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THE FLUVIAL GEOMORPHIC CHARACTER OF THE LOWER REACHES OF MAJOR MACKENZIE RIVER TRIBUTARIES, FORT SIMPSON TO NORMAN WELLS, NORTHWEST TERRITORIES

G.R. Brooks

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Natural Resources Canada   Ressources naturelles Canada

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Cover illustration

View of the mouth of Dahadinni River. At the observed stage, the river occupies only a small proportion of the active channel zone. Mackenzie River is in the background flowing from right to left. GSC 1995-064

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Preface

The Mackenzie Valley region contains abundant natural resources that are important to the economy of Canada. The region is environmentally sensitive and its climate is harsh. Successful development in this area requires an understanding of geomorphic processes. These can be very different from those of southern Canada. The Mackenzie River system is an important component of the landscape in the western Northwest Territories. The river system is a major transportation link for communities and industry. All proposed development located along the rivers must carefully consider hazards resulting from, for example, floods, ice jams, and bank erosion. Such hazard information is not readily available for much of the region.

This report about the Mackenzie River system in the Fort Simpson-Norman Wells area reviews previous local fluvial geomorphic research and the late Quaternary history as it pertains to the rivers. The primary information presented here for the lowest reaches of eight major Mackenzie River tributaries provides a baseline for future studies and development of the area.

Elkanah A. Babcock
Assistant Deputy Minister
Geological Survey of Canada

Préface

La région du fleuve Mackenzie recèle d'abondantes ressources naturelles qui sont importantes pour l'économie du Canada. L'environnement de cette région est fragile et son climat est rigoureux. Pour une mise en valeur réussie de cette région, il faut d'abord comprendre les processus géomorphologiques, qui peuvent différer de ceux que l'on observe dans le sud du pays. Le réseau hydrographique du fleuve Mackenzie est une composante majeure du paysage de la partie occidentale des Territoires du Nord-Ouest. Ce réseau sert de voie de transport importante pour les agglomérations et l'industrie. Dans tout projet proposé de mise en valeur en bordure des rivières, il faut particulièrement tenir compte des dangers liés notamment aux crues, aux embâcles et à l'érosion des berges. De telles informations sur les dangers sont difficiles à obtenir dans presque toute cette région.

Le présent rapport sur le réseau hydrographique du fleuve Mackenzie dans la région de Fort Simpson-Norman Wells passe en revue les recherches menées sur la géomorphologie fluviale locale et l'histoire de la fin du Quaternaire ayant un rapport avec les cours d'eau. Les informations essentielles sur les tronçons inférieurs de huit principaux tributaires du fleuve Mackenzie constituent une base de données pour les études futures et la mise en valeur de cette région.

Elkanah A. Babcock
Sous-ministre adjoint
Commission géologique du Canada

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Abstract

This study presents fluvial geomorphic information on the lowest 4 to 8 km of eight major tributaries of Mackenzie River gathered from fieldwork, aerial photograph interpretation, and available published sources. The tributaries studied are North Nahanni, Root, Willowlake, Blackwater, Dahadinni, Redstone, Keele, and Great Bear rivers which are located between Fort Simpson and Norman Wells, Northwest Territories. Specifically, information for each study reach was compiled on the valley characteristics, hydrology, channel characteristics, lateral channel change, and interaction with Mackenzie River.

The main body of the bulletin reviews previously published fluvial geomorphic research on Mackenzie River and the late Quaternary history as it pertains to the rivers. An overview section contains general information on the methodology, terminology, and the characteristics of the tributaries. River behaviours that should be carefully assessed prior to any development along a lower reach of a tributary are briefly summarized. Specific information on the eight individual tributaries is contained within separate appendices.

Résumé

La présente étude contient des informations sur la géomorphologie fluviale du tronçon inférieur (entre 4 et 8 km) de huit tributaires importants du fleuve Mackenzie. Il s'agit d'informations recueillies sur le terrain ou de données découlant de l'interprétation de photographies aériennes ou tirées de publications antérieures. Les tributaires étudiés sont les rivières Nahanni Nord, Root, Willowlake, Blackwater, Dahadinni, Redstone et Keele et la Grande rivière Bear dont l'embouchure est située entre Fort Simpson et Norman Wells dans les Territoires du Nord-Ouest. Les données recueillies sur chaque tronçon à l'étude ont porté en particulier sur les caractéristiques des vallées, l'hydrologie, les caractéristiques des chenaux et le déplacement latéral et l'interaction de ces rivières avec le fleuve Mackenzie.

La partie principale du bulletin passe en revue les documents publiés sur la géomorphologie fluviale du fleuve Mackenzie et les processus qui ont jalonné l'histoire de ces rivières pendant la fin du Quaternaire. Une section du rapport contient des informations générales sur la méthodologie, la terminologie et les caractéristiques des tributaires. On y présente un bref résumé du comportement des rivières qui devrait être évalué avec soin avant toute mise en valeur prévue le long du tronçon inférieur d'un tributaire. Les informations particulières aux huit tributaires apparaissent dans des annexes séparées.

SUMMARY

Major river confluences are important locations within a watershed to monitor fluvial changes. Between Fort Simpson and Norman Wells, Northwest Territories, eight major tributaries join Mackenzie River. These tributaries are the North Nahanni, Root, Willowlake, Blackwater, Dahadinni, Redstone, Keele, and Great Bear rivers. The tributary watersheds, draining areas ranging from 2700 to 158 000 km^2, each represent major river systems, however, they are small in relation to the enormous size of the Mackenzie River drainage basin. This paper provides fluvial geomorphic information on the lower reaches of these eight major tributaries. The paper also reviews the fluvial geomorphic literature of the upper Mackenzie Valley and summarizes the late Quaternary history pertaining to the river systems.

Brief mention of the eight tributary confluences is contained in the writings of early western travellers who journeyed along Mackenzie River. In the late nineteenth century and into the middle twentieth century, officers of the Geological Survey of Canada made general observations of the rivers while exploring and mapping the bedrock geology of the region. In the 1970s, considerable geomorphic research was undertaken by consulting companies, government agencies, and university researchers in response to proposed pipeline, highway, and railway developments along Mackenzie Valley. Much of this work is related to river crossings of tributaries on the east side of Mackenzie River. Sporadic research has continued into the 1980s on the spring break-up and flooding hazards. Overall, little published work is available on the lower reaches of the eight major tributaries, especially those draining the Mackenzie Mountains to the west of Mackenzie River.

The Holocene history of Mackenzie River and its major tributaries is known only generally. During the waning of the Laurentide ice sheet at the end of the late Wisconsinan Glaciation, a large area marginal to the present day Mackenzie River was inundated by glacial Lake Mackenzie. The lake existed from 11 760 to 10 290 BP, the level of which was controlled by bedrock at The Ramparts, near Fort Good Hope. After drainage of the glacial lake, Mackenzie River and its tributaries incised slowly into the former lake bed. Little is known of this incision, but available evidence from the vicinity of Great Bear River and near The Ramparts suggests that downcutting ceased at least several thousand years ago.

The fluvial geomorphic information was collected from study reaches along the lowest 4 to 8 km of the eight major tributaries on the following topics: study reach description, valley characteristics, hydrology, channel characteristics, lateral channel change, and tributary-Mackenzie River interaction. The study reaches generally are incised into Quaternary deposits of the Mackenzie Lowland or Great Slave Plain. Tertiary bedrock forms the lower valley sides along Great Bear River. Willowlake, Blackwater, and Great Bear rivers are crossed by the Norman Wells pipeline which runs from Norman Wells, Northwest Territories to Zama, Alberta.

SOMMAIRE

Les principales confluences sont des lieux stratégiques pour surveiller les changements d'origine fluviale dans un bassin hydrographique. Entre Fort Simpson et Norman Wells (Territoires du Nord-Ouest), huit tributaires importants se jettent dans le fleuve Mackenzie. Ce sont les rivières Nahanni Nord, Root, Willowlake, Blackwater, Dahadinni, Redstone et Keele et la Grande rivière Bear. Les bassins hydrographiques de ces tributaires drainent une région couvrant entre 2 700 et 158 000 km^2, chacun représentant d'importants réseaux hydrographiques; cependant, ils sont petits comparativement à l'immense bassin de drainage du fleuve Mackenzie. Le présent rapport contient des informations sur la géomorphologie fluviale des tronçons inférieurs de ces huit importants tributaires. On y analyse en outre la documentation portant sur la géomorphologie fluviale du cours supérieur du fleuve Mackenzie et on y résume les processus qui ont jalonné l'histoire de ces rivières durant la fin du Quaternaire.

Il est peu fait mention des confluences des huit tributaires dans les écrits des premiers voyageurs de l'Ouest qui ont poussé leurs expéditions le long du fleuve Mackenzie. Au cours de la fin du XIX^e siècle et jusqu'au milieu de XX^e siècle, les employés de la Commission géologique du Canada ont noté des observations générales sur les rivières pendant qu'ils exploraient et cartographiaient le géologie du substratum rocheux de cette région. Dans les années 1970, de vastes travaux de recherche géomorphologique ont été menés par des sociétés d'experts-conseils, des organismes gouvernementaux et des chercheurs universitaires pour faire suite à des propositions de construction de pipelines, de routes et de voies ferrées dans la vallée du Mackenzie. La plupart de ces travaux étaient liés à des traversées de tributaires à l'est du fleuve Mackenzie. La recherche sur les dangers provoqués par les débâcles et les crues printanières s'est poursuivie sporadiquement jusque dans les années 1980. Dans l'ensemble, les documents publiés sur les tronçons inférieurs des huit principaux tributaires, en particulier ceux drainant les monts Mackenzie à l'ouest du fleuve du même nom, ont été peu nombreux.

Les connaissances actuelles sur l'histoire holocène du fleuve Mackenzie et ses principaux tributaires sont essentiellement générales. Durant la fonte de l'Inlandsis laurentidien, à la fin de la Glaciation du Wisconsinien supérieur, une grande région en bordure du fleuve Mackenzie actuel a été inondée par le Lac glaciaire Mackenzie. Ce lac a existé de 11 760 à 10 290 BP et son niveau était commandé par le socle aux Ramparts, près de Fort Good Hope. Après le drainage du lac glaciaire, le fleuve Mackenzie et ses tributaires ont entaillé lentement l'ancien fond du lac. On connaît peu de choses sur cette érosion, mais les données recueillies près de la Grande rivière Bear et près des Ramparts révèlent que le creusement a cessé il y a au moins plusieurs milliers d'années.

Les informations sur la géomorphologie fluviale proviennent des tronçons inférieurs (entre 4 et 8 km) des huit principaux tributaires. Elles contiennent une description du tronçon à l'étude ainsi que des données sur la vallée, l'hydrologie, les chenaux, le déplacement latéral des chenaux et l'interaction du tributaire avec le fleuve Mackenzie. Les tronçons à l'étude s'encaissent généralement dans les dépôts quaternaires des basses terres du

All of the tributary streams are 'fit' to their respective valley widths, except for Willowlake River which is underfit. Its valley functioned as a meltwater channel during the waning of the late Wisconsinan Glaciation. Numerous slope failures occur along the valley sides of all the tributaries many of which are related to permafrost thaw.

There are no dams or flood control devices along any of the major tributaries, thus all have a natural streamflow. Hydrological data collected by the Water Survey of Canada exists for Root, Willowlake, Blackwater, Redstone, and Great Bear rivers; the others are ungauged. Seven of the eight rivers exhibit a subarctic, nival discharge regime with a very low winter flow and a peak mean monthly flow occurring in the period between May to July. In contrast, Great Bear River experiences a very attenuated discharge regime because of water storage in Great Bear Lake.

The rivers draining the Mackenzie Mountains exhibit 'flashy' discharge regimes that respond rapidly to rainstorms and diurnal snow melt. All of the rivers periodically experience extreme discharges arising from severe rainstorms, except for Great Bear and Blackwater rivers where large lakes in the drainage basins dampen the flows. The most recent severe storm occurred in July, 1988 which produced the historical flood of record along Root and Willowlake rivers.

Channel planforms along the study reaches vary from braided (North Nahanni, Dahadinni, Redstone, and Keele rivers), through meandering (Root and Willowlake), to straight (Blackwater and Great Bear rivers). The different planforms probably reflect contrasting sediment loads between the rivers; the braided rivers have relatively high sediment loads with the straight rivers the lowest. The braided rivers are all located along the west side of Mackenzie River and drain the Mackenzie Mountains. Seven of the eight tributaries are alluvial; the exception is Great Bear River which is confined by Tertiary bedrock. All the tributaries have gravel beds. Sand is present in varying degrees within slackwater areas of the channel and on the river bars; sand and silt form the overbank deposits of the floodplains. All of the rivers are subject to ice-push processes during the spring break-up, but ice-push features are not well preserved along the braided rivers probably because the river banks experience considerable annual erosion or deposition. The lower reaches of the tributaries are subject to backwater caused by major ice jams within Mackenzie River and by the Mackenzie River freshet; Willowlake and Root rivers experience significant backwater conditions at moderate tributary discharges.

Water Survey of Canada data on suspended sediment load is very fragmentary and of limited duration. Generally, the braided rivers draining Mackenzie Mountains carry relatively high suspended sediment loads. A significant amount of bed-material is also transported by the braided rivers as indicated by the considerable amount of channel change that they experience. Turbidity differences between the tributaries and Mackenzie River produce plumes that extend downstream from their confluences.

Mackenzie ou de la plaine du Grand lac des Esclaves. Le substratum tertiaire forme les versants inférieurs de la vallée le long de la Grande rivière Bear. Le pipeline de Norman Wells, qui relie Norman Wells (Territoires du Nord-Ouest) à Zama (Alberta), traverse les rivières Willowlake et Blackwater et la Grande rivière Bear.

Tous les tributaires occupent toute la largeur de leur vallée respective, à l'exception de la rivière Willowlake. La vallée de cette dernière a servi de chenal fluvioglaciaire durant la fin de la Glaciation du Wisconsinien supérieur. On observe le long des versants de vallée des tributaires de nombreuses ruptures de pente dont plusieurs sont dues au dégel du pergélisol.

Comme il n'y a pas de barrages ou de régularisateurs de crue le long de ces principaux tributaires, leur débit est donc dans tous les cas naturel. La Division des relevés hydrologiques du Canada recueille des données hydrologiques dans les rivières Root, Willowlake, Blackwater et Redstone et la Grande rivière Bear; aucune mesure n'est faite dans les autres. Sept des huit rivières ont un régime d'écoulement nival subarctique caractérisé par un débit très faible en hiver et un débit de pointe mensuel moyen entre mai et juillet. Par contre, le débit de la Grande rivière Bear est très atténué par le stockage d'eau dans le Grand lac de l'Ours.

Les rivières drainant les monts Mackenzie affichent des débits «éclairs» du fait qu'elles réagissent rapidement aux orages et à la fonte nivale diurne. Périodiquement, toutes les rivières ont un débit extrême provoqué par des orages violents, à l'exception de la Grande rivière Bear et de la rivière Blackwater où des lacs de grande étendue dans les bassins de drainage atténuent le débit. L'orage violent le plus récent date de juillet 1988; il a produit une crue historique jamais enregistrée le long des rivières Root et Willowlake.

Le tracé des chenaux des tronçons à l'étude varie d'anastomosé (rivières Nahanni Nord, Dahadinni, Redstone et Keele) à sinueux (rivières Root et Willowlake) à rectiligne (rivière Blackwater et Grande rivière Bear). Les différents tracés reflètent probablement des charriages de sédiments variant d'une rivière à l'autre; les rivières anastomosées ont des charges de sédiments relativement élevées tanids que celles des rivières rectilignes sont les plus faibles. Les rivières anastomosées sont toutes situées à l'ouest du fleuve Mackenzie et drainent les monts Mackenzie. Sept des huit tributaires sont délimités par des alluvions; la Grande rivière Bear, qui est limitée par un socle tertiaire, fait exception. Tous les tributaires ont un lit de gravier. Du sable est présent à des degrés divers dans les zones d'eau étale du chenal et sur les bancs; du sable et du silt forment des dépôts de débordement dans les plaines d'inondation. Toutes les rivières sont sujettes à des processus de poussée glacielle durant la débâcle printanière, mais les formes résultantes ne sont pas bien préservées le long des rivières anastomosées du fait probablement d'une érosion ou d'un alluvionnement annuel considérable sur ces rives. Dans les tronçons inférieurs des tributaires, on observe des remous créés par d'importants embâcles dans le fleuve Mackenzie et par la montée des eaux du fleuve Mackenzie; les rivières Willowlake et Root connaissent des conditions de remous significatives en période de débit sortant modéré.

The extent of lateral channel change was assessed by comparing aerial photography from the 1940s or 1950s with more recent coverage from the 1970s or 1980s. The degree of channel erosion varied considerably between the study reaches, ranging from essentially zero along Great Bear and Blackwater rivers, to 340 m (11 $m \cdot a^{-1}$) locally along Redstone River. The factors controlling the amount of lateral channel change varies from river to river. With Great Bear and Blackwater rivers, it is limited by the resistance of the channel boundaries to fluvial erosion. Limiting factors along Willowlake and Root rivers are low stream power and the fact that the majority of the concave (outer) banks of the meanders along both rivers are confined against high valley sides. North Nahanni, Dahadinni, Redstone, and Keele rivers are swift flowing streams, thus, stream power is relatively high. The river banks are formed primarily of contemporary floodplain deposits which appear to present little resistance to fluvial erosion. All four of these rivers experienced considerable lateral channel change.

Reflecting differences in bed-material transport into Mackenzie River, various morphological features are present at the mouths of the tributaries. These features can be categorized generally as: a) low-angled alluvial fans splayed into the bottom of Mackenzie River valley[1] (North Nahanni, Dahadinni, Redstone, and Keele rivers); b) channel junction bars protruding into the Mackenzie River channel (Root and Blackwater rivers) and; c) no obvious morphological effects (Willowlake and Great Bear rivers).

Channel characteristics of Mackenzie River immediately adjacent to a tributary mouth can be controlled directly by a tributary, including: confinement of the Mackenzie River channel against the valley side opposite to the tributary mouth; narrowing of the Mackenzie River channel; deflection of the Mackenzie River channel into the opposite river bank (or valley side); and widening of the Mackenzie River channel. The confinement, narrowing, or deflection of the channel relate directly to the splaying of low-angled alluvial fans and channel junction bars into Mackenzie River valley and the Mackenzie River channel. Channel widening at Willowlake and Great Bear confluences may result from hydraulic deflection of Mackenzie River by the oblique flow from a tributary.

The channel morphology of Mackenzie River changes downstream along its course from Fort Simpson to Norman Wells. Most obviously, this occurs through island and bar development which divides the river into a number of sinuous branches beginning at the Blackwater and Dahadinni confluences and extending downstream for about 125 km (to about 55 km below Keele River). While no single tributary can be identified as solely responsible for causing this change, these islands and bars appear to represent

Les données de la Division des relevés hydrologiques du Canada sur les charges en suspension sont très fragmentaires et s'échelonnent sur une durée limitée. En général, les rivières anastomosées drainant les monts Mackenzie transportent des charges en suspension relativement élevées. Une quantité importante de matériaux de lit est également charriée par les rivière anastomosées comme l'indiquent les changements de chenal importants qu'elles connaissent. Les différences de turbidité entre les tributaires et le fleuve Mackenzie produisent des panaches qui descendent vers l'aval à partir de leur confluence.

On a évalué le changement latéral des chenaux en comparant des photographies aériennes prises durant les années 40 et 50 avec des photographies plus récentes datant des années 70 ou 80. L'érosion des chenaux a varié considérablement entre les tronçons à l'étude, d'essentiellement nulle le long de la Grande rivière Bear et de la rivière Blackwater à 340 m (11 $m \cdot a^{-1}$) par endroits le long de la rivière Redstone. Les facteurs régissant le déplacement latéral des chenaux varie d'une rivière à l'autre. Dans la Grande rivière Bear et la rivière Blackwater, ce déplacement est limité par la résistance des limites du chenal à l'érosion fluviale. Les facteurs limitatifs le long des rivières Willowlake et Root sont un faible débit et le fait que la majorité des rives concaves (extérieures) des méandres des deux rivières sont limitées par des versants de vallée élevés. Les rivières Nahanni Nord, Dahadinni, Redstone et Keele sont des cours d'eau à débit rapide; par conséquent, la force du courant est relativement élevée. Les rives sont surtout composées de sédiments de plaine d'inondation contemporaine qui semblent offrir peu de résistance à l'érosion fluviale. Ces quatre rivières ont connu un déplacement latéral considérable de leur lit.

Reflétant les différents types de sédiments charriés vers le fleuve Mackenzie, les éléments morphologiques observés à l'embouchure des tributaires sont variés. On peut classer ces éléments dans trois catégories générales : a) les cônes alluviaux peu courbés évasés sur le fond de la vallée du fleuve Mackenzie[1] (rivières Nahanni-Nord, Dahadinni, Redstone et Keele); b) les bancs de jonction de chenaux pénétrant dans le chenal du fleuve Mackenzie (rivière Root et Blackwater); et c) aucun effet morphologique évident (rivière Willowlake et Grande rivière Bear).

Certaines caractéristiques du chenal du fleuve Mackenzie jouxtant l'embouchure d'un tributaire peuvent être directement contrôlées par le tributaire. Ce sont notamment le confinement du chenal du fleuve Mackenzie contre le versant de la vallée qui est opposé à l'embouchure du tributaire; le rétrécissement du chenal du fleuve Mackenzie; la déflexion du chenal du fleuve Mackenzie vers la rive opposée (ou versant de vallée); et l'élargissement du chenal du fleuve Mackenzie. Le confinement, le rétrécissement ou la déflexion du chenal sont directement liés à l'évasement des cônes alluviaux peu courbés et des bancs de jonction de chenaux vers la vallée du fleuve Mackenzie et le chenal du fleuve Mackenzie. L'élargissement du chenal aux

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[1] In this paper, the term 'Mackenzie River valley' is defined as the corridor incised into the Great Slave Plain (Fort Simpson to Camsell Bend) or Mackenzie Lowland (Camsell Bend to Norman Wells) that is occupied by Mackenzie River. The term 'Mackenzie Valley' is used in the regional context as is consistent with its common usage.

[1] Dans le présent document, l'expression «vallée du fleuve Mackenzie» désigne le corridor entaillé dans la plaine du Grand lac des Esclaves (de Fort Simpson à la courbe Camsell) ou les basses terres du Mackenzie (de la courbe Camsell à Norman Wells) qui sont occupées par le fleuve Mackenzie. Le terme «vallée du Mackenzie» est utilisé dans le contexte régional et il correspond à l'usage habituel.

temporary bed-material storage features within Mackenzie River that have been derived collectively from Dahadinni, Redstone, and Keele rivers. It may also be the case, however, that cutbank erosion and major slope failures along the valley sides of this reach are supplementing the bed-material supply. Other factors related to the morphological change could include an increase in valley slope (which begins at about the Dahadinni confluence) and changes in the composition (and thus resistance to erosion) of the valley sides. The addition of tributary streamflow probably has an insignificant effect upon Mackenzie River because its discharge is so much larger than that of the eight tributaries.

The planning and design of development projects along the lower reaches of the major tributaries should consider carefully that these rivers can experience major channel change, high backwater conditions, extreme discharges, and severe ice jamming.

Detailed information on the study reaches of the individual rivers is contained in eight appendices.

North Nahanni River flows from the Mackenzie Mountains, and joins Mackenzie River just upstream of Camsell Bend. Along the 7 km study reach, the river occupies a wide stream-cut valley incised 10 to 30 m into the Great Slave Plain. The 400 to 1300 m wide active channel zone is divided by numerous islands and bars, forming a braided planform. Significant channel change occurred along the river between 1948 and 1977. A low-angled alluvial fan extends from the mouth of North Nahanni Valley into and across Mackenzie River valley and confines the Mackenzie River channel against the eastern valley side. The Mackenzie River channel is constricted by this fan adjacent to the tributary mouth.

Root River originates within the Mackenzie Mountains and flows generally eastward eventually merging with Mackenzie River just downstream of Camsell Bend. In the study reach, the river occupies a stream-cut valley incised 40 to 50 m into the Great Slave Plain. There are two levels of alluvial terraces between the contemporary floodplain and the Great Slave Plain. Along the 8 km study reach, the river has an irregular meandering planform. The river exhibits a flashy discharge regime; mean monthly discharge ranges between 9 and 235 $m^3 \cdot s^{-1}$; the historical maximum instantaneous discharge is 7400 $m^3 \cdot s^{-1}$. Channel scars on the floodplain indicate that the river meanders are migrating progressively outwards and downstream, but little measurable migration was detected from a comparison of aerial photographs taken in 1947 and 1977. The lower part of the study reach is subject to backwater from Mackenzie River even when both rivers are at moderate discharge levels. A large channel junction bar formed at the Root River mouth projects into and downstream along Mackenzie River, causing confinement and narrowing of the Mackenzie River channel.

Willowlake River drains an area east of Mackenzie River; its headwaters are situated on the Great Slave Plain. Along the 4.4 km study reach, the river flows within a 700 to 1300 m wide valley that was once a meltwater channel.

confluences de la rivière Willowlake et de la Grande rivière Bear pourrait être dû à la déflexion hydraulique du fleuve Mackenzie par l'écoulement oblique provenant d'un tributaire.

La morphologie du chenal du fleuve Mackenzie se modifie en aval entre Fort Simpson et Norman Wells. Il semble de toute évidence que cette modification est attribuable à la formation d'îles et de bancs qui divisent le fleuve en un nombre de bras sinueux débutant aux confluences des rivières Blackwater et Dahadinni jusqu'à environ 125 km vers l'aval (jusqu'à environ 55 km en aval de la rivière Keele). Même si l'on ne peut attribuer à un seul tributaire ce changement, ces îles et ces bancs semblent représenter des formes d'accumulation temporaires de matériaux de lit dans le fleuve Mackenzie qui proviendraient des rivières Dahadinni, Redstone et Keele. Il se pourrait, cependant, que l'érosion des rives concaves et les principales ruptures de pente le long des versants de la vallée de ce tronçon alimentent les sédiments de lit. D'autres facteurs liés au changement morphologique pourraient inclure un accroissement de la pente de la vallée (qui débute à peu près à la confluence de la Dahadinni) et des changements de composition (donc de résistance à l'érosion) des versants de la vallée. Le débit des tributaires a probablement un effet négligeable sur le fleuve Mackenzie puisque le débit de ce dernier est beaucoup plus élevé que celui des huit tributaires.

Dans la planification et la conception des projets de mise en valeur le long des tronçons inférieurs des principaux tributaires, il faudrait tenir compte du fait que ces rivières peuvent subir un déplacement important de leur chenal, des conditions accentuées de remous, des débits extrêmes et des embâcles importants.

Les informations détaillées recueillies sur les tronçons à l'étude de chaque rivière sont présentées dans huit annexes.

La rivière Nahanni Nord prend sa source dans les monts Mackenzie et se jette dans le fleuve Mackenzie juste en amont de la courbe Camsell. Le long du tronçon à l'étude de 7 km, la rivière traverse une large vallée découpant d'une profondeur de 10 à 30 m la plaine du Grand lac des Esclaves. La zone active du chenal de 400 à 1 300 m de largeur est divisée par de nombreuses îles et de nombreux bancs, d'où son tracé anastomosé. Le chenal a subi un changement important entre 1948 et 1977. Un cône alluvial peu courbé s'étend de l'embouchure de la Nahanni Nord et traverse la vallée du fleuve Mackenzie; il confine le chenal du fleuve Mackenzie contre le versant est de la vallée. La largeur du chenal du fleuve Mackenzie est réduite par ce cône près de l'embouchure du tributaire.

