1.00	1	0	50.00	
18	BLCH	11	1	1		1.00	1	1.00	1	0	50.00	
19	BLUE_CHAN	11	1	1		1.00	1	1.00	1	0	50.00	
20	BL_CLSD_77	1	1	1		1.00	1	1.00	1	0	50.00	
21	BL_OPEN_77	1	1	1		1.00	1	1.00	1	0	50.00	
22	BO_46	1	1	1		1.00	1	1.00	1	0	50.00	
23	BO_66	4	1	1		1.00	1	1.00	1	0	50.00	
24	BROKEN	1	1	1		1.00	1	1.00	1	0	50.00	
25	CBA_46	1	1	1		1.00	1	1.00	1	0	50.00	
26	CBA_66	2	1	1		1.00	1	1.00	1	0	50.00	
27	CBT_46	1	1	1		1.00	1	1.00	1	0	50.00	
28	CBT_66	2	1	1		1.00	1	1.00	1	0	50.00	
29	CD_AQUATIC	1	1	1		1.00	1	1.00	1	0	50.00	
30	CB_AQ_77	1	1	1		1.00	1	1.00	1	0	50.00	
31	CB_TERR	1	1	1		1.00	1	1.00	1	0	50.00	
32	CB_TERR_77	1	1	1		1.00	1	1.00	1	0	50.00	
33	DIST_46	7	1	1		1.00	1	1.00	1	0	50.00	
34	DIST_66	7	1	1		1.00	1	1.00	1	0	50.00	
35	DIST_77	7	1	1		1.00	1	1.00	1	0	50.00	
36	DIST_94	7	1	1		1.00	1	1.00	1	0	50.00	
37	DRFTWD_46	6	1	1		1.00	1	1.00	1	0	50.00	
38	DRFTWD_66	6	1	1		1.00	1	1.00	1	0	50.00	
39	DRFTWD_77	6	1	1		1.00	1	1.00	1	0	50.00	
40	DRFTWD_94	6	1	1		1.00	1	1.00	1	0	50.00	
41	DRY_46	1	1	1		1.00	1	1.00	1	0	50.00	
42	DRY_66	15	1	1		1.00	1	1.00	1	0	50.00	
43	DRY_CHANN	1	1	1		1.00	1	1.00	1	0	50.00	
44	DRY_CH_77	1	1	1		1.00	1	1.00	1	0	50.00	
45	DRY_SWAMP	1	1	1		1.00	1	1.00	1	0	50.00	
46	EQUI_46	10	1	1		1.00	1	1.00	1	0	50.00	
47	EQUI_66	10	1	1		1.00	1	1.00	1	0	50.00	
48	EQUI_77	10	1	1		1.00	1	1.00	1	0	50.00	
49	EQUI_94	10	1	1		1.00	1	1.00	1	0	50.00	
50	ERRORS	15	1	1		1.00	1	1.00	1	0	50.00	
51	H2OLAND_46	4	1	1		1.00	1	1.00	1	0	50.00	
52	H2OLAND_66	9	1	1		1.00	1	1.00	1	0	50.00	
53	H2OLAND_77	1	1	1		1.00	1	1.00	1	0	50.00	
54	H2OLAND_SL	14	1	1		1.00	1	1.00	1	0	50.00	
55	H2OBUSIN	14	1	1		1.00	1	1.00	1	0	50.00	
56	H2O_LAND	1	1	1		1.00	1	1.00	1	0	50.00	
57	ISLAND_46	15	1	1		1.00	1	1.00	1	0	50.00	
58	ISLAND_66	15	1	1		1.00	1	1.00	1	0	50.00	
59	ISLAND_77	15	1	1		1.00	1	1.00	1	0	50.00	
60	ISLAND_94	15	1	1		1.00	1	1.00	1	0	50.00	
61	LABELS_46	18	1	1		1.00	1	1.00	1	0	50.00	
62	LABEL_46	1	1	1		1.00	1	1.00	1	0	50.00	
63	LABEL_66	1	1	1		1.00	1	1.00	1	0	50.00	
64	LABEL_77	1	1	1		1.00	1	1.00	1	0	50.00	
65	LABEL_94	1	1	1		1.00	1	1.00	1	0	50.00	
66	LAKES	1	1	1		1.00	1	1.00	1	0	50.00	
67	LAKES_46	1	1	1		1.00	1	1.00	1	0	50.00	
68	LAKES_66	9	1	1		1.00	1	1.00	1	0	50.00	