La rivière Root prend naissance dans les monts Mackenzie et s'écoule généralement vers l'est pour atteindre le fleuve Mackenzie juste en aval de la courbe Camsell. Dans le tronçon à l'étude, la rivière traverse une vallée fluviale entaillant d'une profondeur de 40 à 50 m la plaine du Grand lac des Esclaves. Deux niveaux de terrasses alluviales s'étendent entre la plaine d'inondation contemporaine et la plaine du Grand lac des Esclaves. Le long du tronçon à l'étude de 8 km, le chenal de la rivière trace des méandres irréguliers. Le régime de la rivière se caractérise par des crues soudaines; le débit mensuel moyen varie entre 9 et 235 $m^3 \cdot s^{-1}$; le débit instantané historique maximal est de 7 400 $m^3 \cdot s^{-1}$. Les cicatrices de chenal sur la plaine d'inondation indiquent que les méandres migrent progressivement vers l'extérieur et vers l'aval, mais la comparaison de photographies aériennes prises en 1947 et 1977 indique une migration faible.

Channel planform consists of regular meanders. Two large bends are present within the study reach with a large slope failure occurring along the outer bank of the upstream meander. Mean monthly discharge ranges between 4 and 335 $m^3 \cdot s^{-1}$; the maximum historical daily discharge is 1910 $m^3 \cdot s^{-1}$. No significant lateral channel change was apparent from a comparison of aerial photographs taken in 1947 and 1972. The lower part of the study reach is affected by backwater from Mackenzie River even during moderate discharge levels.

Blackwater River flows from east of Mackenzie River; the Great Slave Plain, Great Bear Plain, McConnell Range, and Mackenzie Lowland all form parts of the contributing watershed. In the 4 km study reach, the river has a gravel bed and flows within a 900 to 1200 m wide stream-cut valley that is incised 80 to 90 m into the Mackenzie Lowland. It is a relatively straight and swift flowing stream. As recorded at the mouth of Blackwater Lake, mean monthly discharge ranges between 3 and 181 $m^3 \cdot s^{-1}$; the maximum historical daily discharge is 573 $m^3 \cdot s^{-1}$; the discharge regime is attenuated by Blackwater Lake. No significant lateral channel change was apparent from a comparison of aerial photographs taken in 1945 and 1987. A large channel junction bar extends into and downstream along Mackenzie River from the tributary mouth. This bar appears to be a moribund feature, but causes some constriction of the Mackenzie River channel.

Dahadinni River originates within from the Mackenzie Mountains, west of Mackenzie River. The 6 km long study reach occupies a stream-cut valley up to 2000 m wide that is incised 90 m into the Mackenzie Lowland. The river has a gravel bed and a braided planform. The active channel zone is up to 450 m wide. Between 1945 and 1981, up to 9.5 $m \cdot a^{-1}$ of bank erosion occurred along eight zones in the study reach, each zone corresponding roughly to the outer banks of meanders along the major channels. A low-angled alluvial fan extends from the mouth of Dahadinni Valley into and across Mackenzie River valley. This confines the Mackenzie River channel against the eastern valley side, causing the deflection of the valley side and a slight constriction of the channel.

Redstone River originates within the Mackenzie Mountains to the west of Mackenzie River. In the study reach, the river occupies a stream-cut valley incised 50 to 75 m into the Mackenzie Lowland; two terrace surfaces exist between the contemporary floodplain and the lowland surface. Throughout the 6.5 km study reach, the river has a gravel bed with a braided planform. The active channel zone ranges from 300 to 1250 m wide. Mean monthly discharge ranges between 18 and 495 $m^3 \cdot s^{-1}$; the maximum historical daily discharge is 3750 $m^3 \cdot s^{-1}$. Between 1949 and 1981, the boundaries of the active channel zone experienced up to about 11 $m \cdot a^{-1}$ of lateral migration. More extensive erosion occurred along the north side of the active channel zone than the south side. Extending from the mouth of Redstone Valley, a low-angled alluvial fan is splayed across Mackenzie River

La partie inférieure du tronçon à l'étude est le lieu d'un refoulement d'eau en provenance du fleuve Mackenzie même lorsque le débit des deux cours d'eau est modéré. Un vaste banc de jonction de chenaux formé à l'embouchure de la rivière Root pénètre dans le fleuve Mackenzie vers l'aval, causant un confinement et un rétrécissement du chenal du fleuve Mackenzie.

La rivière Willowlake draine une région à l'est du fleuve Mackenzie; sa source est située sur la plaine du Grand lac des Esclaves. Le long du tronçon à l'étude de 4,4 km, la rivière traverse une vallée de 700 à 1 300 m de largeur qui a déjà été un chenal fluvioglaciaire. Le chenal forme des méandres réguliers. Dans le tronçon à l'étude, on observe deux grands coudes marqués par une vaste rupture de pente le long de la rive extérieure du méandre le plus en amont. Le débit mensuel moyen varie entre 4 et 335 $m^3 \cdot s^{-1}$; le débit journalier historique maximal est de 1 910 $m^3 \cdot s^{-1}$. On n'observe aucun déplacement latéral important du chenal entre les photographies aériennes prises en 1947 et en 1972. La partie inférieure du tronçon à l'étude ne présente aucun refoulement d'eau du fleuve Mackenzie même durant les périodes de débit modéré.

La rivière Blackwater s'écoule à l'est du fleuve Mackenzie; la plaine du Grand lac des Esclaves, la plaine du Grand lac de l'Ours, le chaînon McConnell et les basses terres du Mackenzie font tous partie de bassin-versant. Dans le tronçon à l'étude de 4 km, la rivière s'écoule sur un lit de gravier et traverse une vallée fluviale de 900 à 1 200 m de largeur qui s'encaisse d'une profondeur de 80 à 90 m dans les basses terres du Mackenzie. Elle est relativement rectiligne et son débit est rapide. À l'embouchure du lac Blackwater, le débit mensuel moyen varie entre 3 et 181 $m^3 \cdot s^{-1}$; le débit journalier maximal est de 573 $m^3 \cdot s^{-1}$. Le débit est atténué par le lac Blackwater. On n'observe aucun déplacement latéral significatif du chenal en comparant des photographies prises en 1945 et en 1987. De l'embouchure du tributaire, un vaste banc de jonction de chenaux pénètre dans le fleuve Mackenzie vers l'aval. Ce banc semble être une forme moribonde, mais il resserre quelque peu le chenal du fleuve Mackenzie.

La rivière Dahadinni prend sa source dans les monts Mackenzie, à l'ouest du fleuve. Le tronçon à l'étude de 6 m de longueur occupe une vallée fluviale de 2 000 m de largeur qui entaille de 90 m les basses terres du Mackenzie. La rivière a un lit de gravier et un tracé anastomosé. La zone active du chenal atteint 450 m de largeur. Entre 1945 et 1981, jusqu'à 9,5 $m \cdot a^{-1}$ de rive ont été érodés le long de huit zones du tronçon à l'étude, chaque zone correspondant à peu près aux rives extérieures des méandres le long des chenaux principaux. Un cône alluvial peu courbé s'étend de l'embouchure de la vallée de la Dahadinni vers la rive opposée du fleuve Mackenzie. Il confine le chenal du fleuve Mackenzie contre le versant est de la vallée, causant la déflexion du versant de la vallée et un léger resserrement du chenal.

La rivière Redstone prend naissance dans les monts Mackenzie àl'ouest du fleuve Mackenzie. Dans le tronçon à l'étude, la rivière traverse une vallée fluviale creusant d'une profondeur de 50 à 75 m les basses terres du Mackenzie; deux terrasses s'étendent entre le plaine d'inondation contemporaine et les basses terres. Tout au long du tronçon à l'étude de 6,5 km, le lit de la rivière est en gravier et son tracé anastomosé. La zone active du chenal varie de 300 à 1 250 m de largeur. Le débit mensuel moyen

valley. The fan confines the Mackenzie River channel against the eastern valley side, causing the deflection of the valley side and constriction of the channel.

Keele River has its headwaters deep within the Mackenzie Mountains to the west of Mackenzie River. Along the 7.5 km study reach, the river is incised about 60 m into the Mackenzie Lowland; three alluvial terraces are present between the contemporary floodplain and the lowland surface. The river has a gravel bed and a braided planform that is dominated by a sinuous major channel. Between 1949 and 1981, up to 6.3 m·a^{-1} of erosion occurred along the outer banks of meanders formed by the major channel. A low-angled alluvial fan splays from the mouth of Keele Valley into and across Mackenzie River valley which confines the Mackenzie River channel against the eastern valley side.

Great Bear River drains Great Bear Lake and flows westerly into Mackenzie River. Along the 5.5 km study reach, the river has a gravel bed and is relatively straight. It occupies a stream-cut valley incised 40 to 55 m into the Mackenzie Lowland. The river has a very attenuated discharge regime because of water storage within Great Bear Lake; the historical minimum and maximum daily discharges are 367 and 852 m^{3}·s^{-1}, respectively. Between 1944/1945 and 1983, the river experienced no significant lateral channel change.

fluctue entre 18 et 495 m^{3}·s^{-1}; le débit journalier historique maximal est de 3 750 m^{3}·s^{-1}. Entre 1949 et 1981, les limites de la zone active du chenal ont subi une migration latérale atteignant 11 m·a^{-1} environ. L'érosion a été plus forte le long du côté nord de la zone active du chenal que le long du côté sud. S'allongeant de l'embouchure de la rivière Redstone, un cône alluvial peu courbé s'évase à travers la vallée du fleuve Mackenzie. Le cône confine le chenal du fleuve Mackenzie contre le versant est de la vallée, causant la déflexion du versant de la vallée et le resserrement du chenal.

Les eaux de la rivière Keele prennent leur source très loin dans les monts Mackenzie à l'ouest du fleuve Mackenzie. Le long du tronçon à l'étude de 7,5 km, la rivière découpe d'environ 60 m les basses terres du Mackenzie; trois terrasses alluviales s'étagent entre la plaine d'inondation contemporaine et la surface des basses terres. Le lit de la rivière est graveleux et son cours anastomosé est dominé par un chenal principal sinueux. Entre 1949 et 1981, jusqu'à 6,3 m·a^{-1} ont été érodés le long des rives extérieures des méandres formés par le chenal principal. Un cône alluvial peu courbé s'étend de l'embouchure de la Keele vers la rive opposée du fleuve Mackenzie confinant le chenal du fleuve contre le versant est de la vallée.

La Grande rivière Bear draine le Grand lac de l'Ours et se jette vers l'ouest dans le fleuve Mackenzie. Le long du tronçon à l'étude de 5,5 m, le lit est graveleux et relativement rectiligne. Le chenal traverse une vallée fluviale s'encaissant d'une profondeur de 40 à 55 m dans les basses terres du Mackenzie. Le débit de la rivière est très atténué par le stockage du Grand lac de l'Ours; les débits journaliers minimal et maximal historiques s'élèvent respectivement à 367 et 852 m^{3}·s^{-1}. Entre 1944-1945 et 1983, la rivière n'a subi aucun déplacement latéral significatif.

INTRODUCTION

Along any river system, major tributary confluences are points where discharge and sediment are added to the trunk stream. Changes to the discharge regime or sediment supply regime of a tributary resulting from, for example, climatic change or human activities, may cause significant modifications to the regime of the trunk stream. An adjustment to the river morphology may occur in response to this change in regime (see Schumm, 1969). Any such impacts upon the trunk stream arising from changes to tributary regime(s) should be apparent initially at the tributary confluences. The lower reaches of tributaries and their confluences with a trunk stream are, thus, important sites within a watershed and are obvious locations from which to monitor future river change.

Along its course from Great Slave Lake to Mackenzie Delta, a number of major tributaries join Mackenzie River. Each, in itself, represents a large river system, but these appear small relative to Mackenzie River and its enormous drainage basin. Very little published fluvial geomorphic information is available on these major tributaries, particularly the rivers draining the Mackenzie Mountains to the west of Mackenzie River.

This report contains basic fluvial geomorphic information collected along the lowest 4 to 8 km of eight major tributaries joining Mackenzie River between Fort Simpson and Norman Wells, Northwest Territories. The rivers are the North Nahanni, Root, Willowlake, Blackwater, Dahadinni, Redstone, Keele, and Great Bear (Fig. 1 and Table 1). The report provides information about the river valley, hydrology, channel characteristics and behaviour along the study reaches of each tributary, and interaction between the tributary and Mackenzie River. The information is presented as a general overview of the eight tributaries with site specific data on the study reaches in separate appendices. The report also includes reviews of the relevant fluvial geomorphic literature and the late Quaternary history as it applies to Mackenzie River and its major tributaries. The content of the report is intended to assist both future research and development projects undertaken at and near the tributary mouths.

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BACKGROUND

Previous fluvial geomorphic work in the Fort Simpson to Norman Wells section of Mackenzie River

Early literature

Mackenzie (1801) provided the first published account of Mackenzie River. Although written with the bias of a fur trader rather than a scientist, he commented upon the river banks, the entrance of major tributaries, and the river current during a 1789 two-way trip from Great Slave Lake to the Mackenzie Delta. The most identifiable references are made to "Great-Bear-Lake-River" (Great Bear River) and The Ramparts.

A number of observations along Mackenzie River are contained in Franklin (1828) including several excellent maps. In an appendix to Franklin (1828), John Richardson described in considerable detail the bedrock geology along Mackenzie and Great Bear rivers and included brief mention of some river characteristics (banks, channel width, and location of rapids). In his own report (Richardson, 1851), he described many recognizable tributaries and features along Mackenzie River, mentioning some by their present names (e.g. Willowlake River, Blackwater River, and The Ramparts). Interestingly, this report mentions separate floods at Fort Simpson and (the original location of) Fort Good Hope that were caused by ice jams.

Father Emile Petitot was a widely travelled missionary stationed in Fort Good Hope who made numerous exploration trips in Mackenzie Valley from Great Bear Lake to the Arctic coast (see Mackay, 1963a). His experiences are described in a series of reports published between 1875 and 1893 (Petitot, 1875a, b, 1887, 1889, 1891, 1893). Contained in the 1891 and 1893 reports are interesting, although somewhat inaccurate, maps showing numerous mountains, lakes, and rivers in the District of Mackenzie. The maps are based upon his travels and the descriptions of the Dene and Inuit (Mackay, 1963a).

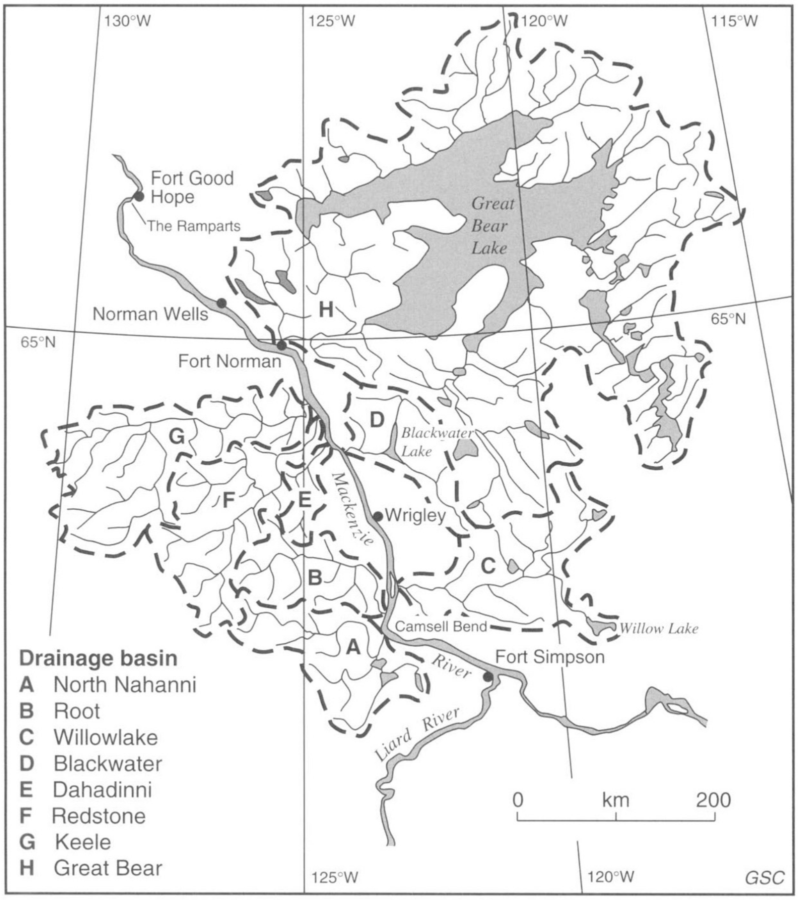

Figure 1.

The upper Mackenzie River showing the major tributaries, settlements, and lakes discussed in the report.

Table 1. Major tributaries along Mackenzie River between Fort Simpson and Norman Wells, Northwest Territories – general information.

River	Downstream position of confluence along Mackenzie River[a] (km)	Length (km)	Drainage basin area (km)	Location of drainage in Mackenzie Valley
North Nahanni	457	270[b]	13 300[c]	west side
Root	480	240[b]	9 820[d]	west side
Willowlake	510	400[b]	21 000[b]	east side
Blackwater	665	210[c]	10 500[e]	east side
Dahadinni	677	125[c]	2 700[b]	west side
Redstone	716	310[b]	16 400[d]	west side
Keele	736	420[b]	26 800[b]	west side
Great Bear	828	115[f]	158 000[g]	east side

[a] River distances as shown on hydrographic charts, beginning from the outlet of Great Slave Lake (Department of Fisheries and Oceans, 1989).

[b] Thakur and Lindeijer (1973).

[c] Estimated.

[d] Water Survey of Canada (1992a).

[e] Bolter, Parish and Trimble Ltd. (1973).

[f] Savigny (1989).

[g] Hardy Associates (1978) Ltd. (1982a).

Ogilvie (1890) contains isolated measurements of the river width, numerous observations of the river banks, and discussion of the names of some major tributaries, all made during an 1887 exploratory survey along Mackenzie River from Fort MacPherson to Great Slave Lake. The report also described an 1844 flood affecting Fort Norman (then situated near Old Fort Point) that was attributed to the failure of a landslide dam along the 'south branch' of the Liard River. In a separate report, Ogilvie (1893) referred to river soundings and stream boat travel times (which reflects the strength of the river current) obtained from boat captains.

Work in Mackenzie Valley by the Geological Survey of Canada began in the late 1880s, initiating a long presence in the region that continues into the 1990s. The early researchers conducted reconnaissance studies along Mackenzie River and noted the confluences of the major tributaries (McConnell, 1891; Bell, 1902, 1903). Particularly interesting is an account by McConnell (1891) of the 1887 spring break-up at Fort Simpson. More detailed descriptions of the major tributaries were made in the 1910s and 1920s as the individual watersheds were explored, although the research emphasis was upon the bedrock geology (e.g., Keele, 1910; Camsell and Malcolm, 1921; Hume, 1922, 1924; Whittaker, 1922, 1923; Williams, 1922, 1923; Kidd, 1932). Of particular note, however, are the observations of Kindle (1918), on ice-push features along the river banks and on the lack of mixing of the Mackenzie and Liard river waters over the first 260 km below their confluence, and Kindle (1920), upon the freezing-up and break-up of Mackenzie River. Into the 1940s, geological research was undertaken in support of oil exploration activities. Some of the reports contain brief references to the tributary river systems (much of this work is unpublished, but summarized by Hume and Link (1945) and Hume (1954)). The major river systems were described briefly by Bostock (1948) within a regional physiographic summary of the northern Cordilleran.

Recent literature

The annual freeze-up and break-up is an important geomorphic process along Mackenzie River and was the subject of late 1950s and early 1960s fluvial geomorphic research. Brown (1957) made observations of the break-up along the river and at the delta while Mackay (1961a, b, 1963a, b, 1967) produced a series of reports that examined the timing, prediction, and possible climatic controls upon river ice freeze-up and break-up. Mackay (1966, 1970) also investigated the mixing of the Liard and Mackenzie river waters and found that there is relatively little mixing for the first 161 to 241 km below their confluence. Rapid mixing then occurs as the river narrows and increases in speed; the waters, however, can still be differentiated chemically as far as 480 km below the confluence.

In the early 1970s, proposals for the construction of highways, pipelines, a railway, and hydroelectric dams provided an impetus for considerable fluvial geomorphic research in Mackenzie Valley. Very limited literature exists for the railway (see Office of Engineer of Location and Construction, 1971) and damming projects (see Crippen G.E. and Associates, 1972; Owen, 1973) as these never proceeded beyond the preliminary planning stages. In contrast, a large number of reports were prepared for the pipeline and highway proposals, although it was not until the 1980s that one of these projects was constructed (the Norman Wells pipeline built by Interprovincial Pipe Line Ltd., which extends from Norman Wells, Northwest Territories, to Zama, Alberta), while the winter road between Fort Simpson and Wrigley finally was converted to an all-season road with work completed in 1994. These reports were completed primarily during the 1970s and early 1980s by consultants and government agencies, but generally are unpublished and often difficult to obtain. Because of this problem, any review of the post-1970 fluvial geomorphic research likely is incomplete. Of note, the vast majority of the reports cited in this paper can be found in the Departmental Library, Indian and Northern Affairs, Hull, Quebec.

From the fluvial geomorphic perspective, much of the pipeline and highway literature focuses upon stream crossings. A general framework for the type of information required for the proposed pipeline and highway projects was outlined by Neill (1973), which, because of the general lack of previous geomorphic work in the region, more or less necessitated starting from scratch. This work was biased strongly towards river systems draining east of Mackenzie River because it was recognized that these rivers represented much less imposing stream crossings than the larger rivers draining from the west (J.A. Heginbottom, pers. comm., April 5, 1993). Consequently, there is a paucity of data for the major river systems located to the west side of Mackenzie River.

A large number of engineering reports on bridge design exists for the Mackenzie Valley highway originally proposed in the early 1970s. Most documents are site specific and contain only minor details about a stream, but a map of the reach immediately proximal to the proposed bridge site is often included along with channel cross-sections that show estimated high water and/or backwater levels. Such reports exist for Big Smith Creek (Slaney, F.F. and Company Ltd., 1973a), Blackwater River (Slaney, F.F. and Company Ltd., 1973b; Canada North Engineering, 1974), Canyon Creek (AESL Consulting Engineers, 1974), Hodgson Creek (Slaney, F.F. and Company Ltd., 1973c), Little Smith Creek (Slaney, F.F. and Company Ltd., 1973d), Martin River (Slaney, F.F. and Company Ltd., 1973e; Public Works Canada, 1977), Ochre River (Slaney, F.F. and Company Ltd., 1973f; Reid, Crowther, Partners Ltd., 1973), River Between Two Mountains (Slaney, F.F. and Company Ltd., 1973g; Public Works Canada, 1975), Saline River (Slaney, F.F. and Company Ltd., 1973h), Shale Creek (Slaney, F.F. and Company Ltd., 1973i) Steep Creek (Slaney, F.F. and Company Ltd., 1973j; Stanley Associates Engineering Ltd., 1973), Whitesand Creek (Slaney, F.F. and Company Ltd., 1973k), and Willowlake River (Lamb, T., McManus and Associates Ltd., 1972a; Lamb, T., McManus and Associates Ltd., 1972b; Slaney, F.F. and Company Ltd., 1973; Cook, 1976; Acres Consulting Services Limited, undated). Common to many of these reports is reference to Bolter, Parish and Trimble Ltd. (1973) who used empirical and slope-area methods to estimate the extreme discharge of every major stream along the highway route between Fort Norman and Fort Simpson (all of the aforementioned streams), most of which were, and still are, ungauged. A similar report exists for streams north of Fort Norman (see Public Works Canada, 1976). This 1970s literature undoubtedly has provided a background for more recent studies undertaken for the construction project (completed in 1994) that converted the Fort Simpson-Wrigley winter road to an all-season road.

For pipeline design, Church (1971) presented a general overview of the fluvial characteristics of the major tributaries of Mackenzie River. Although limited with regard to the information on specific streams, the report is a good review of northern river hydrology and provides a guide for estimating maximum discharges at the various river mouths, even when influenced by backwater conditions from Mackenzie River. Specific details of the stream crossing designs used on the Norman Wells pipeline constructed in the 1980s are contained in UMA-Canuck-Hardy (1983a, b) which show channel and valley cross-sections, water levels, and thalweg profiles. The general approach to the fluvial geomorphic data collection for the pipeline crossings is summarized in Hardy Associates (1978) Ltd. (1982a).

In the early- to mid-1970s, under the auspices of the Environmental Social Program for Northern Pipelines and the Mackenzie Highway Environmental Working Group, studies were initiated in the Mackenzie Valley by a number of government agencies and university researchers to provide an 'objective' database, which would be used for environmental assessment of various highway or pipeline proposals. This work also addressed obvious information gaps in the earlier engineering work. Some of this research has continued into the 1990s although funded by different agencies and occurring at much reduced intensity. The fluvial geomorphic work can be grouped into three general categories: channel process, stream hydrology, and spring break-up.

Overall, channel process studies have been undertaken at only a limited number of sites along Mackenzie Valley. Studies done at Little Smith Creek, River Between Two Mountains, Saline River, and Steep Creek included work on channel migration, vertical stability, and backwater flooding (Day and Egginton, 1976; Egginton, 1976, 1977, 1978, 1980; Egginton and Day, 1976, 1977). A general qualitative assessment of the lateral channel stability along Blackwater River, Hodgson Creek, Little Smith Creek, Martin River, Ochre River, Rainbow Creek, River Between Two Mountains, Saline Creek, Shale Creek, Steep Creek, Whitesand Creek, and Willowlake River is contained in Egginton (1977). In addition, there are reports which assessed fisheries and aquatic habitats along Mackenzie River; these included general descriptions of many stream channels, but also some data on suspended sediment concentrations and water chemistry (Brunskill et al., 1973a, b; Dryden et al., 1973).

Stream flow data is acquired by the Water Survey of Canada (1992a, b) who routinely measure discharge and suspended sediment concentrations, but records exist for only a limited number of streams in the Mackenzie Valley. Most of these records are of relatively short duration and cover varying periods of time (Table 1). The deficiency in streamflow data was addressed to some extent in the 1970s by establishing temporary monitoring sites at a number of small- and medium-sized watersheds (see Egginton and Day, 1976; Jasper, 1976; Egginton, 1977, 1978; Jasper and Anderson, 1977), and also by deriving empirical discharge-drainage area relationships and applying these to the unmonitored watersheds (e.g., Thakur and Lindeijer, 1973, 1974). Of note, suspended sediment data (Water Survey of Canada, 1992b) is still very sparse and is inadequate for the construction of sediment rating curves, particularly for the larger, west side river systems (see also Carson, M.A. and Associates, 1992). In a study testing the feasibility of a methodology, Church et al. (1986) used maps and aerial photographs to calculate the downstream transfer of bed-material sediment over an 85 km reach of Mackenzie River located adjacent to Norman Wells.

Case studies by MacKay et al. (1973) and later by Jasper and Kerr (1992) have shown that the tributary watersheds, particularly those to the west of Mackenzie River, are subject to major flooding and channel change events triggered by periodic severe storms. MacInnes et al. (1990) document erosion problems at several stream crossings along the Norman Wells pipeline that were caused by one of these storms.

Completely unrelated to any highway and pipeline projects, reports by Beardmore et al. (1972a, b) contain descriptions of Keele and Redstone rivers, respectively, written from the perspective of the canoeist.

Research on the spring break-up has addressed a variety of topics. For pipeline and bridge design, it is well recognized that the lower reaches of the tributaries are regularly subjected to backwater flooding by Mackenzie River arising from both high flows and ice jams within the trunk stream (see Day and Egginton, 1976; Egginton and Day, 1977). MacKay and Mackay (1973a) examined the incidence of ice jamming along the Mackenzie River, finding that for any given location it varies from frequent to rare. Specific factors controlling the location of jamming relate to local channel characteristics and include decreasing channel gradient, channel shoaling, variation in channel width, channel splitting by islands or bars, and sharp bends (MacKay and Mackay, 1973a; Prowse, 1984). A number of researchers have attempted to reconstruct ice jamming frequency using dendrochronology (Henoch, 1973; Parker and Josza, 1973; Egginton and Day, 1976, 1977; Egginton, 1977, 1978, 1980; Hardy Associates (1978) Ltd., 1979). Satellite imagery has been used to monitor the break-up (Dey et al., 1977). Ice movement and jamming is reflected in the morphology of the river banks; Mackay and MacKay (1977) described a number of 'ice-push' features along Mackenzie River.

While the intensity of research decreased significantly in the 1980s, river ice break-up has continued to be a major focus of continuing interest. Kamphuis and Moir (1983) provided a detailed account of the break-up and found that it begins generally in the shallower reaches of the river from where ice is transported downstream. This flowing ice can become lodged behind intact ice to form ice jams. Brooks (1993) reported that shearing of the river bank by jammed ice can produce a distinctive scoured bank morphology.

In the 1960s and 1970s it was recognized that, in most years, Mackenzie River below Fort Simpson breaks up before the section of river upstream (Mackay, 1963b; MacKay et al., 1974; MacKay and Mackay, 1973a, b). This phenomena is triggered by a rise in stage of, and the influx of the warmer waters from, Liard River whose confluence is located at Fort Simpson. Break-up at the Liard confluence has been monitored through the 1980s with detailed accounts available for some years (Mackenzie River Basin Committee, 1981; Anderson, 1982; Prowse, 1984, 1986a, b, 1989).

The downstream effects upon Mackenzie River and Mackenzie Delta of large scale hydroelectric developments proposed for the Liard River system were assessed by Hardy Associates (1978) Ltd. (1982b). Significant effects that they identified are a reduced Liard freshet, delay in the spring break-up of Mackenzie River, reduction in size of the Liard River channel and an increase to the daily fluctuation of Liard River discharge.

Beginning in 1967, streamflow of Mackenzie River has been partially regulated by the W.A.C. Bennett Dam along the Peace River in northeastern British Columbia. The effects of this dam upon the monthly streamflow pattern of Mackenzie River at Arctic Red River has been examined by Wiens (1991).

Kriwoken (1983) reconstructed flood events at selected communities along Mackenzie River for community planning purposes. This record extends from the nineteenth century and reveals that most floods are associated with severe backwater conditions generated by major ice jams that formed during the spring break-up.

Late Quaternary geological history of the Mackenzie Valley

General

The Mackenzie Valley was completely overridden by the Laurentide ice sheet during the late Wisconsinan Glaciation (Dyke and Prest, 1987; Hughes, 1987; Vincent, 1989, Fig. 2.7). Regional ice movement generally was towards the northwest flowing roughly parallel to Mackenzie River (see Dyke and Prest, 1987; Hughes, 1987). This prevailing direction of ice movement resulted from the deflection by the Mackenzie Mountains of a westerly flowing ice lobe that originated within the Great Slave Lake area (Craig and Fyles, 1960; Craig, 1965).

During deglaciation, the ice front retreated toward the southeast with the Mackenzie Valley becoming ice-free between 13 000-11 000 BP (Vincent, 1989, Fig. 2.12). The ice retreat was variable in character (thinning, gradual withdrawal, stranded ice masses) and partially controlled by topography (Rutter and Boydell, 1973). In the area to the west of the section of Mackenzie River between The Ramparts and Norman Wells, a series of meltwater channels draining toward the northwest were formed between the front of the retreating Laurentide ice sheet and the margin of the Mackenzie Mountains. Glacial lakes were created where drainage was impeded (Mackay and Mathews, 1973; Hughes and Duk-Rodkin, 1987; Duk-Rodkin and Hughes, 1991, 1993).

Deglaciation

Following deglaciation of the Fort Good Hope area, base level of Mackenzie River valley to the south was controlled by limestone bedrock at The Ramparts. This, combined with downwarping of the land surface by isostatic depression, caused a lake to form in the low-lying areas of the Mackenzie Lowland and Great Slave Plain as they became ice-free (Mackay and Mathews, 1973; Smith, 1992). Named glacial Lake Mackenzie by Smith (1992), the lake was long (800 km) and narrow (5 to 75 km) and once extended from The Ramparts to Fort Simpson. This reconstruction is based upon the general distribution of raised deltaic, fluvial, and lacustrine deposits correlated to the water body, strandlines marking former shoreline(s), and the topography of Mackenzie Valley (see Smith, 1992, Fig. 9). Radiocarbon dating indicates that glacial Lake Mackenzie existed between 11 760 and 10 290 BP (Smith, 1992), and was, therefore, a contemporary of glacial Lake McConnell (see Craig, 1965). Inconsistencies in shoreline dating along the Mackenzie Lowland suggest that the highest shoreline may be diachronous, reflecting differential uplift of the basin (Smith, 1992). Glacial Lake Mackenzie terminated by a combination of isostatic uplift and infilling of the lake basin, and fluvial incision of bedrock at The Ramparts (Mackay and Mathews, 1973; Smith, 1992). Several abandoned channels, including the 25 km long 'Fossil Lake spillway' containing a 'dry falls', are present in the immediate area of The Ramparts and relate to fluvial incision at the lake outlet (see Mackay and Mathews, 1973).

Postglacial

With the demise of glacial Lake Mackenzie after 11 760 to 10 290 BP, fluvial processes became established upon the former lake bed. Continued incision at The Ramparts and general isostatic uplift of the region initiated fluvial downcutting into glaciolacustrine lake deposits and older Quaternary deposits, and in places, Tertiary and older bedrock.

Little is known of the timing of postglacial incision by Mackenzie River and its tributaries. Utilizing radiocarbon dates that are reported in the literature, a limited reconstruction can be attempted. At the lower end of the 'Fossil Lake spillway' near Fort Good Hope immediately downstream of The Ramparts, Mackenzie River attained its present level prior to 2800 BP as indicated by a stump aged 2810 ± 100 BP (I-3912; Mackay and Mathews, 1973) contained within contemporary floodplain deposits. A radiocarbon date from the lower end of Great Bear River near its confluence suggests that Mackenzie River was within 10 m of its present vertical position before 2700 BP (2670 ± 130 BP; GSC 2488; Savigny, 1989).

At 9900 BP, catastrophic flood waters originating from glacial Lake Agassiz passed via the Clearwater and Athabasca valleys into glacial Lake McConnell, then down Mackenzie River valley, eventually reaching the Arctic Ocean (Smith and Fisher, 1992). From the morphology of the Clearwater and Athabasca spillways and the change in water level of glacial Lake Agassiz, the flood discharge is estimated to have lasted for 78 days, peaking at 2.4 x 10^6 $m^3 \cdot s^{-1}$ (Smith and Fisher, 1992). The resulting discharge down Mackenzie River valley is unknown, but probably is significantly less than 2.4 x 10^6 $m^3 \cdot s^{-1}$, because of the dampening effects of water storage within glacial Lake McConnell. Although occurring after the demise of glacial Lake Mackenzie, no geomorphic evidence attributable to the passage of this flood down Mackenzie River valley has yet been discovered (D.G. Smith, pers. comm., June, 1992).

Incision by Mackenzie River into the late Quaternary deposits within the Mackenzie Lowland and Great Slave Plain has formed a valley up to 90 m deep. The valley sides confine the river to a relatively narrow corridor. The Quaternary sediments along the valley sides are prone to a variety of slope failures (see, for example, Chyurlia, 1973; Code, 1973; McRoberts and Morgenstern, 1973; Aylsworth, 1992; Aylsworth et al., 1992; Duk-Rodkin, 1993). Some islands along the river have been mapped as glacial or alluvial terraces (see Rutter et al., 1972; Hanley and Hughes, 1973; Rutter and Boydell, 1972) suggesting that they are remnants of the valley fill or alluvium, as opposed to being stabilized river bars.

OVERVIEW

The information compiled in this report generally follows Kellerhals et al. (1976), but also includes information on the tributary confluences. Data collection is based upon aerial photograph analysis and fieldwork conducted in July-August 1992 along seven of the eight major tributaries; time constraints did not permit fieldwork along North Nahanni River. Specific descriptions of the individual major tributaries follow a systematic format (using the headings listed below) and are contained in eight appendices.

This overview is intended to provide general information about the eight study reaches; specific information about the individual study reaches is contained in the appendices. The overview uses the headings contained in the individual tributary descriptions. Under each heading, there is a summary of the general tributary characteristics, the methodologies used in the data collection, some review of general fluvial geomorphic processes, and discussion of terminology.

Study reach descriptions

The study reaches extend along the lowest 4 to 8 km of the North Nahanni, Root, Willowlake, Blackwater, Dahadinni, Redstone, Keele, and Great Bear rivers. The study reach length quoted in the descriptions was measured with respect to the valley axis. Since the placement of a valley axis is somewhat arbitrary, it is shown on the general map of each study reach.

The physiographic terminology follows Mathews (1986) which is an update of Bostock (1948; see Fig. 2). One term that is not defined, however, is Mackenzie Valley. In this report, 'Mackenzie Valley' is used in a regional context as is consistent with its common usage in the literature. In the regional context, however, it should be noted that Mackenzie Valley is only a 'valley' where it lies between the Mackenzie and Franklin mountains, but the physiographic term Mackenzie Lowland has been applied to this corridor (see Mathews, 1986). To the north and south of the Mackenzie Lowland, Mackenzie River flows across the Great Slave and Peel plains, but there are no mountains or hills east of the river to define a valley. Concerning Mackenzie River directly, the corridor incised into the Great Slave Plain (Fort Simpson to Camsell Bend) or Mackenzie Lowland (Camsell Bend to Norman Wells) that is occupied by the river is referred to as 'Mackenzie River valley'. The meanings of Mackenzie Valley and Mackenzie River valley, thus, are not synonymous.

The lower reaches of the major tributaries are incised into Quaternary deposits of the Mackenzie Lowland and Great Slave Plain. The valley sides generally are composed of Quaternary sediments, although Tertiary bedrock is exposed along Great Bear River and Cretaceous bedrock may be present along the upper part of the Redstone River study reach. The valley sides were not examined in detail, thus the reporting of the presence of bedrock along a study reach relies primarily upon published sources.

Postglacial incision into the Mackenzie Lowland and Great Slave Plain began after the demise of glacial Lake Mackenzie (see section above on Deglaciation in Late Quaternary geological history of the Mackenzie Valley). Multiple terraces are present along Great Bear, Keele, Redstone, Blackwater, Willowlake, and Root study reaches, but analysis of the terrace deposits is required to establish that they actually have an erosive origin. In particular, a prominent terrace occurring 5 to 10 m above the water surfaces of Keele, Redstone, and Blackwater rivers may represent either a period of vertical stability or of major aggradation. The coring of wetlands or small lakes situated upon the terraces may provide dateable organic materials relevant to the terrace abandonment, and thus provide information on the postglacial incision of the major tributaries. Such data would also be relevant to Mackenzie River since the trunk river controls the base level of the tributaries.

Most of the areas proximal to the study reaches are covered with boreal forest and wetlands, and are uninhabited although Fort Norman is situated at the mouth of Great Bear River (Fig. 1) and several occupied cabins are present at the mouth of Willowlake River. The east side tributaries are crossed by the Norman Wells pipeline and Fort Simpson-Fort Good Hope winter road; a bridge was completed in 1994 which spans Willowlake River and is part of an all-season road from Fort Simpson to Wrigley.

Valley characteristics

Seven of the eight tributaries appear to 'fit' the width of their valleys; only Willowlake River is obviously underfit, being mapped as a meltwater channel (Rutter et al., 1972).

All of the study reaches lie within the zone of discontinuous permafrost. Fieldwork did not address the distribution of permafrost within the study reaches. Permafrost, however, is present within the study reaches. The floodplains of Root, Willowlake, Blackwater, Dahadinni, Redstone, and Keele rivers are mapped within an intermediate subdivision of the discontinuous permafrost zone with the ice content ranging from nil to moderate (Heginbottom and Radburn, 1992; Heginbottom and Ruhland, unpub. map manuscript, 1994). The floodplain along the study reach of North Nahanni River is mapped within the sporadic subdivision of discontinuous permafrost with a nil to low ice content (Heginbottom and Ruhland, unpub. map manuscript, 1994). During fieldwork, no ground ice was observed at any fresh cutbanks nor were any thermal-erosional niches encountered (a morphology common to eroding ice-rich river banks).

The presence of permafrost is quite variable in the Mackenzie Lowland and Great Slave Plain adjacent to the study reaches. The areas immediately beside the Blackwater, Dahadinni, Redstone, Keele, and Great Bear study reaches are mapped within the intermediate and extensive subdivisions of discontinuous permafrost with ice contents ranging from nil to high (Heginbottom and Radburn, 1992). It appears that permafrost in the Mackenzie Lowland and Great Slave Plain can be more extensive and have a greater ice content than the

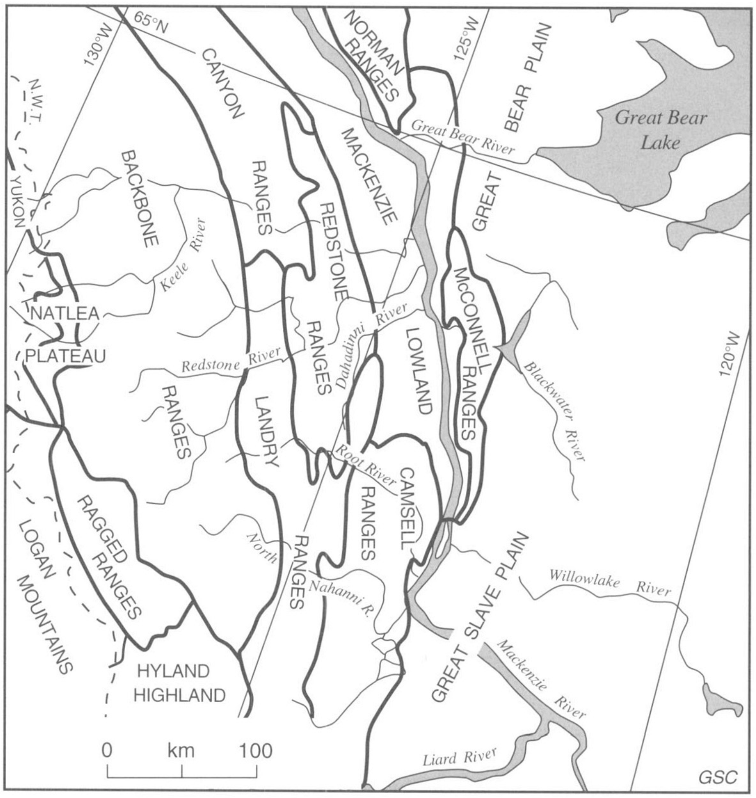

Figure 2.

Regional physiographic map of the western Northwest Territories and eastern Yukon Territory (after Mathews, 1986).

floodplains of these study reaches (except at Great Bear River which lacks a floodplain). Adjacent to Willowlake, Root, and North Nahanni rivers permafrost appears less widespread. The areas beside these streams are mapped within the intermediate and sporadic subdivisions of discontinuous permafrost with ice contents ranging from nil to high (Heginbottom and Ruhland, unpub. map manuscript, 1994).

Since the study reaches are arranged spatially north-south along the Mackenzie Valley, the presence of permafrost generally should increase northwards and, presumably, have a correspondingly greater influence upon geomorphic processes. However, there is no obvious river characteristic occurring between the study reaches that might reflect this trend. The presence of permafrost is not believed to influence significantly the fluvial processes occurring within the channel (Church, 1971), but could influence bank erosion (see Church and Miles, 1982).

Along the valley sides of the study reaches and Mackenzie River, numerous slope failures were observed both in the field and on aerial photographs which are types common to slopes containing permafrost (e.g., retrogressive and block slides/flows; also see Code, 1973). At Willowlake and Blackwater rivers, the occurrence of the valley side slope failures has been accentuated by large forest fires which occurred in 1979.

Some slope failures are situated along cutbanks where the river channel is confined directly against a valley side. The undercutting and removal of failed debris by stream erosion undoubtedly accentuates the erosion on the overlying slope. The degree of river confinement against the valley sides varies considerably between the study reaches; expressed as a proportion of the total length of valley sides, it ranges from 0% (Redstone River) to 40% (Root River).

Hydrology

Discharge

Streamflow data were obtained from records of the Water Survey of Canada (Table 2; Water Survey of Canada, 1992a; C.W. Brumwell, written comm., September 27, 1993). Streamflow records of varying duration and time period are available for Great Bear, Redstone, Blackwater, Willowlake, and Root rivers; reference is made only to those stations reasonably close to the river mouths. For watersheds lacking streamflow records, comments are made on the probable pattern of monthly discharge.

There are no dams or flood control devices along any of the eight major tributaries, thus all have a natural streamflow. With the exception of Great Bear River, mean monthly discharge in all of the gauged rivers peaks in May or July, decreases gradually through July to December, is very low through January to March, and then rises again in April to repeat the cycle (Fig. 3). The peak discharge in the spring or early summer is generated by the combination of annual snow melt and rainfall. As the snow pack wanes, discharge drops off and, through the summer, becomes more dependent upon base flow. A very low discharge occurs in winter when precipitation occurs as snow and the land surface is frozen extensively, thus minimizing base flow. All the rivers except Great Bear River exhibit the subarctic, nival regime described

Table 2. Water Survey of Canada streamflow and sediment stations located near mouths of major tributaries between Fort Simpson and Norman Wells, N.W.T.

Station name	Station number	Duration of record	Type of data	Area (km^2)
Blackwater River near the mouth	10HC005	1986	- discharge	10 400
Blackwater River at outlet of Blackwater Lake	10HC006	1983-1985	- discharge	7 850
Great Bear River at outlet of Great Bear Lake	10JC003	1961-	- discharge	145 000
Mackenzie River at Fort Simpson	10GC001	1938-	- discharge	1 270 000
Mackenzi e River at Norman Wells	10KA001	1943- 1973	- discharge - suspended sediment	1 570 000
Redstone River 63 km above the mouth	10HB005	1974- 1987-	- discharge - suspended sediment	15 400
Redstone River near the mouth	10HB001	1963-1974 1973	- discharge - suspended sediment	16 400
Root River near the mouth	10GA001	1974- 1987-	- discharge - suspended sediment	9 820
Willowlake River above Metahdali Creek	10GB006	1975-	- discharge	20 200
Willowlake River below Metahdali Creek	10GB001	1964-1974 1973-1974	- discharge - suspended sediment	20 500

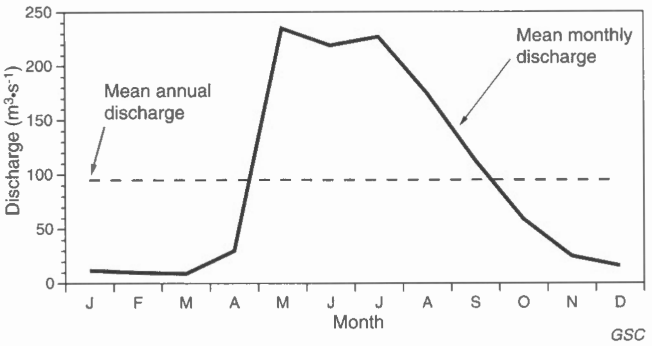

***Figure 3.** Mean monthly discharge pattern of a subarctic, nival regime. Data is for Root River (Water Survey of Canada, 1992a).*

by Church (1974). In contrast, Great Bear River experiences a very attenuated discharge regime because of water storage within Great Bear Lake which occupies a large proportion of the drainage basin and is located relatively close to the river mouth.

The tributaries to the west side of Mackenzie River are generally described as having 'flashy' discharge regimes (e.g., Jasper and Kerr, 1992) because streamflow can rise and fall rapidly in response to rain storms and diurnal snow melt. This characteristic is not apparent, however, from the average monthly discharge pattern. The east side rivers have a less responsive discharge regime because of the presence of lakes and wetlands which attenuate the passage of water through the drainage basin (Church, 1974). Also, the more subdued topography of the plains and lowlands east of Mackenzie River does not cause major orographic uplift of moist air masses as can occur in the Mackenzie Mountains and generate widespread, intense rainfall (see Jasper and Kerr, 1992).

Most of the rivers, particularly those draining the Mackenzie Mountains, periodically experience large increases in discharge, as a result of severe summer rain storms. Of the gauged rivers, both Root and Willowlake rivers experienced their historic maximum discharges in early July 1988, the result of severe rain storms that affected much of the southwestern District of Mackenzie (see Jasper and Kerr, 1992). The ungauged west side rivers also carried high discharges that were the product of this storm. Of note, however, Jasper and Kerr (1992) estimate that the discharges experienced by the Root and Willowlake rivers did not exceed the 100 year event suggesting that such discharges occur periodically and are part of the 'normal' discharge regime of these rivers. Such storms do not cause large increases in the discharge of Great Bear River, however, because of the proximity of Great Bear Lake to the river mouth (Fig. 1); the storage of water within this lake basin severely dampens the flood discharge downstream. A similar dampening effect occurs along Blackwater River because of Blackwater Lake, but to a lesser extent.

The geomorphic effects of the July 1988 discharges is still reflected by the 1992 morphology of the Keele, Redstone, Dahadinni, and North Nahanni rivers which experienced floodplain erosion, channel avulsions, and considerable modification to their braided channel networks.

Of note, Mackenzie River can be hydraulically dammed by extreme discharges originating from Root and North Nahanni rivers, producing a measurable backwater effect extending upstream as far as Fort Simpson (P. Wood, pers. comm., May 18, 1993). Presumably, similar affects can be caused by extreme discharges of the other large west side rivers, such as Keele and Redstone.

Sediment load

Little published information is available on sediment transport rates along the study reaches. A general assessment of bed-material transport can, however, be made based upon lateral channel change. Along a meandering river, it is generally recognized that bed-material transport is proportional to the amount of bank erosion and deposition (Neill, 1971) and will be reflected as lateral channel change. This premise likely can be applied to a braided stream although the pattern of erosion and deposition is more complex. In general, the relative amount of channel change is interpreted to reflect qualitatively the amount of bed-material being transported along a study reach.

Site visits and the comparison of aerial photographs reveal that lateral channel change along Great Bear, Willowlake, and Blackwater rivers (all east side rivers having single channels) has not been significant suggesting that bed-material transport is relatively low. Consistent with this, the Great Bear and Blackwater study reaches are situated relatively close to large lakes (Great Bear and Blackwater lakes) which function as sediment traps limiting the supply of sediment downstream. In contrast, Keele, Redstone, Dahadinni, and North Nahanni rivers all have braiding channel planforms which experience considerable bar, bank, and island erosion, thus suggesting relatively high bed-material transport rates. Along the Root River study reach, lateral channel change is insignificant, but active cutbanks are present along the outer banks of the meanders. The Root River bed-material transport rate appears to be relatively low, but probably is intermediate with respect to the east side and braided west side rivers. In general, bed-material transport rates along the west side rivers appear to be greater than the east side rivers.

There is a complete absence of published data concerning bed load transport. From the preceding discussion on bed-material transport, North Nahanni, Dahadinni, Redstone, and Keele rivers all likely transport a 'significant' bed load. While 'insignificant' bed load is transported by Willowlake, Blackwater, and Great Bear rivers and probably by Root River.

Water Survey of Canada suspended sediment records exist for only Redstone, Willowlake, and Root rivers (Water Survey of Canada, 1992b). These records are fragmentary and of insufficient duration for the construction of suspended sediment rating curves (see also Carson, M.A. and Associates, 1992). Because of the limited records, all discussion of suspended sediment load on the unmeasured rivers is inherently qualitative.

Suspended sediment concentrations generally vary throughout the year, being relatively high during the spring freshet then decreasing gradually through the summer to produce relatively clear waters by autumn. Based upon the existing records (Water Survey of Canada, 1992b), the range of concentrations is much greater for the west side rivers than the east side rivers as exemplified by data from Root (6-1670 mg·l^{-1}) and Redstone (21-1960 mg·l^{-1}) rivers, and Willowlake River (4-251 mg·l^{-1}), respectively. At any time of the summer or fall, higher discharges triggered by summer storms increase the water turbidity. Although unmeasured, Great Bear and Blackwater rivers probably experience very low suspended concentrations throughout the year because of sediment trapping in Great Bear and Blackwater lakes.

P. Wood (pers. comm., January 13, 1994) reported that Root River carries a suspended sediment load that is consistent with the other west side rivers. Although little lateral channel change occurs along the study reach, significant channel change occurs along meandering and braided reaches situated upstream 14 to 45 km and above 45 km from the river mouth, respectively (P. Wood, pers. comm., January 13, 1994). It may be the case that a large quantity of suspended sediment is being derived from these upstream reaches and is being transported as a wash load through the lower part of the river.

All of the tributaries produce a plume that persists downstream along Mackenzie River which is the product of contrasting turbidity between the tributary and the trunk stream. Generally, the turbidity of the east side rivers is lower than Mackenzie River, while the west side river turbidity is higher during the freshet and early summer and after major rainstorms, but lower in the late summer, autumn, and winter. A clear water plume originating from Great Bear River is reported to extend as much as 80 km downstream of its confluence (Mackay, 1966).

Channel characteristics

Between the study reaches, channel planform is variable, ranging from braided (Redstone and North Nahanni rivers), transitional braided-meandering (Keele and Dahadinni rivers; hereafter grouped with the braided streams), meandering (Willowlake and Root rivers), and straight (Great Bear and Blackwater rivers). The transitional braided-meandering rivers probably fall within the wandering gravel-bed river morphology (see Desloges and Church, 1989).

The primary planform control is believed to be sediment supply (see section above on Sediment load). The straight study reaches are situated downstream of large lakes which severely limit the sediment supply, while in contrast, the braided streams all receive a relatively high sediment supply from the Mackenzie Mountains. The sediment supply to the meandering reaches is somewhere intermediate to the braided and straight streams. Thus, the basic control upon the channel planform appears to the physiographic character of the watershed. Root River is the only stream draining the Mackenzie Mountains that is not braided, but 45 km upstream of its confluence with Mackenzie River, it exhibits a braided planform.

The major tributaries are gravel-bed streams. Sand is present in varying degrees within slackwater areas of the channel and upon the river bars while sand and silt form the overbank deposits of the floodplain. Seven of the eight study reaches are alluvial and flow within relatively wide valley bottoms at least partially composed of floodplain deposits; the exception, Great Bear River, is confined within a narrow valley incised into Tertiary bedrock.

When describing the braided rivers, it is more useful to refer to an active channel zone rather than to the channels actually carrying water at any given time. Because of the shallow cross-section of these rivers, their morphology is stage dependent and thus highly variable over the spring/summer/autumn; any observations at a specific discharge may be spurious under different flow conditions (e.g., braiding index).