APPENDIX D (con't): TerraSoft Feature Class Table

#	Feature	Clr	LT	Thk	Pattern	mm	Sh	mm	Fnt	Slnt	Prio	Comment
69	LAKES_77	1	1	1		1.00	1	1.00	1	0	50.00	
70	ODA_46	1	1	1		1.00	1	1.00	1	0	50.00	
71	ODA_66	2	1	1		1.00	1	1.00	1	0	50.00	
72	ODT_46	1	1	1		1.00	1	1.00	1	0	50.00	
73	ODT_66	2	1	1		1.00	1	1.00	1	0	50.00	
74	OD_AQUATIC	1	1	1		1.00	1	1.00	1	0	50.00	
75	OD_AQ_77	1	1	1		1.00	1	1.00	1	0	50.00	
76	OD_TERR	1	1	1		1.00	1	1.00	1	0	50.00	
77	OD_TERR_77	1	1	1		1.00	1	1.00	1	0	50.00	
78	POPLAR_46	14	1	1		1.00	1	1.00	1	0	50.00	
79	POPLAR_66	14	1	1		1.00	1	1.00	1	0	50.00	
80	POPLAR_77	14	1	1		1.00	1	1.00	1	0	50.00	
81	POPLAR_94	14	1	1		1.00	1	1.00	1	0	50.00	
82	RIVSBLU_77	1	1	1		1.00	1	1.00	1	0	50.00	
83	RIVS_46	1	1	1		1.00	1	1.00	1	0	50.00	
84	RIVS_66	9	1	1		1.00	1	1.00	1	0	50.00	
85	RIVS_77	9	1	1		1.00	1	1.00	1	0	50.00	
86	RIVS_94	9	1	1		1.00	1	1.00	1	0	50.00	
87	RIVS_BLACK	1	1	1		1.00	1	1.00	1	0	50.00	
88	RIVS_BLUE	1	1	1		1.00	1	1.00	1	0	50.00	
89	RIV_BLU_77	1	1	1		1.00	1	1.00	1	0	50.00	
90	ROADS	1	1	1		1.00	1	1.00	1	0	50.00	
91	ROADS_46	1	1	1		1.00	1	1.00	1	0	50.00	
92	ROADS_66	7	1	1		1.00	1	1.00	1	0	50.00	
93	ROADS_77	1	1	1		1.00	1	1.00	1	0	50.00	
94	RUNWAY	1	1	1		1.00	1	1.00	1	0	50.00	
95	RUNWAY_46	1	1	1		1.00	1	1.00	1	0	50.00	
96	RUNWAY_66	5	1	1		1.00	1	1.00	1	0	50.00	
97	RUNWAY_77	1	1	1		1.00	1	1.00	1	0	50.00	
98	SALIX_46	3	1	1		1.00	1	1.00	1	0	50.00	
99	SALIX_66	3	1	1		1.00	1	1.00	1	0	50.00	
100	SALIX_77	3	1	1		1.00	1	1.00	1	0	50.00	
101	SALIX_94	3	1	1		1.00	1	1.00	1	0	50.00	
102	SAL_ALD_46	12	1	1		1.00	1	1.00	1	0	50.00	
103	SAL_ALD_66	12	1	1		1.00	1	1.00	1	0	50.00	
104	SAL_ALD_77	12	1	1		1.00	1	1.00	1	0	50.00	
105	SAL_ALD_94	12	1	1		1.00	1	1.00	1	0	50.00	
106	SAL_EQ_46	2	1	1		1.00	1	1.00	1	0	50.00	
107	SAL_EQ_66	2	1	1		1.00	1	1.00	1	0	50.00	
108	SAL_EQ_77	2	1	1		1.00	1	1.00	1	0	50.00	
109	SAL_EQ_94	2	1	1		1.00	1	1.00	1	0	50.00	
110	SAND_46	5	1	1		1.00	1	1.00	1	0	50.00	
111	SAND_66	5	1	1		1.00	1	1.00	1	0	50.00	
112	SAND_77	5	1	1		1.00	1	1.00	1	0	50.00	
113	SAND_94	5	1	1		1.00	1	1.00	1	0	50.00	
114	STREETS	1	1	1		1.00	1	1.00	1	0	50.00	
115	STREETS_46	1	1	1		1.00	1	1.00	1	0	50.00	
116	STREETS_66	7	1	1		1.00	1	1.00	1	0	50.00	
117	STREETS_77	1	1	1		1.00	1	1.00	1	0	50.00	
118	VEG_LAB_46	15	1	1		1.00	1	1.00	1	0	50.00	
119	VEG_LAB_66	15	1	1		1.00	1	1.00	1	0	50.00	
120	VEG_LAB_77	15	1	1		1.00	1	1.00	1	0	50.00	
121	VEG_LAB_94	15	1	1		1.00	1	1.00	1	0	50.00	
122	WAVE_SHOAL	1	1	1		1.00	1	1.00	1	0	50.00	
123	WETPOLY_46	1	1	1		1.00	1	1.00	1	0	50.00	
124	WETPOLY_66	1	1	1		1.00	1	1.00	1	0	50.00	
125	WETPOLY_77	1	1	1		1.00	1	1.00	1	0	50.00	
126	WETPOLY_94	1	1	1		1.00	1	1.00	1	0	50.00	
127	WET_46	2	1	1		1.00	1	1.00	1	0	50.00	
128	WET_66	2	1	1		1.00	1	1.00	1	0	50.00	
129	WET_77	2	1	1		1.00	1	1.00	1	0	50.00	
130	WET_94	2	1	1		1.00	1	1.00	1	0	50.00	
131	WS_46	1	1	1		1.00	1	1.00	1	0	50.00	
132	WS_66	4	1	1		1.00	1	1.00	1	0	50.00	
133	WV_SHL_77	1	1	1		1.00	1	1.00	1	0	50.00	
134		1	1	1		1.00	1	1.00	1	0	50.00	
135		1	1	1		1.00	1	1.00	1	0	50.00	

Appendix E: Digitizing Error Test

A) 2Km X 2Km Square (400ha)



Inside Pen-line:
Perimeter = 7928.250m
Area = 393.113ha

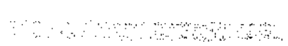
Outside Pen-Line:
Perimeter = 8081.838m
Area = 408.121ha

B) 2Km X 2Km Triangle (200ha)

Inside Pen-line:
Perimeter = 6785.766m
Area = 197.431ha

Outside Pen-Line:
Perimeter = 6972.267m
Area = 207.998ha

C) 2Km Straight Line



Distance Between Top & Bottom Edges (in m):

23.472	27.034	20.458	23.447	28.268	22.787
22.429	21.732	21.427	13.289	35.479	23.924

Average: 23.642m

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