The active channel zone represents the area of a valley bottom that is inundated during a 'bankfull' discharge. Its morphology is approximated by the unvegetated or sparsely vegetated areas of the valley bottom that have been inundated 'recently'. The occurrence of an extreme event will modify the morphology of the active channel zone to accommodate the excessive flow through, for example, bank erosion, island erosion, bar formation, and channel avulsions – the net result being the widening of the active channel zone. Such widening is not necessarily permanent as the active channel zone will gradually narrow and 'recover' over the succeeding years through, for example, channel abandonment, bar and island accretion, and revegetation of bars and inactive channels. The degree of active channel zone modification that occurs during an extreme event is dependent on the magnitude of the discharge, but also partially upon the amount of recovery that has happened since the last extreme event. The occurrence of an extreme discharge will initiate a new period of active channel zone recovery. The braided reaches in this study experienced their most recent extreme discharge in July 1988. In 1992, the large areas of sparsely vegetated bars and inactive channels within the respective active channel zones that were observed at 'normal' July and August discharge levels reflect this event. Recognizing that the active channel zone experiences this widening and then recovery is critical to the understanding of the braided river behaviour. This type of channel behaviour is not unique to the braided tributaries of the upper Mackenzie Valley and has been documented elsewhere (e.g., Hickin and Sichingabula, 1988).

The terms active, inactive, and abandoned channels are descriptions of the river channels that are intended to facilitate discussion of the active channel zone and floodplain. These refer to the state of a channel at the time of the site visit or aerial photography and are not intended to be rigid definitions. In general, an active channel is one carrying a portion of the river discharge. An inactive channel is analogous to an active channel but is more or less dry. It may, however, contain large areas of stagnant water because of a high water table or backwater. The inactive channel will carry discharge at higher river stages and probably has done so within at least the past few years; it may have a sporadic cover of herbaceous vegetation. An abandoned channel is dry and has at least a discontinuous cover of vegetation. It is subject to infilling when inundated during high river stages, but may become reactivated during an extreme flow.

Floodplain construction within the active channel zone of the braided rivers occurs through two basic processes: accretion along the convex bank of a channel associated with the progressive lateral migration of a bend, and the attachment of islands to the floodplain. This latter process begins generally with the stabilization of the bar surface by vegetation to form an island, which is followed by the abandonment of the channel separating the island from the floodplain, and the gradual infilling and colonization by vegetation of the abandoned channel to eventually 'attach' the island to the floodplain. The progressive lateral migration process is particularly common along the smaller, single channels that flow around large islands and is analogous to that occurring along a meandering river.

All of the tributaries studied are subject to river ice processes during the spring caused by both tributary and Mackenzie River ice. In general, break-up along the tributaries precedes that of Mackenzie River (Mackay, 1963b). The presence of intact Mackenzie River ice causes tributary ice to jam just above the river mouth until the Mackenzie River ice cover finally breaks up. Reflective of this jamming are ice-push features that include boulder pavements and boulder ridges (see Mackay and MacKay, 1977). These are common along Great Bear, Root, and Willowlake rivers. Such features are not prominent along the braided streams perhaps because the river banks are subject to significant annual erosion or deposition. Knocked over trees, which were observed on the floodplains of Keele and Redstone rivers up to 5 to 10 m above the observed water surface, are presumably the product of ice thrusting. No ice-push features were observed along Blackwater River whose swift and shallow waters may not be subject to significant ice jamming.

The lower ends of the study reaches are prone to backwater conditions caused by either ice jamming within Mackenzie River, the Mackenzie freshet, or both. Even during the relatively moderate discharges observed during the fieldwork, both Root and Willowlake rivers were affected by a significant backwater condition that extended several hundred metres upstream and imposed a very tranquil flow over this distance. Backwater conditions are undoubtedly much more significant during the spring, affecting all of the major tributaries to some degree. Severe ice jams in Mackenzie River can cause backwater flooding of a tributary mouth. The maximum upstream extent of a given height of backwater is not known and probably varies from river to river depending upon the valley slope of the tributary. As an example of how far upstream backwater can extend, P. Wood (pers. comm., January 13, 1994) reported that the Water Survey of Canada gauging station located about 10 km above the mouth of Root River can be affected by backwater during high stages of Mackenzie River.

Attributable to backwater are accumulations of sand that were observed on bar or bank surfaces at and near the river mouths which were generally more widespread and thicker than those deposits situated further upstream. At the river mouths, the bars and inactive channels located away from the main channels of the braided rivers commonly are covered with a veneer of silt and clay, which probably represents fine grained sediments that settled out of suspension within the low energy depositional environment generated by the backwater conditions.

Along the lower parts of the Great Bear, Willowlake, and Root rivers there is a measurable widening of the channel which probably relates to the presence of backwater conditions from Mackenzie River. This widening of the channel causes a marked decrease in the velocity of the tributary flow in order to maintain flow continuity, a situation analogous to that at a river estuary (Church, 1971, 1974).

Lateral channel change

Lateral channel change along the study reaches was assessed by comparing aerial photographs taken in different decades. Aerial photograph coverage along Mackenzie Valley began in the late 1940s and early 1950s and continued to the 1970s and the early 1980s; it ranges in scale from about 1:19 000 to 1:60 000 (Table 3). Along the east side rivers, large-scale aerial photograph coverage taken in the 1980s exists for areas immediately adjacent to the Norman Wells pipeline (between 1:10 000 to 1:11 000 scale).

The aerial photograph comparison was done using a Saltzman Projector and 1:50 000 scale NTS maps. For each study reach, aerial photograph images were projected upon, and aligned carefully with, the NTS map. On a separate piece of paper for each aerial photograph series, the relevant fluvial features were traced carefully to create channel position maps of a consistent scale for each year of aerial photography. Because of stage differences between the aerial photograph series, the vegetation lines were used to define the channel boundaries (or active channel zone in the case of the braided streams). Using a light table, the older channel position map for each study reach was superimposed upon the youngest map and then traced to produce a diagram depicting the net lateral channel change over the time span of the aerial photography. In practice, it was found that the large scale 1980s aerial photography for Willowlake River contained too much distortion to be superimposed accurately upon the base maps, thus only the smaller scale photography spanning the 1940s and 1970s was used.

The lateral channel displacements obtained from the aerial photograph comparison diagrams were found to be within 50 m of those obtained by measuring the changing distances of the river boundaries relative to static features on the aerial photographs. This suggests that the error in the channel change diagrams is roughly ±50 m. Apparent lateral channel displacements of less than 50 m are therefore not considered to be significant. As a comparison, Hickin and Sichingabula (1988) reported an error of ±25 m using a similar methodology, but using a base map of 1:25 000 scale.

Along many of the study reaches, distinct 'zones' of erosion are apparent which generally relate to the concave banks of a channel. Measurements of lateral channel migration represent the maximum bank retreat occurring within an individual zone of erosion. The exception to this is along Redstone River where lateral change was measured perpendicular to, and at regular intervals along, the valley axis. The erosion here occurs more or less along the entire north side of the active channel zone and thus is not easily divisible into zones.

Between the major tributaries, the maximum amount of lateral migration varies considerably ranging from essentially zero (Great Bear and Blackwater rivers) to as much as 340 m or about 11 m·a^{-1} (locally on Redstone River between 1949 and 1981). For the braided rivers, this lateral displacement relates to the migration of the active channel zone boundaries rather than to individual channels within the active channel zone. Major modification to the islands and bars has also occurred, but the pattern is confusing and difficult to interpret because of stage differences between aerial photograph series. Thus, the amount of lateral displacement along a braided stream does not reflect the stability of the islands and bars within the active channel zone.

Along any reach of a river, the rate of lateral channel migration (M) is dependent upon a number of factors. In order to better understand the control(s) of the pattern of erosion along, and the rates of migration measured within the study reaches, it is instructive to review these factors. Hickin (1988) has summarized these in the qualitative statement:

$$M = f\,(\Omega, b, G, h, T_b) \qquad (1)$$

Variables Ω, b, and G are the driving forces in the relationship, initiating erosion of the bank, where Ω is stream power (essentially the discharge-slope product) representing the energy within the flow that is available to detach and remove detritus; b is a parameter expressing the planform geometry, and relates to the focusing of the stream power against river banks; and G represents the sediment transport rate along the river. On most rivers G is a passive factor, a product of the lateral migration and not the cause of it. The remaining variables are the resisting forces, where: h is the height of the outer bank, and relates to the volume of material to be removed by the river for each unit of lateral bank retreat; and

Table 3. List of aerial photographs used in study[a].

River	Date of photography d/m/a	Flight line	Photograph numbers	Focal length of camera (inches)	Flying height (ft. a.s.l.)	Scale
North Nahanni	14/7/1977	A24725	134-137	6	15 500	1:30 300
North Nahanni	16/7/1977	A24726	223-225	6	15 500	1:30 300
North Nahanni	24/5/1948	A11337	113-114 138-139	6	20 000	1:39 300
Root	14/7/1977	A24725	201-205	6	15 500	1:30 300
Root	12/9/1961	A17496	16-18	6	20 300	1:39 900
Root	24/7/1947	A11019	11-13	6	20 000	1:39 300
Willowlake	23/10/1987	A27230	79-81 148-151	6	5 800	1:10 900
Willowlake	15/6/1972	A22859	93-94	6	18 500	1:36 300
Willowlake	16/7/1947	A10992	78-80	6	20 000	1:39 300
Blackwater	23/10/1987	A27229	85-88 95-98	6	5 600	1:10 600
Blackwater	15/6/1972	A22859	33-35	6	18 500	1:36 400
Blackwater	4/7/1972	A22887	12-14	6	18 800	1:37 000
Blackwater	23/7/1945	A8716	34-38	8.3	14 000	1:19 950
Dahadinni	23/7/1981	A25821	167-169	6	28 500	1:56 400
Dahadinni	18/8/1971	A22427	52-53	6	26 000	1:51 400
Dahadinni	23/7/1945	A8717	57-61	8.3	14 000	1:19 800
Redstone	23/7/1981	A25822	12-15 23-25	6	28 500	1:56 600
Redstone	3/9/1972	A23038	131-132	6	30 000	1:59 500
Redstone	13/6/1949	A11974	221-223 274-279	6	20 000	1:39 500
Keele	23/7/1981	A25822	42-45 48-49	6	28 500	1:56 600
Keele	31/7/1972	A22973	14-18	6	30 000	1:59 600
Keele	13/6/1949	A11973	218-224	6	20 000	1:39 600
Keele	13/6/1949	A11974	305-307	6	20 000	1:39 600
Great Bear	3/7/1983	A26354	133-136	6	13 100	1:25 800
Great Bear	4/7/1975	A24089	85-88 96-100	6	12 800	1:25 200
Great Bear	26/6/1945	A8312	86-89	8.3	14 000	1:19 950
Great Bear	?/7/1944	A7154	105-109	8.3	14 000	1:19 950

[a] All of the aerial photographs are from the National Air Photo Library, Ottawa

T_b is the erosional resistance of the outer or concave bank, being a function of the bank failure mechanism(s) and the geotechnical properties of the bank materials (viz., grain size, cohesiveness, fabric, packing, moisture content, organic matter content, bulk density, and compaction).

Lateral migration along the individual study reaches can be qualitatively explained to some degree with respect to the variables in equation (1). Great Bear and Blackwater rivers are swiftly flowing streams with relatively straight channels; neither has experienced significant lateral channel migration at least since the 1940s. Great Bear River is confined within a narrow valley incised into relatively resistant Tertiary bedrock while the banks of Blackwater River are composed of a coarse boulder lag that form a natural rip-rap along the channel. For both streams, the resistance of the channel boundaries to erosion (T_b) appears to limit the lateral migration. Limited stream power (Ω) may be an additional factor along Great Bear River since the river annually experiences a very limited range of discharge to which the channel boundary likely has become equilibrated and is not subject to extreme flows. Willowlake and Root rivers have well developed meanders, but flow (particularly towards their mouths) is relatively tranquil at moderate discharges because of a backwater effects from Mackenzie River; neither stream has experienced significant lateral displacement aside from some short sections of Root River. Low stream power appears to be an important factor, but stream power may increase considerably during the freshet or more extreme discharge events of the tributaries. More importantly, the majority of the concave (outer) banks of the meanders of both rivers are confined against high valley sides composed of Quaternary sediments; excessive bank height (h) thus limits channel migration. Keele, Dahadinni, and North Nahanni rivers all experienced significant lateral active channel zone displacement along zones of erosion that alternate regularly from side to side along the study reaches; on Redstone River, the erosion occurs primarily along the north side of the active channel zone. Active channel zone displacement along these braided rivers relates to two basic processes: 1) erosion along the concave banks of the major channels where they are positioned against the active channel zone boundary, and 2) avulsions during extreme discharges, causing the reactivation of abandoned channels that had become part of the floodplain; both processes relate to flow being concentrated against the river banks (b). All four rivers are swift flowing, thus, stream power (Ω) is relatively high, particularly during extreme discharges. The existence of the wide active channel zones suggest that the river banks represent low resistance to erosion; significantly, bank erosion has been occurring laterally into floodplain or terrace deposits that have a relatively low height (h) above the river bed. Overall, high Ω and b, and low h are the important factors with the braided channels experiencing considerable lateral channel change.

Interaction between tributaries and Mackenzie River

Interaction at the tributary mouth

Each tributary mouth exhibits a discernible morphology. These morphologies vary in scale and between the rivers, but can be placed into three general categories: a) a low-angled alluvial fan splayed into the bottom of Mackenzie River valley originating from the tributary valley mouth; b) a channel junction bar protruding into the Mackenzie River channel from the tributary river mouth and; c) no obvious morphological feature (Fig. 4). All three categories are intended as generalizations of a continuum of morphologies with types a) and c) representing end members.

Concerning the study reaches, the lower reaches of North Nahanni, Dahadinni, Redstone, and Keele rivers flow over low-angled alluvial fans splayed into and across Mackenzie River valley from the tributary valley mouths (Fig. 4a). The best defined of these fans is that at the mouth of Redstone River; those at North Nahanni and Keele rivers are more subtle features. The fan at the Dahadinni River mouth appears to be intermediate between fan and channel junction bar morphologies. At Root and Blackwater rivers, the tributary emerges into Mackenzie River valley, flows across the valley bottom and has constructed a large channel junction bar into and downstream along the Mackenzie River channel (Fig. 4b). The feature at Blackwater River, however, appears moribund and is probably relict. Channel junction bars are also part of the low-angled fans at Redstone and Keele rivers, but these are secondary features relative to the fans. At Willowlake and Great Bear rivers, there are no obvious morphological features present at the tributary mouth (Fig. 4c).

The development of the three different morphologies probably reflects varying amounts of sediment storage. Assuming a similar ability of Mackenzie River to transport sediment delivered into it, the variable controlling the type of morphology probably is the supply of bed-material from the tributaries. Considering the three morphologies, low-angled alluvial fans are present at the mouths of North Nahanni, Dahadinni, Redstone, and Keele rivers. Not coincidentally, these are braided rivers which drain from the Mackenzie Mountains and which have a relatively high rate of bed-material transport (see section above on Sediment load). The relict channel junction bar at the mouth of Blackwater River and an absence of obvious morphological features at the mouths of Willowlake and Great Bear rivers likely reflect relatively low bed-material transport. In contrast, bed-material transport along Root River is intermediate relative to the other rivers and a channel junction bar is present at the river mouth.

Characteristics of Mackenzie River immediately adjacent to a tributary mouth may be controlled directly by features associated with the tributary. For the eight study reaches, these characteristics include: confinement of the Mackenzie River channel against the valley side opposite the tributary mouth (Fig. 5a); deflection of the Mackenzie River bank (or valley side) opposite the tributary mouth (Fig. 5b); and narrowing (Fig. 5c) or widening (Fig. 5d) of the Mackenzie River channel. The type(s) and the degree of control upon the Mackenzie River channel varies between tributary confluence. The confinement, narrowing, and deflection of the channel relates directly to the splaying of low-angled alluvial fans and channel junction bars into Mackenzie River valley and the Mackenzie River channel (Fig. 4 and 5; Table 4). These characteristics often occur together. Channel widening may be the product of hydraulic deflection of the Mackenzie River flow against the opposite river bank by the oblique tributary flow. However, this is regarded as a possible tributary control upon Mackenzie River since it is not clear if the widening of the channel at the mouths of Great Bear and Willowlake rivers actually relates to the entrance of the tributary. It represents a plausible explanation to this widening, but similar channel widening occurs elsewhere along the river that is unrelated to a tributary confluence.

The formation of the low-angled alluvial fans within the valley bottom may be causing aggradation of Mackenzie River, steepening the Mackenzie channel slope adjacent to, and for a short distance downstream of, the fan and a decrease in the immediate upstream gradient of Mackenzie River. Such influences are typical of alluvial fans splaying across narrow valley bottoms, but are unconfirmed in Mackenzie River valley. This needs to be verified by the detailed surveying of the Mackenzie River water surface across the tributary mouths. The 15 m contour interval on the 1:50 000 scale hydrographic charts is too large to detect any slight changes in valley slope associated with these fans. The longitudinal profile of Mackenzie River constructed from these charts, however, suggests that there is no major local change in valley slope coinciding with a major tributary confluence (Fig. 6).

Downstream influence

While there are obvious changes in the channel morphology of Mackenzie River between Fort Simpson and Norman Wells (as described below in this section), none of the eight tributaries of this study can be identified as being solely responsible for instigating any of these changes. The tributaries contribute both discharge and sediment to Mackenzie River both of which may be collectively or individually controlling the morphology of Mackenzie River. However, the specific contribution of either variable in controlling the morphology of Mackenzie River is difficult to isolate. The addition of discharge from the individual tributaries,

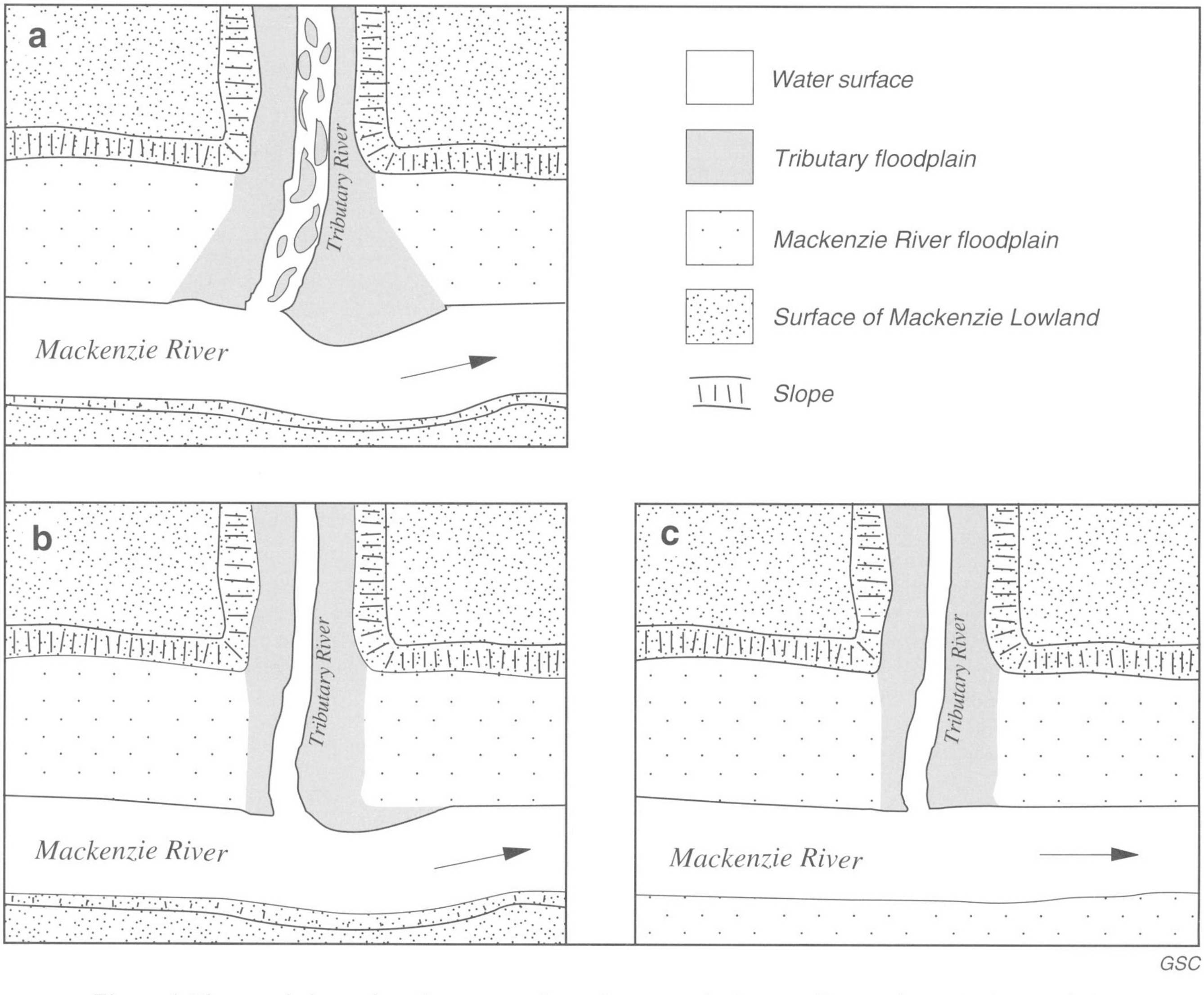

Figure 4. *The morphology of a tributary mouth can be categorized generally as either:* ***a****) a low-angled alluvial fan,* ***b****) a channel junction bar, or* **c***) no obvious morphological feature.*

however, may not have an important effect upon Mackenzie River because its streamflow is considerably larger than that of any of the tributaries. Of note, there is an obvious widening of Mackenzie River just downstream of Fort Simpson. This is in response to the addition of Laird River which represents a major supplement to the Mackenzie River flow.

Concerning the contribution of bed material, there are noticeable changes to the downstream morphology of Mackenzie River that are consistent with an increase in sediment supply to the trunk river (see Schumm, 1969) and which coincide roughly with tributary confluences. Immediately below both Root and North Nahanni rivers, there is bar and island development that results in the splitting of the channel. In the case of North Nahanni River, this influence persists for only a short distance downstream while at Root River it becomes obscured by islands composed of remnant Quaternary deposits which were formed from the postglacial incision of Mackenzie River. Beginning between the Blackwater and Dahadinni confluences and extending downstream for about 125 km (to about 55 km below Keele River), islands and bars divide Mackenzie River into a number of sinuous branches while upstream of the reach from Wrigley to Blackwater River, Mackenzie River is relatively narrow and straight. The presence of islands and bars beginning below Blackwater River is interpreted to represent the temporary storage of bed-material sediments being transported by Mackenzie River. The origin of this sediment probably arises from the collective sediment supply of Dahadinni,

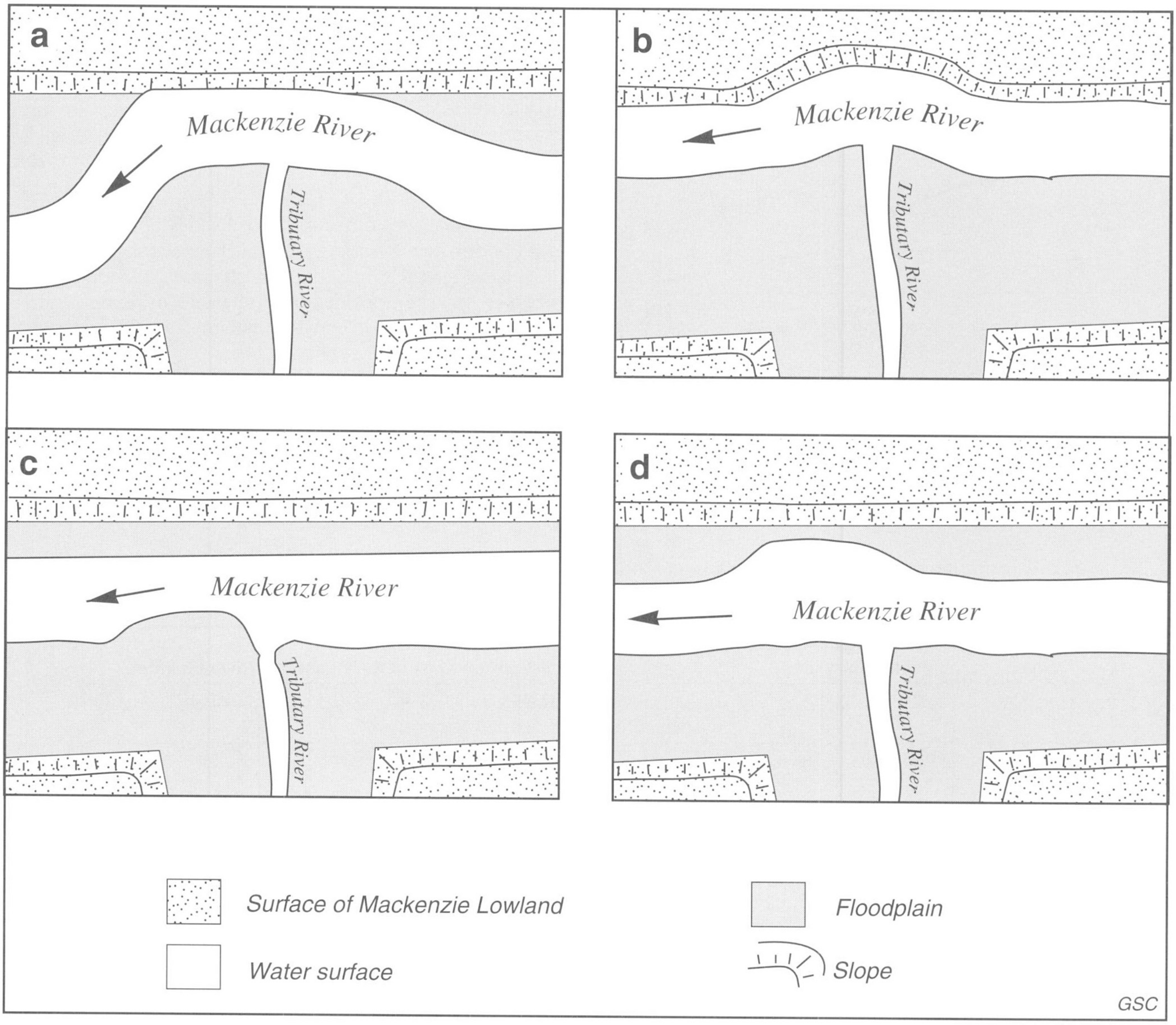

Figure 5. *Characteristics of Mackenzie River immediately adjacent to a tributary mouth that may be controlled directly by features associated with the tributary are:* ***a****) confinement of the channel against the valley side opposite the tributary mouth;* ***b****) deflection of the bank (or valley side) opposite the tributary mouth; and* ***c****) narrowing and* ***d****) widening of the Mackenzie River channel.*

Redstone, and Keele rivers, but other factors may also be important. Cutbank erosion and major slope failures are common along the valley sides of this stretch of river (Aylsworth, 1992; Duk-Rodkin, 1993), and may be supplementing the bed-material supply and thus contributing to the change in river morphology. An increase in valley slope of Mackenzie River may also be important since it appears to generally steepen, beginning at roughly the Dahadinni confluence (Fig. 6). This steepening may cause an increase in stream power, and thus increase the ability of the river to erode its banks. Finally, a change in the valley side composition may result in a variation in bank strength, hence affecting the resistance of the bank to fluvial erosion. It is not possible to isolate these variables sufficiently to assess the relative contribution of each to the change in Mackenzie River channel morphology, but perhaps they explain why the change in channel morphology begins just below Blackwater confluence rather than Dahadinni confluence. There is no obvious effect upon Mackenzie River attributable to Willowlake and Great Bear rivers, both of which have a relatively low supply of bed material to Mackenzie River.

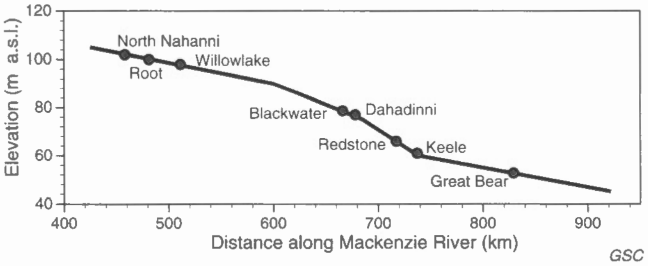

Figure 6. Longitudinal profile of Mackenzie River. The water surface elevations and river distances were obtained from hydrographic charts (Department of Fisheries and Oceans, 1989).

ENGINEERING APPLICATIONS

The construction of any structure beside or across the lower reaches of the eight major tributaries requires a careful assessment of the fluvial geomorphology at the proposed site. Since a river reach is affected directly and indirectly by processes occurring in the reaches immediately upstream and downstream of it, the assessment should examine at least several kilometres of river above and below the proposed site. By examining this longer length of river, fluvial characteristics may be revealed that are common elsewhere along the river and which reasonably might be expected to occur at the proposed construction site.

The fluvial geomorphic assessment requires consideration of a number of variables. Variables which are of considerable importance to tributaries along Mackenzie River are discussed briefly below. This discussion is intended to apply generally to all tributaries of Mackenzie River not just the eight rivers examined in this study.

All alluvial rivers flowing within a valley bottom containing a floodplain will undergo lateral channel change through progressive lateral migration and channel avulsions. Both processes may be considerably enhanced by extreme discharges. Progressive lateral channel migration happens at varying rates, dependent upon a number of factors (see section on Lateral channel change, above). Its occurrence can be recognized from the general appearance of a river bend, specifically: a fresh cutbank along the outer bank; recent point bar deposits on the inner bank; and an obvious succession of

Table 4. Summary of the controls upon the morphology of the Mackenzie River channel at the major tributary confluences.

River	Morphological feature at tributary mouth	Controls upon the morphology of the Mackenzie River channel
North Nahanni	alluvial fan	- confinement of the Mackenzie River channel against opposite side of valley - narrowing of the Mackenzie River channel
Root	channel junction bar	- narrowing of the Mackenzie River channel
Willowlake	none obvious	- widening of the Mackenzie River channel due to hydraulic deflection(?)
Blackwater	channel junction bar	- narrowing of the Mackenzie River channel - very slight deflection of opposite bank of Mackenzie River
Dahadinni	alluvial fan	- confinement of the Mackenzie River channel against opposite side of valley - slight narrowing of the Mackenzie River channel - deflection of opposite bank of Mackenzie River
Redstone	alluvial fan	- confinement of the Mackenzie River channel against opposite side of valley - narrowing of the Mackenzie River channel - deflection of opposite bank of Mackenzie River
Keele	alluvial fan	- confinement of the Mackenzie River channel against opposite side of valley - narrowing of the Mackenzie River channel
Great Bear	none obvious	- widening of the Mackenzie River channel due to hydraulic deflection(?)

progressively older vegetation moving from the inner bank onto the floodplain. Average rates of migration can be determined from historical aerial photographs or dendrochronology (see Hickin, 1988). Avulsions are intrinsic to braided rivers, but will occur along a single channelled stream. Since an avulsion results in the sudden relocation of a river channel, if unanticipated, structures situated in abandoned channels and low lying areas of the floodplain may be at risk even if sited well back from the river. The occurrence of avulsions along a river can be recognized from features on the floodplain, all readily apparent in aerial photographs (e.g., abandoned channels, channel scars, and oxbow lakes).

Except for the tributaries whose discharge is moderated by lakes situated relatively close to the river mouths, all of the Mackenzie River tributaries experience a wide range of discharges, but particularly those streams draining the Mackenzie Mountains (see section on Hydrology, above). It is, thus, important to estimate properly the extreme discharges which could reasonably be expected to occur along these rivers. Underestimating extreme flows can result in structures vulnerable to flooding being situated in locations that are inundated periodically. When structures are positioned within a channel, this narrows the immediate channel cross-section resulting in a local acceleration of flow. If the channel is constricted severely, erosion problems may be experienced during high flows.

Extreme discharges may not appear in existing streamflow records. The period of streamflow monitoring along many rivers is relatively short and may not have coincided with the occurrence of an extreme flow. The magnitude of extreme flows commonly are determined empirically, but it is not always known how representative the predicted discharges are in terms of the actual flood frequency of the river. It is thus important to recognize the occurrence of past extreme events even if the date and discharge cannot be accurately determined. Such information may be obtained from historical records (e.g., Hudson's Bay Company journals), high water marks along the channel, and possibly inferred from obvious instances of major channel change between sets of historical aerial photographs.

All of the tributaries are subjected to backwater effects from Mackenzie River. Extreme backwater conditions causing flooding generally are most extensive during the spring break-up when the stage of Mackenzie River can be raised by large ice jams which obstruct the river flow. Backwater conditions result in the lower reaches of the tributaries regularly being subjected to water levels greater than those arising from exclusively the discharge regime of the tributary. Settlements and structures which are vulnerable to flooding should not be situated on the floodplains of these rivers without careful consideration of backwater levels.

The annual spring break-up of river ice is a major event along Mackenzie River. Flowing ice can become jammed within the channel, raising river stage and causing backwater flooding upstream and into the lower reaches of the tributaries (see previous paragraph). More significantly, ice can become piled up along the channel margins and be pushed along and up onto the river banks. The physical presence of this moving ice represents a direct and powerful threat to any structures adjacent to or spanning a stream.

The break-up processes along the lower reaches of the tributaries are not well documented, but break-up must be considered carefully in any project design. In general, the height at which ice affects the river bank is related closely to river stage at the time of break-up, but stage can be accentuated by backwater conditions arising from ice jamming downstream along Mackenzie River. Locally, ice may be thrust considerably higher than the river level by the interaction of the ice debris and the river current. At any proposed site, the maximum ice limit needs to be determined carefully. This may be done by examining the bank morphology for evidence of ice scouring, and gouging, and the vegetation growing on the river bank for damage attributable to ice. Structures vulnerable to ice damage should be positioned well back from the estimated ice limit. A structure that spans a river must allow sufficient clearance to permit ice to pass unobstructed beneath it. Structures which encroach upon a channel must be armored to avoid ice damage, but if they encroach too far into the channel, ice jams may form behind them.

As a general comment, the decision in the early 1970s to locate proposed pipeline and highway crossings across major east side rivers rather than those on the west side was, in retrospect, the correct choice. The Norman Wells pipeline and the Fort Simpson to Wrigley all-season road were both eventually constructed and cross the major east side rivers. The North Nahanni, Dahadinni, Redstone, and Keele rivers, with their wide active channel zones and floodplains, major bank erosion, and the flashy discharge regimes all represent imposing rivers which are formidable obstacles to development.

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APPENDIX A

North Nahanni River

STUDY REACH DESCRIPTION

North Nahanni River is 270 km long and drains an area of about 13 300 km^2 (Table 1). The river originates within the Backbone Range of the Mackenzie Mountains and flows generally eastward through the Landry and Camsell ranges. Within the Camsell Range, about 75 km above the river mouth, the river course shifts southward. After about 35 km, the Nahanni River course switches to the north-northeast, a direction it follows to the Great Slave Plain where the river merges with Mackenzie River near Camsell Bend (Fig. 2).

The study reach extends along the lowest 7 km of North Nahanni River. Immediately upstream of the study reach, the river occupies a wide valley within the Camsell Range. The river emerges from the mountains to occupy a broad valley incised into the Great Slave Plain (Fig. A1). Over its lowest 800 m, the river cuts diagonally across the bottom of Mackenzie River valley.

Bedrock forming the Camsell Range is exposed along the study reach only at the base of Lone Mountain (Fig. A1). Lone Mountain is part of a thrust-faulted block associated with the Nahanni thrust fault. Bedrock forming the mountain

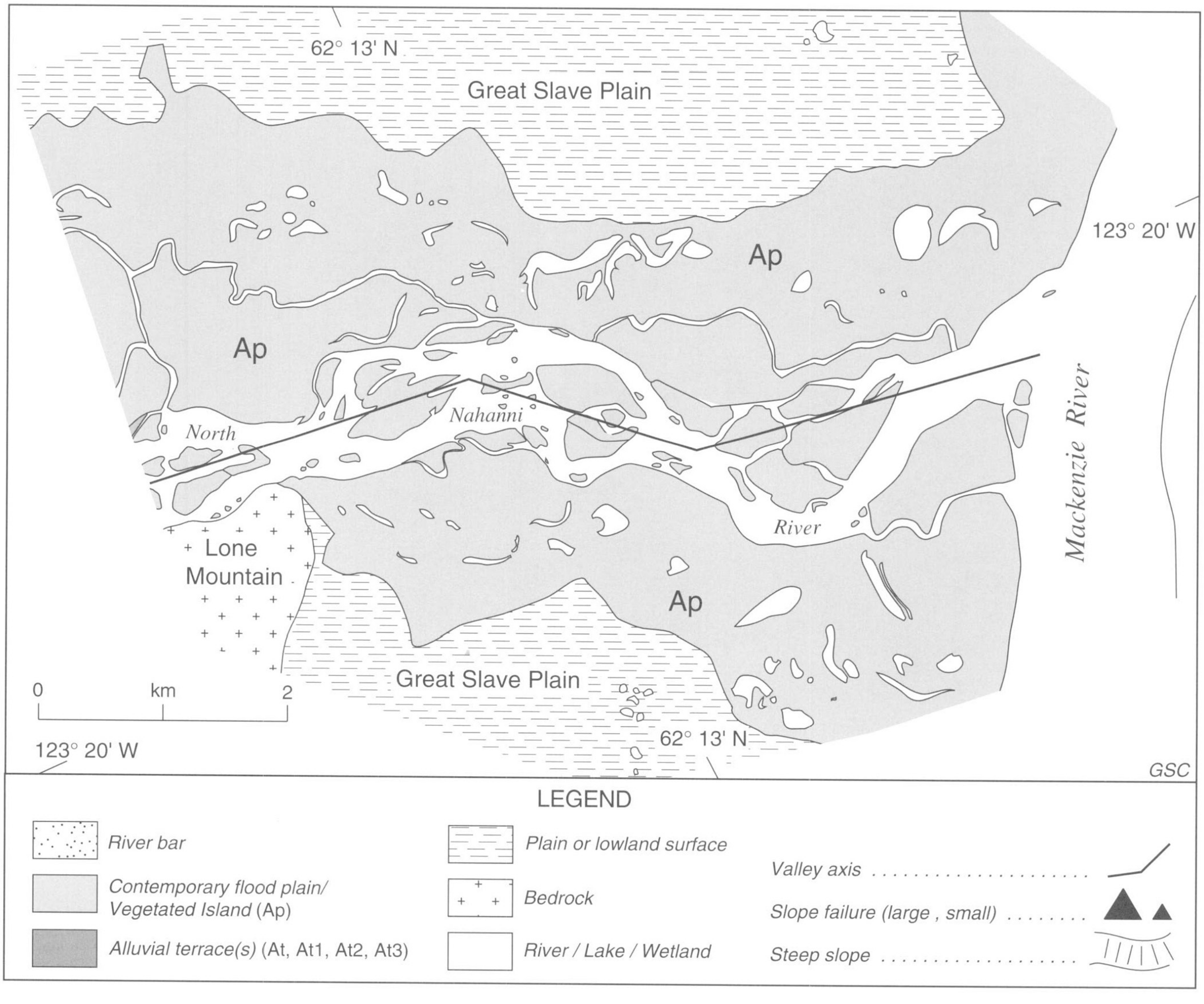


Figure A1. *Physiographic map of the North Nahanni River study area (uncorrected from aerial photographs NAPL A11337-113, -138).*

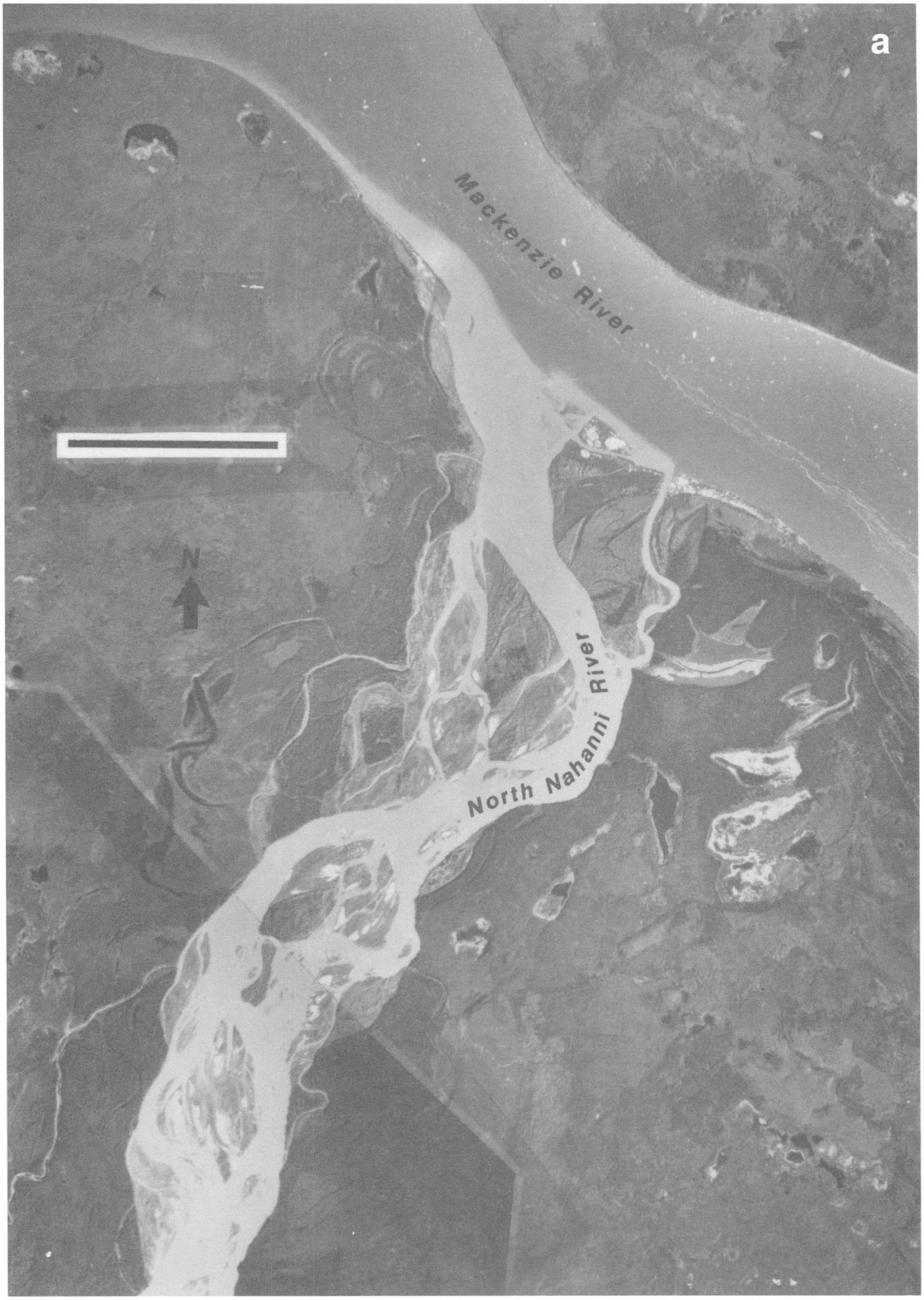


Figure A2. Sequence of aerial photographs for the North Nahanni River study reach ***a****) 1948 (NAPL A11337-113, -138), and* ***b****) 1977 (NAPL A24725-135, A24726-224); the black bar on each mosaic represents one kilometre.*

Figure A2b.

is composed of the Middle Devonian Arnica (dolomite), Manetoe (dolomite), and Nahanni (limestone) formations and Upper Devonian Fort Simpson (shale and mudstone) Formation (Douglas and Norris, 1974). The Arnica Formation forms the base of the mountain where it is in contact with the river. The Fort Simpson Formation at least partially underlies the study reach, but is buried by Quaternary deposits of the Great Slave Plain.

The area of the Great Slave Plain adjacent to the study reach is mapped as a silt and gravel glaciofluvial plain that in places overlies glaciolacustrine silts and clays (Rutter et al., 1972). The plain is covered with a mature coniferous forest; wetlands and small lakes are also present, some of which occupy thermokarst depressions (Rutter et al., 1972).

The glaciofluvial deposits appear to be part of a large, raised braided delta that was prograding into glacial Lake Mackenzie during the waning of the late Wisconsinan Glaciation (see Smith, 1992). The underlying glaciolacustrine deposits probably also originated within glacial Lake Mackenzie. The postglacial history of stream incision into deposits of the Great Slave Plain is not known.

VALLEY CHARACTERISTICS

North Nahanni River flows along the study reach within a stream-cut valley incised 10 to 30 m into the Great Slave Plain; the depth of incision decreases toward the river mouth. The valley bottom ranges from 2800 to 4700 m wide. Lateral migration of the channel has formed numerous irregularities in the valley sides; some of the indentations are curved, having formed from the outward migration of river channels (Fig. A1). The river width appears to fit the valley.

In general, North Nahanni River is positioned within the valley bottom well away from the valley sides; direct confinement of the channel occurs only at the foot of Lone Mountain in the upper part of the study reach (Fig. A1). This confinement represents 8% of the total length of the valley sides along the study reach. Probably as a result of this low amount of confinement, no major slope failures along the valley sides are apparent in the aerial photographs (Fig. A2a).

The valley bottom along the study reach consists entirely of contemporary floodplain deposits (Ap surface in Fig. A1); no terraces occur between the level of the floodplain and the Great Slave Plain. The floodplain is continuous along the northern side of the river and is interrupted along the southern side only where the river is positioned directly against Lone Mountain. Numerous channel scars and narrow, elongated lakes are present on the floodplain, which mark former channel positions (Fig. A1 and A2b). On the areas of the floodplain distal with respect to the river, the scars are less well defined to the south than to the north of the river suggesting that the southern distal floodplain is older than the northern distal floodplain (Fig. A2b). Near the river mouth, the floodplain contains scars relating clearly to North Nahanni River (Fig. A2b), but the deposits may also include Mackenzie River overbank sediments.

Along both sides of the river, the distal floodplain areas generally are covered with a dense, mature coniferous forest. A large 'patch' of deciduous forest on the north side of the river cuts across both the floodplain and the Great Slave Plain (lighter toned area underlying the north arrow in Fig. A2b) and may be an old fire scar.

Adjacent to the channel and including the vegetated islands within the active channel zone, the forest predominately is deciduous and composed of a mosaic of different aged forest tracts. Throughout the floodplain, former channel positions are delineated by the curvilinear lines within the surface texture of the forest (Fig. A2b). Numerous inactive channels are delineated by breaks in the forest cover that cut across the islands and adjacent floodplain areas.

HYDROLOGY

There is no streamflow and sediment load records for North Nahanni River. The discharge regime is likely to be similar to that of Root River, which occupies the adjacent watershed immediately to the north. In common with the other mountain rivers draining the area west of Mackenzie River, the discharge regime likely is flashy, rising rapidly in response to rain storms. There are marked fluctuations in diurnal discharge during the spring and summer months in response to snow melt in the mountains (Hume, 1922). During extreme discharges, North Nahanni River is reported to cause the hydraulic damming of Mackenzie River producing a backwater effect that can be detected upstream as far as Fort Simpson (P. Wood, pers. comm., May 18, 1993).

North Nahanni River has a relatively high bed-material transport rate as indicated by the considerable amount of channel change occurring within the study reach (see section Lateral channel change, below). Suspended sediment load varies throughout the year. River waters are reported to be milky in the spring and summer months, but clear in the late summer, autumn, and winter (Hume, 1922; Department of Fisheries and Oceans, 1989).

CHANNEL CHARACTERISTICS

Along the study reach, North Nahanni River is an alluvial stream with a gravel bed. Hume (1922) describes the river current as flowing swiftly, but without dangerous rapids. Valley slope averages 0.001, measured from the 1:50 000 scale NTS map 95J/3, between 6 and 18.5 km above the river mouth.

The active channel zone ranges from 400 to 1300 m wide and is divided by islands and bars into numerous branches typical of a braided planform. Within the active channel zone, one to two major channels are readily apparent along the study reach (Fig. A2b). The river bars within the active channel zone include side, mid-channel, and point bars (Fig. A2b). The size and shape of the bars is very different between the aerial photographs taken in 1948 and 1977, reflecting channel change and differences in river stage (Fig. A2). Discharge of North Nahanni River in the 1948 aerial photographs (Fig. A2a) was obviously high, because the floodplain

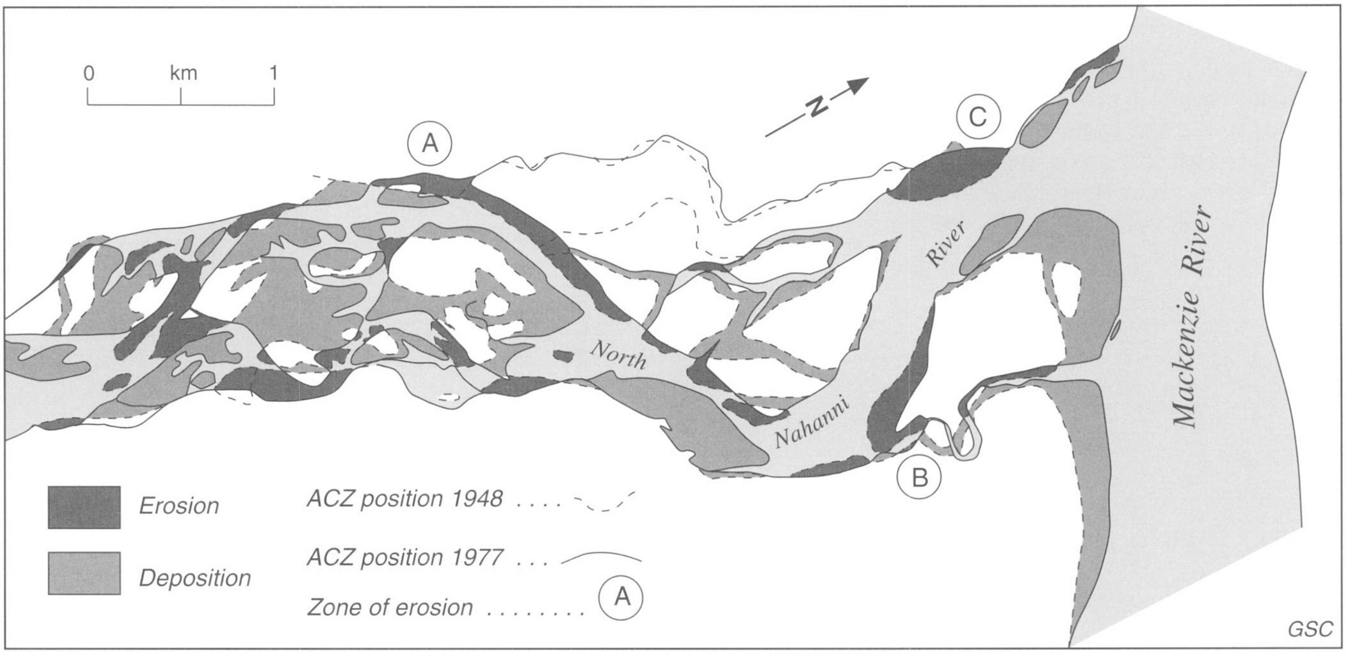


Figure A3. *Net channel change along the North Nahanni study reach between 1948 and 1977; ACZ = active channel zone.*

adjacent to the river and many of the channels cutting across the islands are inundated. This river stage coincides with the freshet, since floating ice is present in Mackenzie River indicating that the photographs were taken shortly after break-up (the photographs were taken on May 24, 1948; Table 3). The water surface probably closely approximates bankfull discharge of the river.

Hume (1922) reports that abundant driftwood supplied by bank erosion is present along the channels and upon the bars.

LATERAL CHANNEL CHANGE

The comparison of aerial photograph reveals that significant lateral channel change occurred between 1948 and 1977, including modification to the major and secondary channels within the active channel zone (Fig. A3). Obvious changes are the progressive lateral migration of major and secondary channels, island and bar creation, and channel avulsions, although some of these differences may be partially due to the lower river stage in the 1977 aerial photography.

The pattern of channel change within the active channel zone is somewhat confusing (Fig. A3) and thus difficult to quantify because of the braided character of the river and the stage difference between the two sets of photographs. The most easily quantifiable change, however, is the outward migration of the major channel which forms three 'meanders' along the lower half of the study reach (designated A, B, and C in Fig. A3). Beginning with the upstream 'meander', maximum retreat in each of the bends between 1948 and 1977 is 100, 167, and 200 m which represent average migration rates of 3.5, 5.8, and 6.9 $m \cdot a^{-1}$, respectively.

The wide valley bottom, numerous channel scars, and narrow, elongated lakes on the floodplain indicate clearly that the active channel zone of North Nahanni River has shifted considerably in the past. Floodplain construction appears to have occurred through two processes. The numerous channel scars and the mosaic of different-aged forest tracts on the floodplain indicate that channel abandonment has resulted in the attachment of islands to the floodplain. Curvilinear lines within the surface texture of the forest reveals that floodplain and island construction has occurred through progressive lateral channel migration whereby complimentary deposition and erosion take place along the convex and concave banks of bends, respectively.

NORTH NAHANNI-MACKENZIE INTERACTION

The wide expanse of the Ap surface (Fig. A1) at the lower end of North Nahanni River indicates that the river mouth has migrated back and forth within a 4800 m corridor relative to Mackenzie River. Between 1948 and 1977, erosion occurred on the north side of the channel (Fig. A3) suggesting that the river mouth currently is migrating northwards (downstream relative to Mackenzie River). This migration appears to be happening through progressive lateral migration of the channel.

The river mouth extends 800 m beyond the mouth of the North Nahanni Valley and the river appears to have constructed a low-angled alluvial fan across the bottom of Mackenzie River valley. This fan seems to control the lateral position of Mackenzie River, confining it against the eastern side of Mackenzie River valley directly opposite the tributary.

Coinciding with this confinement, the width of Mackenzie River narrows from 1500 to 3000 m upstream to 750 to 1000 m adjacent to the river mouth.

North Nahanni River transports a relatively high bed-material load into Mackenzie River (see section on Hydrology, above). The lack of a major channel junction bar extending into and downstream along Mackenzie River suggests that this sediment is being carried downstream by the trunk stream. At least partially reflective of this, the channel of Mackenzie River becomes divided by numerous islands and bars beginning 2 to 3 km below of the river mouth and extending downstream over the next 11 km. This division of the Mackenzie River channel may not be solely attributable to supply of bed material from North Nahanni River, since clusters of islands and bars are also present intermittently upstream over a distance of about 45 km where no major tributaries join the river.

APPENDIX B

Root River

STUDY REACH DESCRIPTION

Root River is 240 km long and drains an area of about 9820 km^2 (Table 1). The river originates within the Landry and Redstone ranges of the Mackenzie Mountains and flows eastward through the Camsell Range (Fig. 2). About 60 km above the river mouth, Root River turns roughly southward, eventually emerging onto the Great Slave Plain and joining Mackenzie River about 19 km downstream of Camsell Bend.

The study reach extends along the lowest 8 km of Root Valley, encompassing about 11 km of channel length (Fig. B1). The uppermost 1 km flows within a gap in the Root River anticline, which forms the eastern edge of the Camsell Range. The lower 7 km of the river are incised 40 to 50 m into Quaternary deposits of the Great Slave Plain. The direction of flow within the study reach is roughly eastward, but because of the river's irregular meandering planform (see section on Channel characteristics, below), the actual direction of flow over this course varies between south-southwest and northeast.

At the upper end of the study reach, the southern extension of the Root River anticline forms a prominent mountain ridge immediately to the north of the river (Fig. B1) and a well-defined hill to the south. Bedrock forming both landforms dips east-southeasterly at about 25° and is composed of Upper Devonian sandstone, siltstone, shale, and limestone of the Trout River and Redknife formations and Upper Devonian shale (Douglas and Norris, 1974). East of the anticline, the

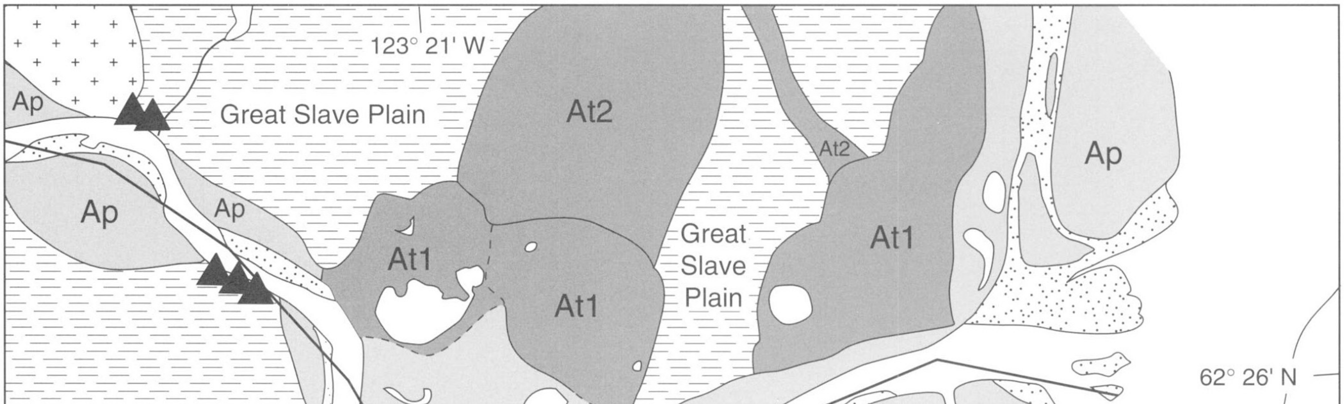


Figure B1. Physiographic map of the Root River study area (uncorrected from aerial photograph NAPL A17496-17). Refer to Figure A1 for legend.

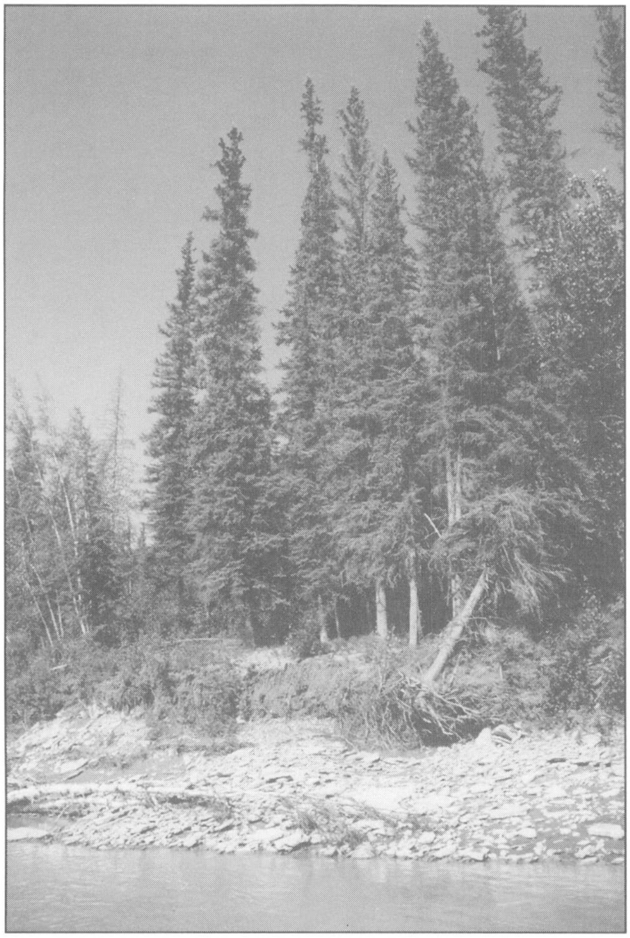


Figure B2. Outcrop of fractured bedrock along a cutbank in the upper part of the Root River study reach. GSC 1993-177AA

Upper Devonian shale continues to dip east-southeasterly extending under the Great Slave Plain, then eventually upturning to form the Root River syncline; it outcrops nearby on the eastern side of Mackenzie River (Douglas and Norris, 1974). Despite the proximity of the ridge to the river, bedrock outcrops only along 20 to 30 m of bank (Fig. B2) on the north side of the channel at the upstream end of the study reach (7.3 km above the river mouth; Fig. B1).

The area of the Great Slave Plain adjacent to the study reach is mapped as a sandy glaciofluvial plain (Rutter et al., 1972). The local stratigraphy is not known in detail, but consists generally of Quaternary deposits composed of glaciofluvial sand, silt, and gravel overlying glaciolacustrine sand and silt, all probably relating to glacial Lake Mackenzie (Rutter et al., 1972; Smith, 1992). The sandy glaciofluvial plain and terrace surfaces are pitted with numerous lakes and wetlands, some of which occupy thermokarst depressions (see Rutter et al., 1972). The area is covered with a dense, mature coniferous forest.

Smith (1992, Fig. 10) shows the general area of the study reach inundated by glacial Lake Mackenzie. He reported a 10 290 ± 180 BP (AECV-917C) radiocarbon age obtained from a wood sample found along Mackenzie River near the confluence of Root River. The wood was positioned about 7 m above the present water surface and buried 4 m within Mackenzie River fluvial-deltaic sediments that overlie (glacio-?) lacustrine sediments. This radiocarbon date represents the last time glacial Lake Mackenzie could have occupied this area of the Great Slave Plain (Smith, 1992). Since the vertical position of the fluvial surface above the wood is well below the reconstructed maximum water level of glacial Lake Mackenzie, it seems that Mackenzie and Root rivers were well incised into the Great Slave Plain at this time. The presence of small lakes and wetlands on the alluvial terraces could provide datable materials relevant to this river incision.

Figure B3.

Slope failures along the concave bank opposite the large point bar along the Root River study reach; the leaning of some trees on the upper bank is the product of slope movement. GSC 1993-177CC

VALLEY CHARACTERISTICS

The valley bottom along the study reach ranges from 400 to 3200 m; the widest area was formed by the lateral migration of a large meander in the middle part of the reach (Fig. B1).

Confinement of Root River directly against the valley sides (beneath the Great Slave Plain and At1 surfaces) occurs intermittently throughout the study reach (Fig. B1), but is particularly prevalent along the concave bank of the large meander in the middle part of the study reach. Overall, direct confinement against the valley sides represents about 40% of the total length of the valley sides along the study reach.

Extensive sections of the valley side slopes are failing actively (Fig. B1), coinciding with the direct confinement of the river against the valley sides. Fresh scars originating from detachment block sliding, and to a lesser extent rotational failures, occur along concave banks of the study reach. These scars are particularly prominent along the outer bank of the large meander where they extend up to 5 to 15 m above the river surface (Fig. B3); leaning trees are present immediately above the scars. Failed debris at the base of the scars commonly is fresh in appearance and includes live vegetation which has been rafted down the slope. The general lack of older debris suggests that either the bank failures have occurred only recently or that the river annually is removing the failed debris, thus preventing its accumulation at the base of the slope. Lineations running parallel to channel along these failing slopes are visible in Figure B4c just downstream of the apex of the large meander. These features are interpreted as tensional cracks due to block sliding or rotational failure. Their presence on all of the aerial photographs suggests that the bank failures have been occurring since at least 1947 (Fig. B4).

In the general location of the study area, there are at least three major alluvial surfaces incised into the Great Slave Plain (Ap, At1, and At2 in Fig. B1). The Ap surface is the lowest and generally ranges from 3 to 5 m above the observed water surface. This surface forms a major portion of the valley bottom (Fig. B1). Fresh cutbank exposures of the Ap deposits were not common, as many of the banks are accretionary or stable. An exposure about 7.5 km above the river mouth revealed about 4 m of interbedded silt and sand overbank deposits; the lower 1 m being obscured by slumped material (Fig. B5). Presumably these overbank deposits overlie gravel, since the river has a gravel bed. The Ap surface generally is covered with a dense coniferous forest. Adjacent to the channel along the convex side of the meanders, the mature forest gets progressively younger, eventually grading to the grasses and shrubs that are present on the freshly deposited surfaces of the point bars; these latter plants represent the initial stages of the forest succession. Also close to the channel, lineations in the texture of the forest in Figure B4b run roughly parallel to the river marking former channel positions. In the lower half of the study reach, particularly at the river mouth, the Ap surface is dissected by several inactive channels that carry discharge at relatively high river stages (Fig. B4c). The Ap surface is interpreted as contemporary floodplain deposits of Root River, but near the river mouth it probably consists of a combination of Root and Mackenzie river floodplain deposits.

The At1 surface occurs discontinuously along both sides of Root River and represents the intermediate terrace between the Ap and At2 surfaces. As estimated from 1:50 000 scale NTS map 95J/6, the surface is 30 to 40 m above the river. The general orientation of the curved back walls of the various At1 terrace fragments suggests that they were formed by an ancestral Root River as it shifted laterally within the area of the present river course. The At1 surface is densely covered with a mature coniferous forest. The At1 surface is interpreted as a terrace relating to Root River.

The At2 surface forms the highest surface incised into the Great Slave Plain. From 1:50 000 scale NTS map 95J/6, the surface is estimated be 40 to 50 m above the water level of Root River and is densely covered with a mature coniferous forest. The forest cover and the margins of the At2 surface delineate a faint network of braided paleochannels that run roughly parallel to the present course of Mackenzie River (Fig. B4b). These channels occur along either side of the present Root Valley, but are interrupted by lower, and thus younger, Ap and At1 surfaces. The At2 surface is interpreted as a terrace surface formed by Mackenzie River probably immediately following the demise of glacial Lake Mackenzie.

HYDROLOGY

Root River streamflow is measured at a station located ‘near the river mouth’, beginning in 1974. Based upon the 1974 to 1992 record (Water Survey of Canada, unpub. data), the mean annual discharge is 95 $m^3 \cdot s^{-1}$ with the maximum and minimum monthly discharges being 235 (May) and 9 (March) $m^3 \cdot s^{-1}$, respectively (Fig. B6; C. Brumwell, written comm., September 27, 1993). The minimum historical daily discharge is 2 $m^3 \cdot s^{-1}$ recorded on April 3, 1979. The mountainous landscape which forms the majority of the Root River drainage basin imposes a ‘flashy’ discharge regime upon the river which is typical of the west side rivers (Jasper and Kerr, 1992).

The highest maximum daily discharge on record is 5730 $m^3 \cdot s^{-1}$ (estimated) measured on July 1, 1988; but an estimated instantaneous discharge of 7400 $m^3 \cdot s^{-1}$ was also recorded on the same day. This streamflow was the product of a major storm system that caused widespread flooding throughout the region in early July 1988 (see Jasper and Kerr, 1992).

The bed-material transport rate appears to be relatively low because no significant lateral channel change appears to have occurred along the study reach between 1947 and 1977 (see section on Lateral channel change, below). P. Wood (pers. comm., January 13, 1994), however, reported that Root River carries a relatively high suspended sediment load as is typical of the west side rivers. A partial record of Root River suspended sediment data exists for the 1987 to 1990 period, also measured at the ‘near the Root River mouth’ station (Water Survey of Canada, 1992b). The highest concentrations were obtained during the spring and early summer months (May to July) and range from 345 to 1670 $mg \cdot l^{-1}$. During the late summer and autumn months (August to October), sediment concentrations fell markedly, ranging from 6 to 63 $mg \cdot l^{-1}$. Because of the short record, the representativeness of these concentrations is not known. Although unrecorded, the winter concentrations undoubtedly are also very low. Significantly, the 1670 $mg \cdot l^{-1}$ was obtained during the waning stages of the early July 1988 flood of record (July 5, 1988) suggesting that large quantities of suspended sediment are carried by Root River during extreme discharges. During the July 27, 1992 site visit, the suspended sediment load caused the river waters to be very turbid under moderate discharge conditions.

P. Wood (pers. comm., January 13, 1994) described Root River as being analogous to the braided rivers in terms of the discharge regime and in the suspended sediment transport rates.

CHANNEL CHARACTERISTICS

Along the study reach, Root River is a single channel stream with a gravel bed. The channel ranges from 200 to 450 m wide (Fig. B1). During the site visit (July 27, 1992), discharge was 273 $m^3 \cdot s^{-1}$ (D. Anderson, written comm., February 3, 1993). Flow in the upper part of the study reach was moderately swift, accelerating over a riffle situated within the channel opposite the head of the secondary channel that cuts across the large meander (Fig. B1). Below the riffle to the river mouth, flow was very tranquil, probably reflecting backwater conditions caused by Mackenzie River.

Along the study reach, the channel has an irregular meandering planform with a sinuosity of about 1.4. This sinuosity reflects primarily the presence of the large meander along the middle third of the study reach which has a relatively high amplitude and wavelength (Fig. B1). In contrast, the upper third of the study reach consists of several meanders of relatively low amplitude and wavelength while the lower third curves gently. At its mouth, Root River divides into a main channel and two secondary channels. The control upon the downstream change in sinuosity and the eventual splitting of the channel is not known, but may be related to a backwater influence from Mackenzie River or a downstream change in valley slope (valley slope is not known), or a combination of both.

The major types of bars within the study reach are point and side bars. The general distribution of these bars varies downstream with the point bars being situated along the upper two-thirds of the study reach while the side bars occur primarily along the lower third where the river curves gently.

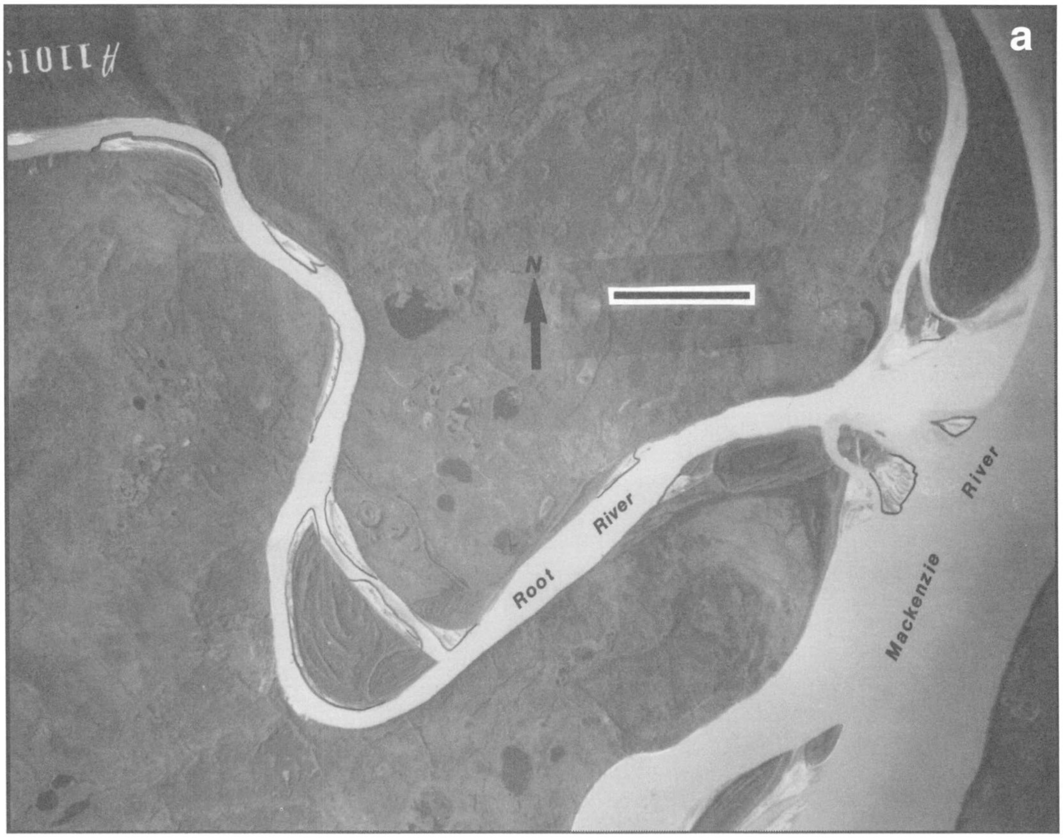


*Figure B4. Sequence of aerial photographs of the Root River study reach **a**) 1947 (NAPL A11019-12), **b**) 1961 (NAPL A17496-17), and **c**) 1977 (NAPL A24725-203); the black bar on each photograph represents one kilometre. The greater number of river bars in b) reflects a lower river stage than in a) and c). Some of the bars in a) have been outlined and shaded to enhance their profile.*

Figure B4b.

Figure B4c.

Along the upper two-thirds of the study reach, point bar morphology varies downstream. In the upstream area, the point bars have a low-angled gravel bar platform that forms a long and wide surface. In the middle area of these bars, a suprabar platform consisting of sand is positioned well back from the edge of the water. Grasses and shrubs are present discontinuously on the back area of the bars, eventually thickening to form a continuous cover where the suprabar platform grades into overbank deposits of the floodplain. In contrast, along the middle third of the study reach, the point bars lack a well defined bar platform, and instead consist of a gently sloped face composed of gravel and in some places, sand. Suprabar platform and overbank sand form a cap on the higher areas of these point bars and on the edge of the floodplain (Fig. B7). This downstream change in point bar morphology is perhaps due to a change in valley slope, a backwater influence from Mackenzie River, or both.

The side bars along the lower third of the study reach consist of thick sand and silt deposits that presumably overlie gravel. The surface cover ranges from barren to sparsely vegetated. Adjacent to the floodplain, the vegetation cover abruptly becomes continuous, a change that appears to mark a high water line. The accumulation of thick sand deposits on the side bars may reflect backwater conditions originating from Mackenzie River.

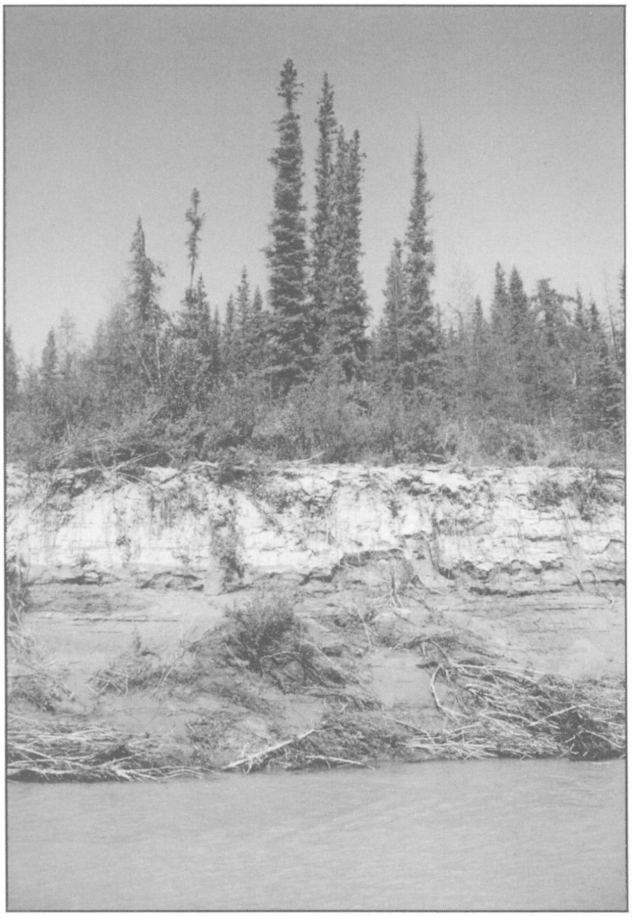


Figure B5. *Overbank sand and silt deposits of the contemporary flood plain (Ap surface) along Root River exposed at a cutbank. Only the upper 2 m of the bank represent in situ deposits; the lower half of the deposits are buried beneath slumped debris. GSC 1993-177DD*

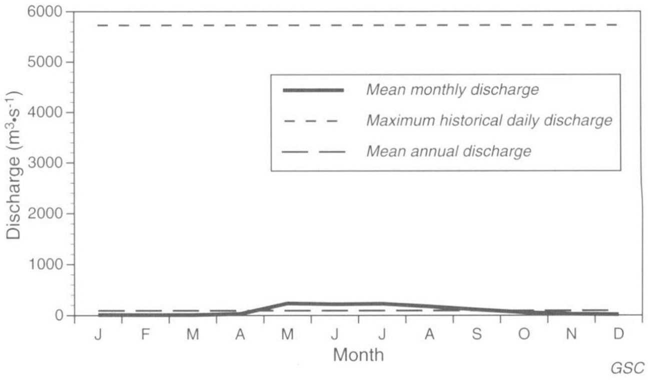


Figure B6. *Hydrograph of the Root River streamflow, 1974-1992, 'Root River near the mouth' station (Water Survey of Canada, unpub. data).*

Active cutbank erosion is present generally along the concave banks, being best developed along the large meander and opposite the point bar located furthest upstream.

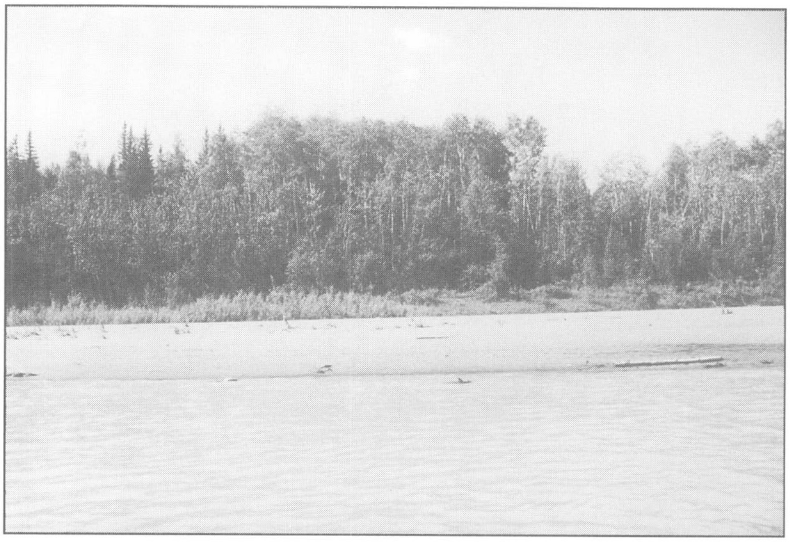
Immediately downstream of the outcropping of bedrock located about 7.3 km above the river mouth (see section on Study reach description, above), are at least six dead tree trunks projecting from the side of the river bank. These trees are situated below the surface of the floodplain within 2 m of the observed water surface and are devoid of bark. Some appeared to be in growth position. Exactly what these trees represent is not known. If in situ, they grew upon a surface located significantly below the contemporary Root River floodplain.

Erosion along the cutbanks and valley sides is introducing vegetative debris into the river. Live trees and shrubs incorporated within failed debris are common along many of the active cutbanks, while numerous undermined and leaning trees at the bank edges represent a future contribution (Fig. B8). Despite this supply, relatively little vegetative debris was observed within the study reach except at the river mouth where a number of isolated logs and small log jams are stranded upon bars. The vegetative debris ultimately is being delivered into Mackenzie River.

Ice-push features in the form of damaged trees, boulder pavement, and loose boulder pavement (Fig. B9) occur discontinuously up to 5 m above the observed water surface along stable banks throughout the study reach. They are best developed along the straight and concave banks, 4 to 7 km above the river mouth. About 10 km above the river mouth, a prominent boulder 'bar', about 30 m long and up to 1 m above the observed water surface, occurs along the base of an eroding concave bank. This 'bar' is believed to represent channel lag that was pushed into a ridge by river ice during break-up. Elsewhere along some active cutbanks are minor accumulations of gravel which may also be a product of this process.

Figure B7.

Sand deposit forming the surface of a typical river bar along the lower half of the Root River study reach. GSC 1993-177EE



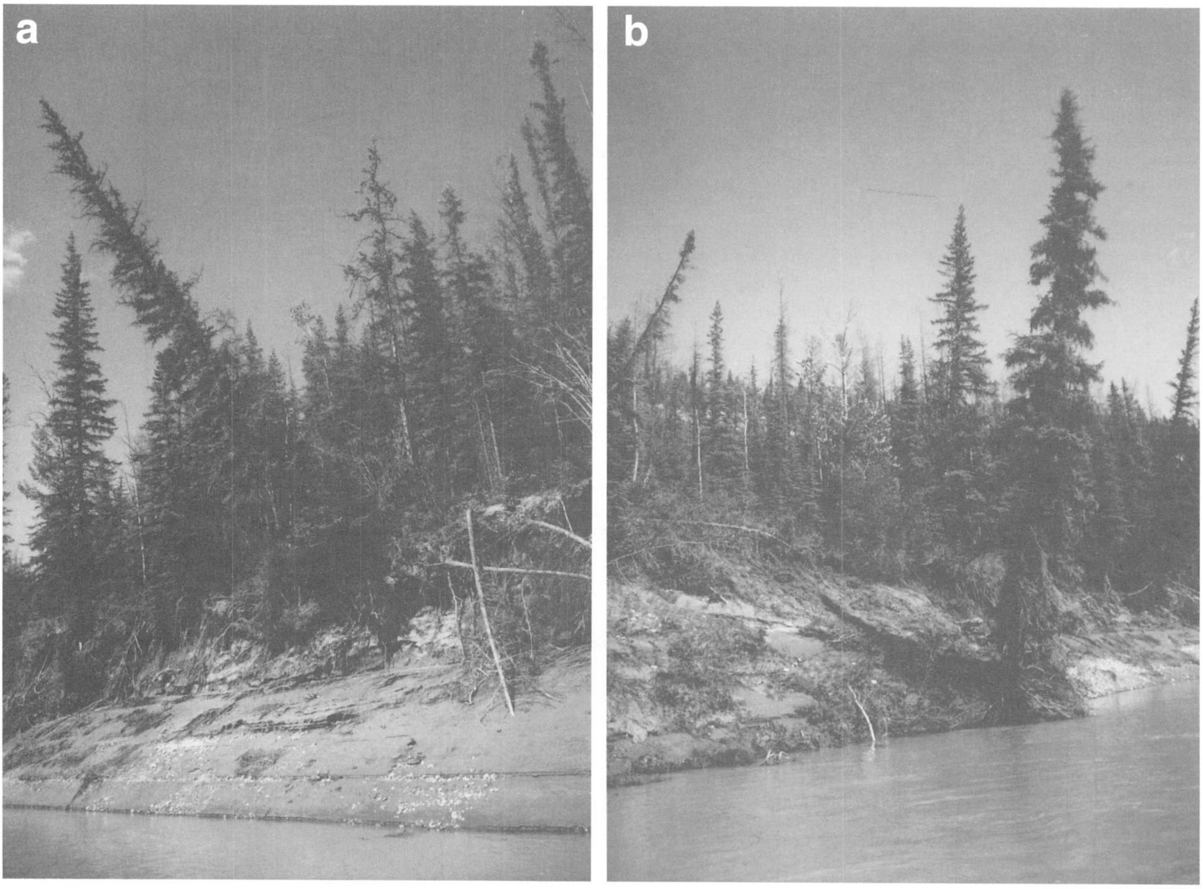


Figure B8. *Cutbank erosion along Root River is introducing vegetative debris to the river;* ***a****) an undermined tree at an active cutbank that is leaning towards the channel (GSC 1993-177FF), and* ***b****) an upright tree that has slid down the river bank as part of a detachment block slide (GSC 1993-177GG).*

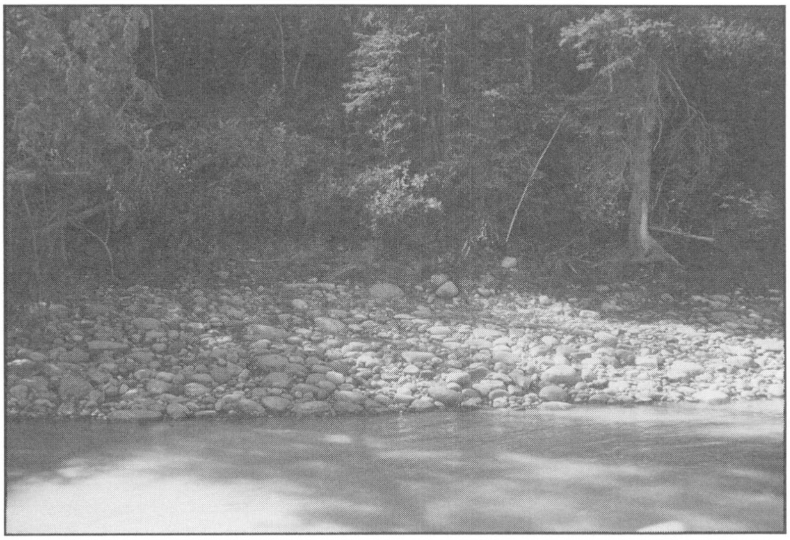


Figure B9.

Boulder pavement along a bank of the Root River study reach. GSC 1993-177HH

LATERAL CHANNEL CHANGE

Channel migration along the Root River study reach is occurring through the progressive lateral and downstream migration of the meanders. Evidence of this is shown by the occurrence of active cutbank erosion along many of the concave banks, and by the curvilinear texture of the forest along the convex side of the meanders which delineates former positions of the channel (Fig. B4b). In Figure B10, much of the channel change is not significant with respect to the ±50 m error of the aerial photograph comparison technique. Inspection of the aerial photographs (Fig. B4a, b, c) confirms that there has been little change in the position of the channel relative to static features along the river valley. It should be noted that some of the apparent accretion along the concave banks and the upstream-most point bar may reflect lower river stages at the time of the 1977 aerial photography relative to that of 1947, rather than 'real' accretion.

The lack of significant lateral channel migration between 1947 and 1977 probably relates to the cutbanks being generally located where the river is confined directly against the Great Slave Plain or At1 surfaces. The importance of the bank height in limiting migration is exemplified by the lack of migration of the large meander despite the presence of extensive 'fresh' slope failures along the opposite concave bank. The bedrock outcrop along the concave bank of the upstream-most meander (see section on Study reach description, above) appears to represent only slight resistance to river erosion, since there is only a very minor deflection in the concave bank toward the river channel.

Another variable which might be limiting the channel migration is a backwater influence from Mackenzie River, which severely reduces flow velocity (and thus stream power) along the lower several kilometres of Root River. While the upstream extent of the backwater varies, depending upon stage differences between the two rivers, the low flow velocity greatly limits bank erosion over some of the study reach for at least part of the year.

The major secondary channel that cuts across the floodplain deposits on the convex side of the large point bar predates the 1947 aerial photography (Fig. B4a). The channel is unvegetated and appears to have been recently active in all three sets of aerial photographs and also during the July 1992 site visit. Since this channel represents a shorter and steeper route for the river, it may eventually capture the main flow of the river, cutting off the large meander.

ROOT-MACKENZIE INTERACTION

The presence of the Ap surface along both sides of the Root River mouth (particularly on the south side) indicates that the tributary has shifted laterally within an about 2 km wide corridor relative to Mackenzie River (Fig. B1). The presence of active cutbanks along the north side of the channel, along the lower 2 km of the study reach, suggests that the present migrational trend is northwards (downstream relative to Mackenzie River). Comparison of aerial photographs (Fig. B10), however, indicates that no significant migration actually has occurred between 1947 and 1977.

The tranquil nature of flow along the lower 6 km of the channel indicates that Root River is subject to a significant backwater effect from Mackenzie River. During high stages of Mackenzie River, a backwater influence can extend upstream beyond the Water Survey of Canada gauging station located about 10 km above the mouth of Root River (P. Wood, pers. comm., January 13, 1994).

Backwater effects from Mackenzie River probably are an important control upon several morphological characteristics of the lower study reach because of the imposed decrease in stream power, a situation analogous to a river estuary. These characteristics are: the sand texture of the side bars; the relatively straight lower channel; and the splitting of the channel at the river mouth (see section on Channel characteristics, above).

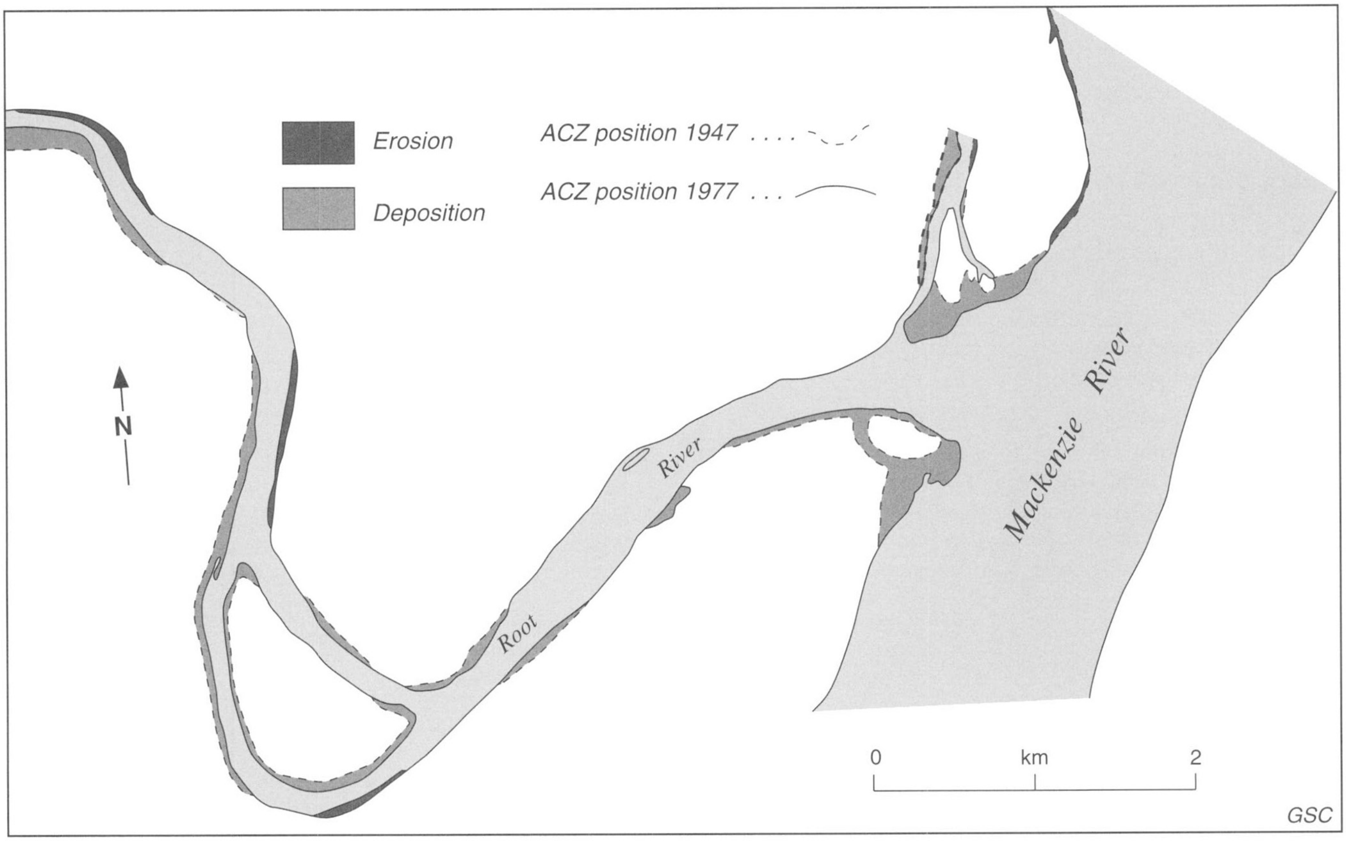


Figure B10. Net channel change to the Root River study reach between 1947 and 1977; ACZ = active channel zone.

During extreme discharges triggered by summer rain storms, flow from Root River is reported to cause hydraulic damming of Mackenzie River (P. Wood, pers. comm., May 18, 1993).

A large channel junction bar projects from the Root River mouth about 1 km into and 4 km downstream along the Mackenzie River channel (Fig. B4a). The higher vegetated areas of the bar, however, probably are at least partially composed of Mackenzie River floodplain deposits. A submerged portion of this bar extends 1.5 km further upstream across the mouth of Root River. The presence of this channel junction bar causes a marked constriction of the adjacent Mackenzie River channel from 1500 down to 1100 m wide. During moderate river stages, logs carried by Root River become stranded upon the shallow, submerged portions of the bar causing the accumulation of vegetative debris at the river mouth; these shoals eventually become exposed at low river stages. Since the observed stranded logs all appeared to be relatively fresh, this debris probably is remobilized during the freshet of the succeeding year, thus inhibiting the formation of large log jams at the tributary mouth.

Downstream of the Root River mouth, Mackenzie River widens and becomes divided by numerous islands and bars. It is likely that this change in channel morphology at least partially reflects the supply of bed-material from Root River, although this supply may be relatively low. However, not all of these islands reflect contemporary channel processes since the largest island (McGern Island) has been carved from Quaternary deposits by the postglacial incision of Mackenzie River. An additional control upon the channel morphology of Mackenzie River relates to bed-material supply from the North Nahanni River which enters Mackenzie River about 23 km upstream (see section on North Nahanni-Mackenzie interaction in Appendix A). Immediately below the North Nahanni River, Mackenzie River also widens and is divided by a number of islands, probably in response to bed-material supply from the North Nahanni River. While the North Nahanni River influence seems to wane toward the Root River mouth (Mackenzie River narrows and the frequency of islands diminishes greatly about 13 km below the North Nahanni-Mackenzie confluence), it cannot be entirely disregarded and thus probably should be regarded as a partial control upon the Mackenzie River planform below Root River.

APPENDIX C

Willowlake River

STUDY REACH DESCRIPTION

Willowlake River is 400 km long and drains an area of about 21 000 km^2 (Table 1). The river generally follows a westerly course, originating within the Great Slave Plain (Fig. 2). Willow, Hornell, Clive, and Bulmer lakes occupy relatively large basins within the watershed, but all are located far upstream of the river mouth.

The study reach extends along the lowest 4.4 km of Willowlake River which encompasses a 6.5 km length of river channel (Fig. C1). The upper 2.5 km of this reach flows within the lower end of a relatively straight valley extending from the southeast (Willowlake Valley) which is incised 40 to 50 m into the Great Slave Plain. About 3 km above the river mouth, the valley turns to follow a more westerly direction for the remaining distance to Mackenzie River (Fig. C1). Along this westerly course, the north side of the valley is formed by a lower surface ('Mackenzie River valley surface') some 10 to 20 m above the river, which appears to represent the late Pleistocene bottom of Mackenzie River valley prior to incision by the rivers. The Great Slave Plain drops sharply to the level of the Mackenzie River valley surface; a steep scarp clearly defines the boundary between the two surfaces (Fig. C1).

In the general area of the Willowlake confluence, Mackenzie River is split into two major channels east and west of McGern Island. This island is formed of remnant

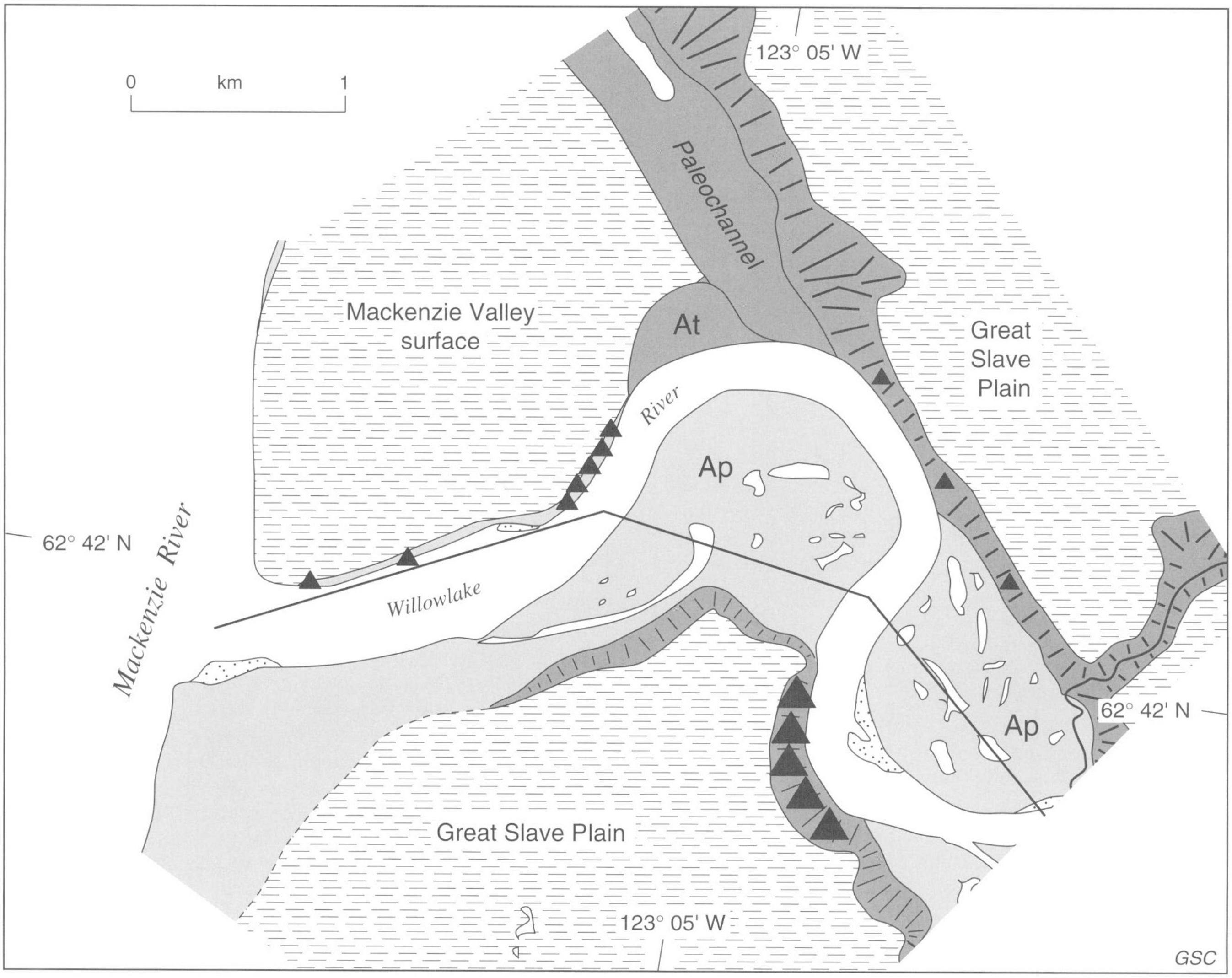


Figure C1. Physiographic map of the Willowlake River study area (uncorrected from aerial photograph NAPL A22859-94). Refer to Figure A1 for legend.

Quaternary deposits rather than being stabilized alluvium. Willowlake River enters the channel of Mackenzie River along the east side of McGern Island.

Within the study reach, the Norman Wells pipeline and the Fort Simpson-Wrigley winter road cross Willowlake River about 2.5 km above the river mouth (Fig. C2c). An all-season bridge was completed in 1994 at the winter road crossing, as part of a project to convert the winter road to an all-season road. Several inhabited Dene cabins are located along the northern bank at the river mouth (Fig. C2).

Bedrock underlying the study reach consists of Upper Devonian shale and mudstone, and siltstone of the Fort Simpson Formation, but may also include Middle Devonian shale of the Horn River Formation (Douglas and Norris, 1974). No outcrops of bedrock were observed along the study reach.

Immediately adjacent to the study reach, the surficial geology of the Great Slave Plain to the north of the river is primarily morainic till plain marked by drumlinoid features (Rutter et al., 1972). To the south of the river, the Great Slave Plain consists of a sandy glaciofluvial plain that Smith (1992, Fig. 1 and 10) interpreted as deltaic deposits related to glacial Lake Mackenzie. Several beach ridges run across this plain in a roughly north-south direction (parallel to Mackenzie River) that are also believed to relate to glacial Lake Mackenzie. This glaciofluvial plain slopes moderately toward the west, merging with the Mackenzie River floodplain, but the boundary between the two features is not obvious on aerial photographs. The Mackenzie River valley surface located near the river mouth (Fig. C1) is mapped as a sand and silt glaciolacustrine plain which probably represents sedimentation within the bottom of glacial Lake Mackenzie. Rutter et al. (1972) mapped a paleochannel that runs to the northwest across this surface, alongside the edge of the Great Slave Plain (Fig. C1).

The general area adjacent to the study reach was once covered with a mature coniferous forest, but was extensively burned in July 1979 (R. Lanoville, pers. comm., December 11, 1992). Natural regrowth has been occurring ever since, forming a mixed coniferous and deciduous cover within the burned areas.

Along the study reach, material exposed along the valley sides consists entirely of Quaternary deposits, although the exact composition was not examined in detail. Smith (1992, Fig. 7) shows a lithostratigraphic log of a river bank located at "Willowlake River mouth" consisting of fluvial sediments over a lacustrine deposit; the two units are separated by slumped material.

The postglacial history of Willowlake River incision into the Great Slave Plain is not known.

VALLEY CHARACTERISTICS

The bottom of Willowlake Valley along the study reach ranges from about 700 to 1300 m wide. Rutter et al. (1972) mapped the valley bottom, including the paleochannel extending to the northwest, as a meltwater channel. Dyke and Prest (1987) showed ancestral Willowlake River draining a lobe of the Laurentide ice sheet at about 11 000 BP, implying that the valley was carrying meltwater at roughly this time. Along the upper 2 km of the study reach, Willowlake River is underfit relative to the valley width (Fig. C1), but this is much less obvious along the lower 2.5 km of the reach, presumably because the meltwater discharge was divided between the present river course and the paleochannel extending to the northwest.

Confinement of Willowlake River directly against the valley sides generally occurs along the concave sides of the meanders (Fig. C1) and represents about 25% of the total length of the valley sides along the study reach.

Numerous small and medium sized slides and flows caused by rotational, retrogressive, and block failures are present along the valley sides, particularly where the river is confined directly against the valley sides (Fig. C1 and C3). All of these slope failures may have been accentuated to some degree by a 1979 forest fire which probably altered the geothermal characteristics of the ground cover. A particularly prominent failure scar that predates the 1947 aerial photography occurs along the concave bank on the south side of the valley between 3.3 to 4 km above the river mouth (Fig. C2a). Distinct 'steps' within the scar suggest that the slope is experiencing rotational block failure. The present role of the river in perpetuating the failure is not clear, although a significant portion of the failed debris is being reworked where it is in contact with the river. Roughly the middle third of the failure, however, appears stable since the lower slope of the failed debris dips gently and is covered with dense vegetation cover (grasses and shrubs; Fig. C4).

There are at least two surfaces below the Mackenzie Valley surface (Ap and At; Fig. C1). The Ap surface represents a large proportion of the valley bottom and is present along both sides of the valley, interrupted only where the river is confined directly against the valley sides. The Ap surface is 2 to 7 m high relative to the observed river surface, generally increasing in height downstream toward the valley mouth. The surface is covered with a dense vegetation cover consisting primarily of a mixture of coniferous and deciduous trees, which represents survival and regrowth from a 1979 forest fire. Elongated small lakes and wetlands oriented roughly in the downstream direction are relatively common on the surface (Fig. C1) and probably represent old channel scars. Immediately adjacent to the channel, the forest vegetation cover abruptly changes to shrubs and grasses which seems to mark a high waterline (along the lower 2 km of the river, this vegetation boundary coincides with a driftwood line). The composition of the Ap surface is not known precisely because of the absence of fresh cutbanks; Rutter et al. (1972) have mapped it as an alluvial terrace consisting of gravel, sand, and silt. The Ap surface is interpreted as the contemporary floodplain of Willowlake River, but toward the river mouth it becomes indistinguishable from the Mackenzie River floodplain.

The At surface occurs only on the north side of the river between 2 and 2.5 km above the river mouth and forms an arcuate terrace cut into the Mackenzie River valley surface and paleochannel (see section on Study reach description, above; Fig. C1). The At surface is 5 to 7 m above the river surface and covered primarily with a young, mixed coniferous and deciduous forest. Situated along the concave side of a meander, this surface is subject to cutbank erosion from the river, but little erosion has occurred recently, since much of the bank is covered with grasses and shrubs. The At surface was not well exposed, but at least the upper few metres consists of sand. The At surface is interpreted as a terrace of Willowlake River.

HYDROLOGY

The streamflow of Willowlake River was monitored from 1964 to 1974 at a station located 'near the river mouth' (Water Survey of Canada, 1992a). In 1975, the station was moved 1 to 2 km upstream to a site 'above Metahdali Creek' which is situated roughly 15 km upstream of the river mouth. From the 1975 to 1992 record of the 'Willowlake River above Metahdali Creek' station (C. Brumwell, written comm., September 27, 1993), the mean annual discharge is 71 $m^3 \cdot s^{-1}$ with the maximum and minimum mean monthly discharges being 335 (May) and 4 (March) $m^3 \cdot s^{-1}$, respectively (Fig. C5).

The highest daily discharge usually occurs in late April or May, being associated with spring melt and generally coinciding with the highest mean monthly discharge. The maximum daily discharge on record is 1910 $m^3 \cdot s^{-1}$ (including the 1964 to 1974 record) which occurred on July 2, 1988 in response to a major rain storm that caused widespread flooding throughout the region (see Jasper and Kerr, 1992). The lowest daily discharge generally occurs in March or early April.

The insignificant channel change experienced by Willowlake River between 1947 and 1987 (see section on Lateral channel change, below), suggests that bed-material transport rates are relatively low. Some suspended sediment load, however, is carried. Suspended sediment measurements were recorded for complete months at the 'near the river mouth' station between May and September, 1973 with a partial monthly record existing for May, June, August, and September of 1974 (Water Survey of Canada, 1992b). Based upon the complete monthly record, maximum and minimum concentrations were 160 (May 7) and 15 (June 24) $mg \cdot l^{-1}$; total suspended sediment load for the period was 99 400 tonnes

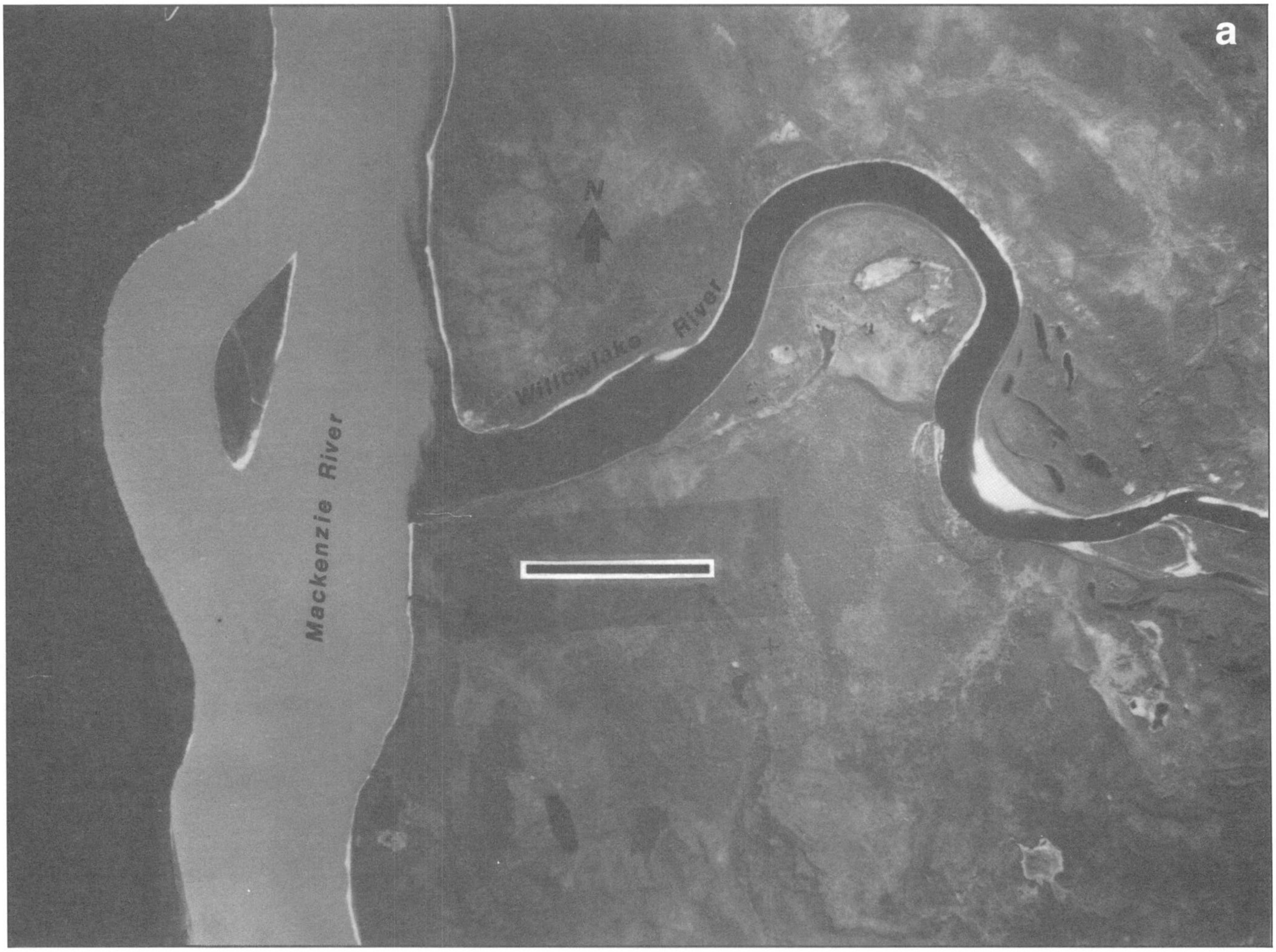


Figure C2. Sequence of aerial photographs of the Willowlake River study reach ***a)*** *1947 (NAPL A10992-79);* ***b)*** *1972 (NAPL A22859-94); and* ***c)*** *1987 (NAPL A27230-80, -148, 150); the black bar on each photograph represents one kilometre.*

Figure C2b.

Figure C2c.

or 6.6 x 10^4 m^3. Because of the short record, the representativeness of these concentrations and load is not known. During the July 28, 1992 site visit, and in aerial photographs, the river waters appeared clear, except for a brown stain from organic acids originating from extensive wetlands upstream. The dark and clear Blackwater River waters form an obvious plume that extends downstream along Mackenzie River from the tributary mouth (Fig. C2).

CHANNEL CHARACTERISTICS

Willowlake River is a single-channel stream with a gravel bed; minor sand and silt deposits are present in slackwater areas of the channel. Upstream of Metahdali Creek, the channel has a sand bed (P. Wood, pers. comm., May 18, 1993). Along the study reach, the channel generally widens downstream from 150-200 m to 300-350 m.

Channel planform consists of regular meanders (sinuosity about 1.5). This planform, however, exists only over the lower 5 km of the river valley. Over a distance of 7 km upstream above the study reach, the river exhibits a relatively straight planform with a sinuosity of 1.05. The specific control for this increased sinuosity is not known, but possibly relates to a backwater influence from Mackenzie River, downstream change in valley slope, or both. Valley slope cannot be measured from 1:50 000 scale NTS map 95J/10 because of the lack of contour lines crossing the river in the general area of the study reach. From data in UMA-Canuck-Hardy (1983b), channel slope extending for 1500 m upstream and 900 m downstream of the Norman Wells pipeline is estimated to be 0.00003, but this probably reflects a backwater effect from Mackenzie River.

During the site visit (July 28, 1992), streamflow was 180 $m^3 \cdot s^{-1}$ at the 'Willowlake River above Metahdali Creek' station (D. Anderson, written comm., February 3, 1994). Flow was relatively swift to tranquil in the upper part of the study reach, and very tranquil over the lower 3.5 km. The tranquil flow near the tributary mouth reflects a backwater effect from Mackenzie River. The upstream extent of this backwater effect likely varies with stage fluctuations between the tributary

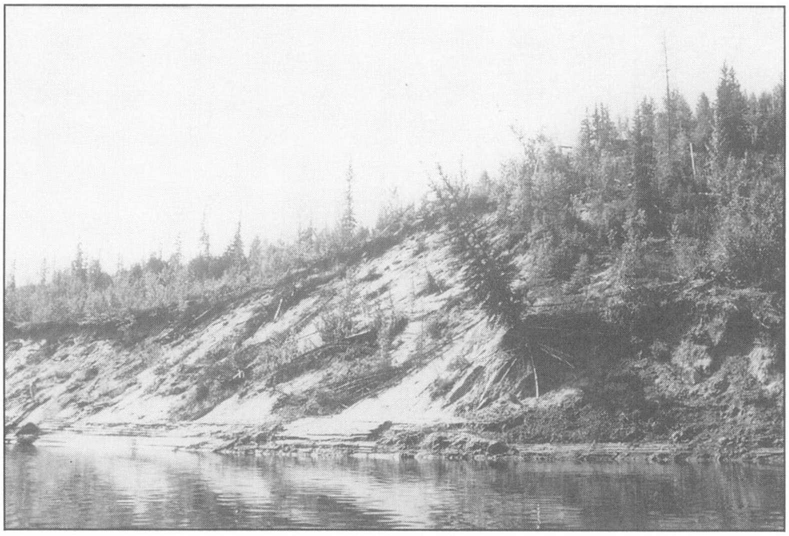


Figure C3.

Detachment block sliding along the concave bank of the upstream-most meander where Willowlake River is confined directly against the valley side. GSC 1993-177S

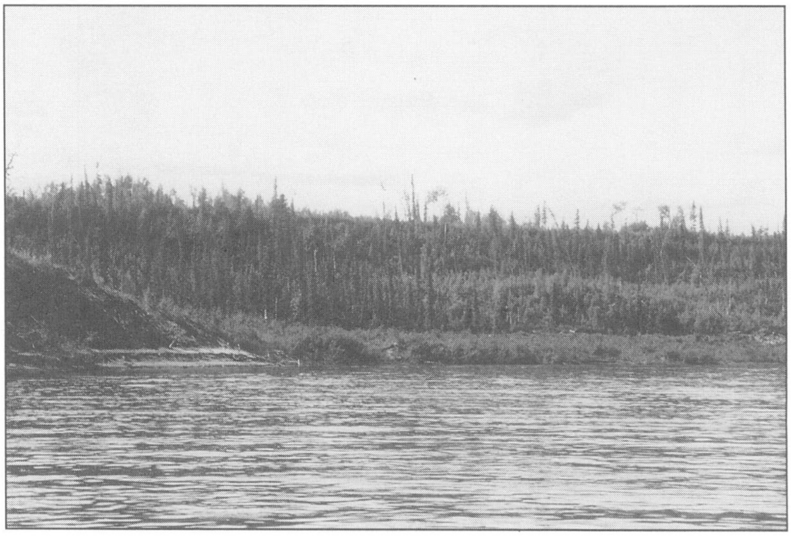


Figure C4.

The large valley side failure opposite the upstream-most meander along the Willowlake River study reach (GSC 1993-177I). In the centre and towards the right of the picture, note the gently sloped, vegetated surface at the river level which is in marked contrast to the eroding face in Figure C3.

and trunk stream. A backwater influence probably causes the general widening of the river toward the river mouth as the hydraulic geometry adjusts to the drop in flow velocity, a situation analogous to a river estuary.

Active channel bars are not common along the study reach. Those that do occur include two point bars situated along the convex sides of the two large meanders and several small side bars (with sand and gravel surfaces) located within 2 km of the river mouth (Fig. C2c). Morphologically, the two point bars are very different. At the observed discharge, a large and wide bar platform that slopes very gently toward the channel was exposed at the upstream point bar. Adjacent to the water surface, this bar platform was unvegetated, consisting of gravel (boulders and cobbles). In the areas back from the channel, the gravel was partially covered by fresh sand deposits forming linear ridges (1 to 2 m wide, less than 10 cm high, and up to tens of metres long) running along the bar surface. These sand ridges eventually coalesce and thicken to form a suprabar platform, 2 to 3 m above the river, before finally merging with overbank deposits of the floodplain. Ice push gouges and furrows are also common on this area of the bar. Shrubs and grasses occur singly and in small bunches on the bar, eventually forming a continuous cover on the back area of the bar platform and on the suprabar platform. As mentioned above, the transition from shrub and grass cover on the bar to the forest cover of the floodplain is abrupt and probably delineates a high water mark.

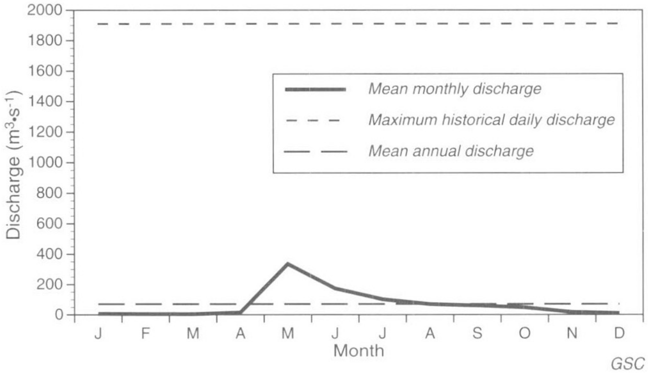


Figure C5. Hydrograph of the Willowlake River streamflow, 1975-1992. 'Willowlake River above Metahdali Creek' station (Water Survey of Canada, unpub. data).

In contrast, the surface of the downstream point bar slopes moderately (about 15°) from the floodplain surface (about 4 m above the water surface) to the river. The bar surface consists of gravel (boulders) near the water surface and gravel (cobbles) and sand on the intermediate and higher parts of the bar face. The bar surface generally is vegetated with a discontinuous to continuous cover of grasses and shrubs; 'fresh' deposits represent only a relatively small portion of the bar surface. In places, the sand and boulder surface appears to resemble a loose boulder pavement, the product of ice-push processes (Fig. C6). The control upon the differing morphology of the two point bars is not known, but may relate to a diminishing influence of backwater originating from Mackenzie River.

During low discharges in the late summer and autumn, minor undulations in the river bed begin to protrude from the water surface and appear as mid-channel and side bars. The occurrence of such bars is stage dependent, although they represent shoals within the channel at higher discharges (compare Fig. C2a and C2b with C2c).

The river banks in the study reach (excluding the point bars) are variable in morphology, but three general types can be recognized. Cutbanks extending up to 20 m above the water surface generally are present opposite the point bars. Of note, the cutbank along the At surface (see section on Valley characteristics, above) is discontinuously covered by grasses and shrubs and appears to have been inactive recently. A second type of bank consists of a loose boulder pavement (boulders and sand) extending up to 4 m above the water surface and which supports a discontinuous to continuous vegetation cover situated upon a moderately sloped face. This type of bank, which is believed to be the product of ice-push processes, is particularly prominent along the lower 2 km of the study reach. The third type of bank is a low angled surface

Figure C6.

Loose boulder pavement on the downstream-most point bar along the Willowlake River study reach. Note the dead trees on the floodplain in the background, the product of a July 1979 forest fire. GSC 1993-177A

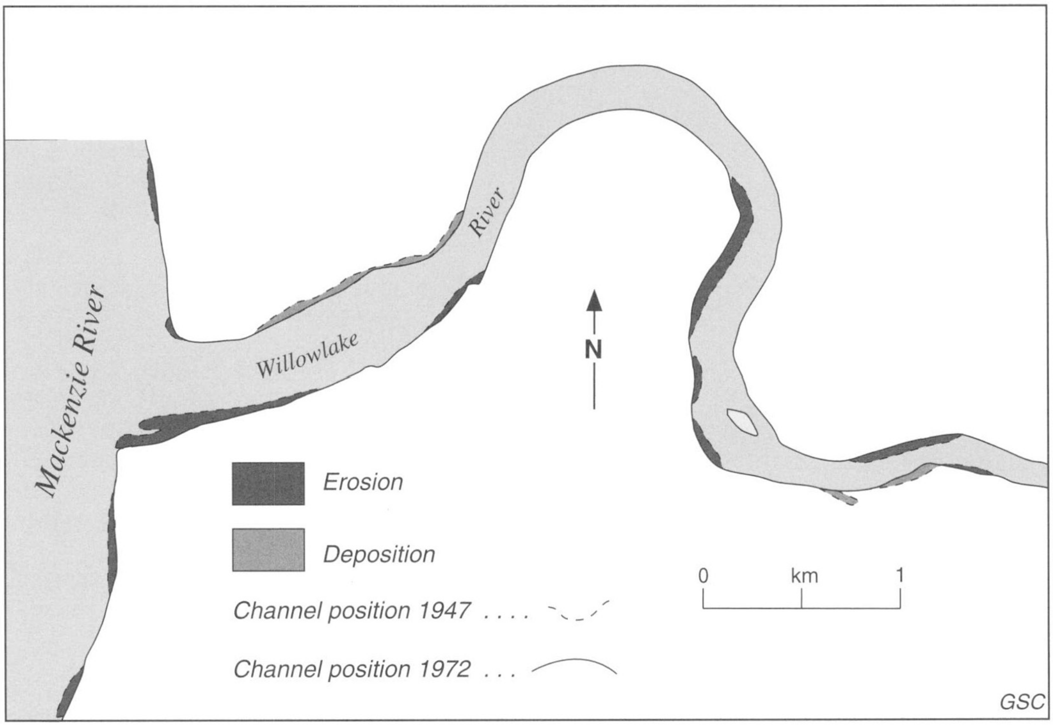


***Figure C7.** Apparent net channel change along the Willowlake River study area between 1947 and 1972.*

supporting a dense vegetation cover of grasses and shrubs. This type of bank is most prominent along the north side of the channel in the inflexion zone between the two meanders, but it also occurs in places opposite the upstream point bar. With the exception of the active cutbanks along the toe of the prominent scar, the river banks generally appear to be stable, experiencing neither significant accretion nor erosion.

Ice-push features are present along the study reach in the form of loose boulder pavement and occasional ice gouges in the river bank (see Fig. C6). In 1992, the study reach experienced severe ice jamming during break-up that resulted in ice overtopping the rip-rap and fill installed as part of a new bridge foundation. This severe jamming is reported to have been related to a large ice jam across Mackenzie River near River Between Two Mountains which would have caused high backwater into the lower reach of Willowlake River, thus, raising the level of ice-thrusting. The level of ice thrusting in 1992 was the highest to occur since at least the 1940s (R. Freschaf, pers. comm., March 19, 1993).

LATERAL CHANNEL CHANGE

Along the Willowlake River study reach, no significant lateral channel migration is apparent in the aerial photographs taken between 1947 and 1972[1] (Fig. C7); the apparent changes that occur reflect stage differences in the river at the time of the photography. This lack of lateral migration probably reflects the location of the active cutbanks against the high valley side or terrace. Willowlake River is also subject to a backwater influence from Mackenzie River which imposes low flow velocity along much of the study reach. This would result in low stream power, thus limiting the ability of the river to erode the high banks.

WILLOWLAKE-MACKENZIE INTERACTION

At the river mouth, the presence of Ap surface adjacent to the channel indicates that Willowlake River has shifted laterally relative to Mackenzie River within a roughly 750 m long corridor (Fig. C1). Field observations and the aerial photograph comparison reveals that there has been no significant lateral migration of the river mouth since 1947 (Fig. C7).

When observed on July 28, 1992, the lower 3.5 km of the river were affected directly by backwater from Mackenzie River, resulting in very tranquil stream flow. The effects of backwater undoubtedly varies with relative stage differences between the two rivers. Characteristics along the study reach that backwater might directly influence include: the development of the regular meandering planform along the study

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[1] The aerial photograph comparison was handicapped by the extreme variation in scale between the 1987 photographs and those from 1947 and 1972 coverage. Specifically, the large scale photography of the 1987 series could not be accurately fitted to the topographic base map. This photography has thus not been incorporated into Figure C7, but close examination of the channel position relative to static features proximal to the river channel reveals that there has been little change between 1972 and 1987 (Fig. C2).

reach from the previously straight channel just upstream; the downstream change in point bar morphology; the general widening of the river channel; and the increasing height of the contemporary floodplain deposits downstream along the study reach.

Probably reflective of a relatively low bed-material transport to Mackenzie River, there is no obvious morphological feature at the mouth of Willowlake River. However, the Mackenzie River channel adjacent to the river mouth experiences an obvious widening from about 900 m just upstream of the confluence to a maximum total width of 2000 m just downstream. A small island is situated mid-channel roughly opposite the river (Fig. C2a). It is not clear if this widening is attributable to the entrance of Willowlake River since similar widenings occur elsewhere along Mackenzie River that are unrelated to the entrance of a tributary. The hydraulic deflection of the Mackenzie River flow by the oblique Willowlake River flow represents a possible explanation for this widening.

In the general area of Willowlake confluence, numerous bars and islands split the Mackenzie River channel forming a multi-channelled platform. Except for the small island immediately adjacent to the confluence, this multi-channelled morphology is not attributable to Willowlake River. Some of the islands and bars may be the product of bed-material supply from North Nahanni and Root rivers, while McGern Island was formed from the incision of Mackenzie River into Quaternary deposits.

APPENDIX D

Blackwater River

STUDY REACH DESCRIPTION

Blackwater River is 210 km long and drains an area of about 10 500 km^2 (Table 1). The headwaters of the river are situated within the Great Slave Plain from where the river flows north-northwest onto the Great Bear Plain and into the southern end of Blackwater Lake (Fig. 2). From an outlet on the west side of Blackwater Lake, the river flows westward through a gap in the McConnell Range of the Franklin Mountains, across the Mackenzie Lowland and into Mackenzie River (Fig. 2).

The study reach extends along the lower approximately 4 km of Blackwater River, beginning immediately below the confluence of a major (unnamed) creek entering from the north (Fig. D1). Over the upper 2 to 4 km of the study reach, the river flows within a stream-cut valley (Blackwater Valley) incised 80 to 90 m into the Mackenzie Lowland. Blackwater Valley opens into Mackenzie River valley 1 to 2 km above the river mouth (Fig. D1). Blackwater River is crossed by the Wrigley-Fort Norman winter road and the Norman Wells pipeline about 600 and 1500 m above the mouth, respectively (Fig. D2c).

Bedrock underlying the study reach consists of Upper Devonian shale and mudstone, and siltstone of the Fort Simpson Formation, but may include Middle Devonian shale of the Horn River Formation (Douglas, 1973). These rock formations are not reported to outcrop along the valley sides of the study reach.

Surficial geology of the Mackenzie Lowland adjacent to the study reach relates directly to the former presence of glacial Lake Mackenzie (see Smith, 1992). Rutter and Boydell (1972)

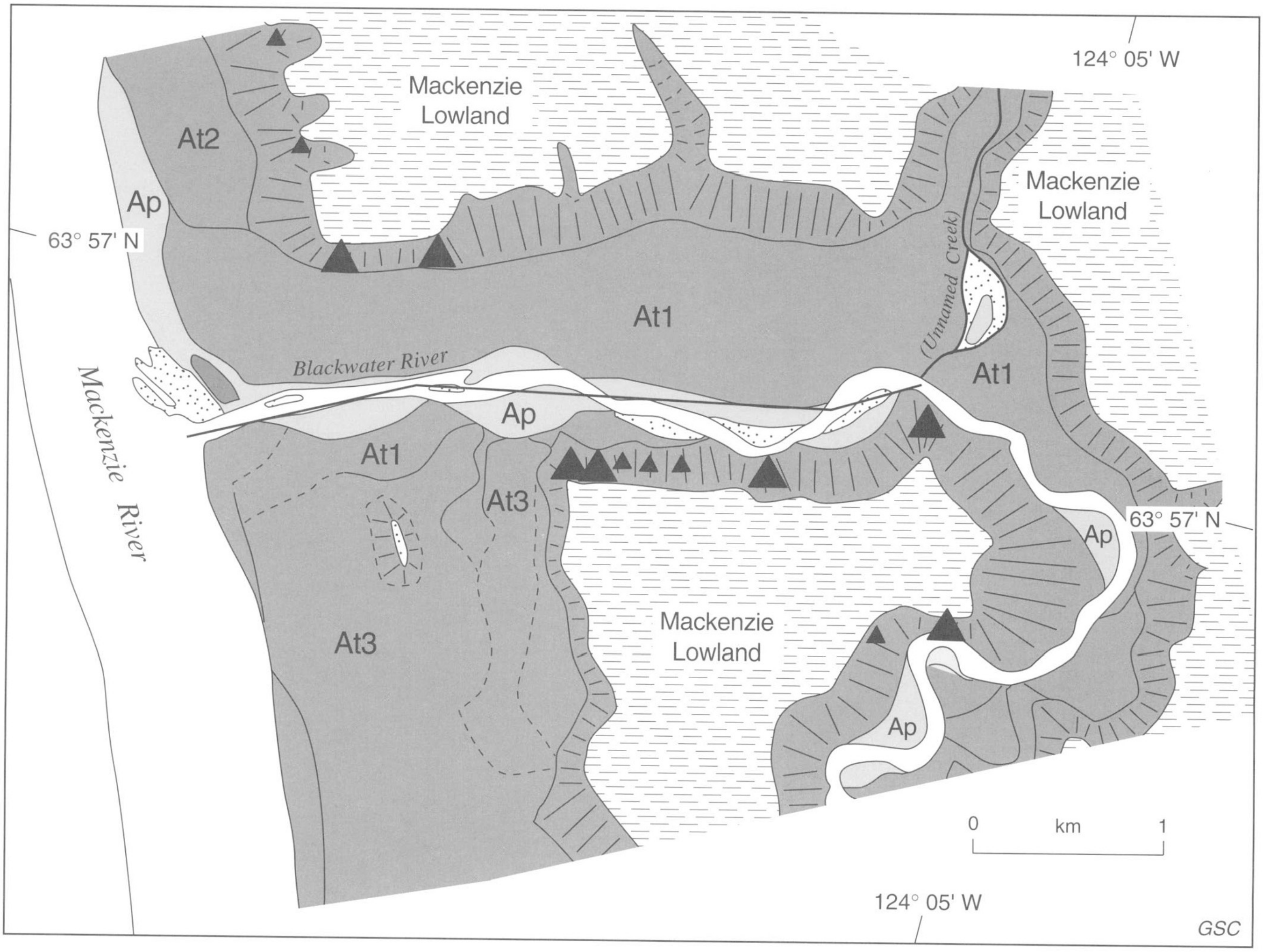


Figure D1. Physiographic map of the Blackwater River study area (uncorrected from aerial photographs NAPL A22887-13, A22859-34). Refer to Figure A1 for legend.

mapped the area as silty glaciolacustrine plain, while Smith (1992, Fig. 1) shows deltaic deposits immediately to the east of the Blackwater-Mackenzie confluence. It is not clear if the transition from glaciolacustrine plain to deltaic deposits occurs within or to the east of the study reach.

The surface of the Mackenzie Lowland is densely forested with coniferous trees, but large tracts of this surface, including the sides and bottom of Blackwater Valley, were burned in July 1979 (R. Lanoville, pers. comm., December 11, 1992). Regrowth of the forest is occurring naturally and is in an early stage of succession. Several small lakes and wetlands are present on the lowland surface to the north of the study reach.

The sides of Blackwater Valley are believed to consist entirely of Quaternary deposits (see Douglas, 1973). Although the composition of the valley sides was not examined in detail, a lithostratigraphical log of a river bank from the "Blackwater River mouth" in Smith (1992, Fig. 7) reveals about 85 m of unconsolidated material. More specifically, the deposits consist of interbedded lacustrine and fluvial sediments (about 0 to 15 m), lacustrine sediments (about 15 to 35 m), unexposed sediments (about 35 to 55 m), and 'till' (about 55 to 85 m). The till unit probably extends beneath the level of the Mackenzie River water surface. The lateral persistence of these units upstream along Blackwater Valley is not known.

The postglacial history of Blackwater River incision into the Mackenzie Lowland is not known.

VALLEY CHARACTERISTICS

Along the study reach, the width of the valley bottom is fairly uniform, ranging from 900 to 1200 m (Fig. D1). The study reach is situated immediately downstream of a valley confluence where an unnamed creek valley joins Blackwater Valley (Fig. D1). Upstream of the study reach, Blackwater Valley is very different from the study reach, being sinuous with irregular meanders, and considerably narrower (the valley bottom ranges from 200 to 600 m wide). It is not known why Blackwater Valley straightens and widens quite suddenly with the merging of the unnamed creek valley.

Numerous small- to medium-sized slope failures occur along the relatively steep 80 to 90 m high valley sides of the study reach. Most of the failures are located on slopes that are not being undercut by the river (Fig. D1 and D2c). Many of these failures are situated on burned ground, suggesting that their presence is related to the July 1979 forest fire, probably being caused by the deepening of the permafrost active layer due to the resulting change in the vegetation cover. One exception to this is a large cutbank failure located on the southern valley side about 3 km above the river mouth which is present in all of the aerial photographs (Fig. D1 and D2).

Along the study reach, Blackwater River is positioned toward the southern side of the valley. Direct confinement of the river against the valley side occurs only along the upper quarter of the study reach, resulting most notably in the formation of the large cutbank mentioned above. The confined length of river, expressed as a proportion of the total length of the valley sides formed by the Mackenzie Lowland, At2 and At3 surfaces (Fig. D1), is about 7%. Above the study reach, where Blackwater Valley is sinuous and relatively narrow, cutbank erosion of the valley sides is much more common.

At least four surfaces relating to fluvial activities occur below the level of the Mackenzie Lowland (Fig. D1). The Ap surface represents a series of fragmentary surfaces 1 to 3 m above the river that are present along both sides of the river within a 250 m wide zone. Vegetation growing on the Ap surface generally ranges from a patchy to nearly continuous cover of herbaceous vegetation and saplings; isolated stands of mature coniferous trees occur sporadically on some of the higher areas. Half buried boulders are scattered about the Ap surface. On some parts of the Ap surface, there are relatively fresh tongues of sand or gravel representing recent flood deposits (Fig. D3), while abandoned channels form linear depressions up to several metres deep running more or less parallel to the river. On August 2, 1992, one of these channels had standing water in its downstream end. From the sediments visible along the river banks, the composition of the Ap surface generally appears to be gravel (boulders and cobbles) overlain by a discontinuous cover of silt and sand up to several tens of centimetres thick. This capping of fine sediment is particularly well developed near the river mouth. Combined, the Ap surface is interpreted as the contemporary floodplain of Blackwater River.

The At1 surface is situated 4 to 5 m above the river surface. It is paired and represents a large portion of the valley bottom, particularly to the north of the river, where it forms a continuous plain along the study reach. This surface is covered with a mature coniferous forest, much of which was burned in July 1979. Channel scars on this surface are apparent in the texture of the vegetation cover, particularly along the lower half of the study reach to the north of the river (Fig. D2a). An alluvial fan is splayed part way across the valley bottom that originates from a large gully draining the north side of the valley. An exposure along the river reveals that the At1 surface is composed of a boulder unit about 2 m thick overlain by 2 to 3 m of poorly sorted, massive, sand and gravel (Fig. D4). The At1 surface is interpreted as an alluvial terrace of Blackwater River. The existence of this extensive surface along the valley bottom suggests that Blackwater River was vertically stable several metres above its present position at some time in the past. It is not known if this terrace is aggradational or erosional in origin. The combined Ap and At1 surfaces form the bottom of Blackwater Valley.

The At2 surface was not observed directly, but on the aerial photographs it appears to be several metres higher than the At1 terrace. This surface is covered with a mature coniferous forest. The extension of the At2 surface downstream along Mackenzie River valley rather than Blackwater Valley suggests that it relates to Mackenzie River.

At3 is a complex of surfaces of different heights that will be described together. Some of the surfaces represent fragments of flat terraces up to tens of metres above the river while others appear somewhat irregular in topography. The At3 terrace complex extends upstream (to the south) along

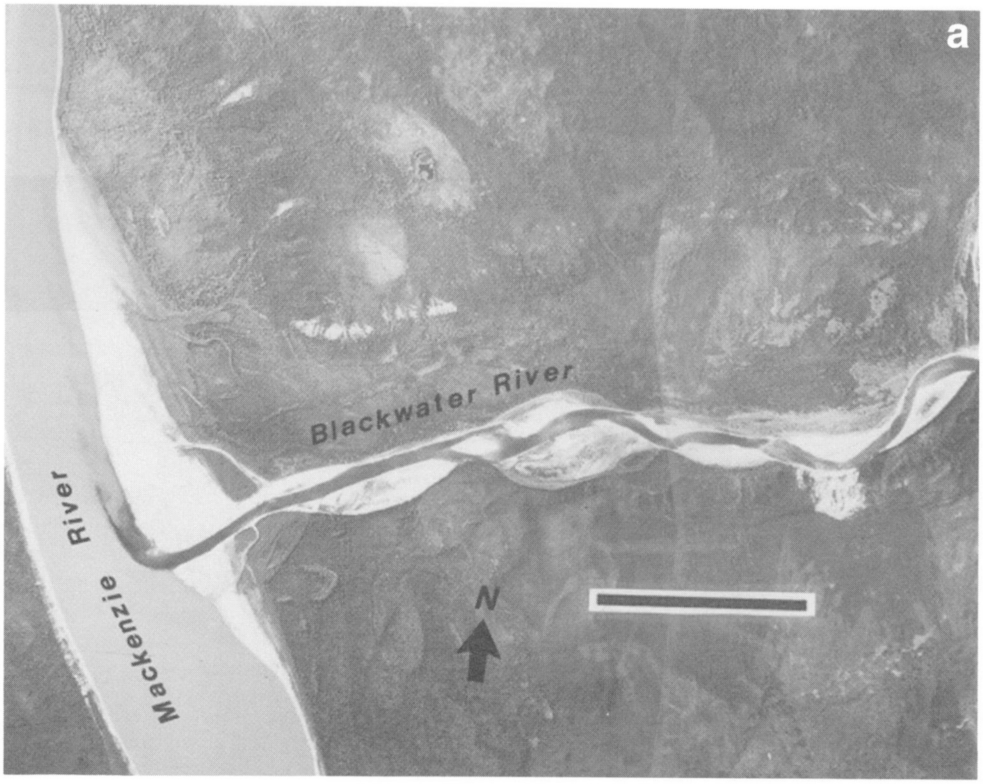


Figure D2. *Sequence of aerial photographs of the Blackwater River study reach* ***a****) 1945 (NAPL A8716-35, -36),* ***b****) 1972 (NAPL A22859-34, A22887-13), and* **c***) 1987 (NAPL A27229-87, -96); the black bar on each photograph represents one kilometre.*

Figure D2b.

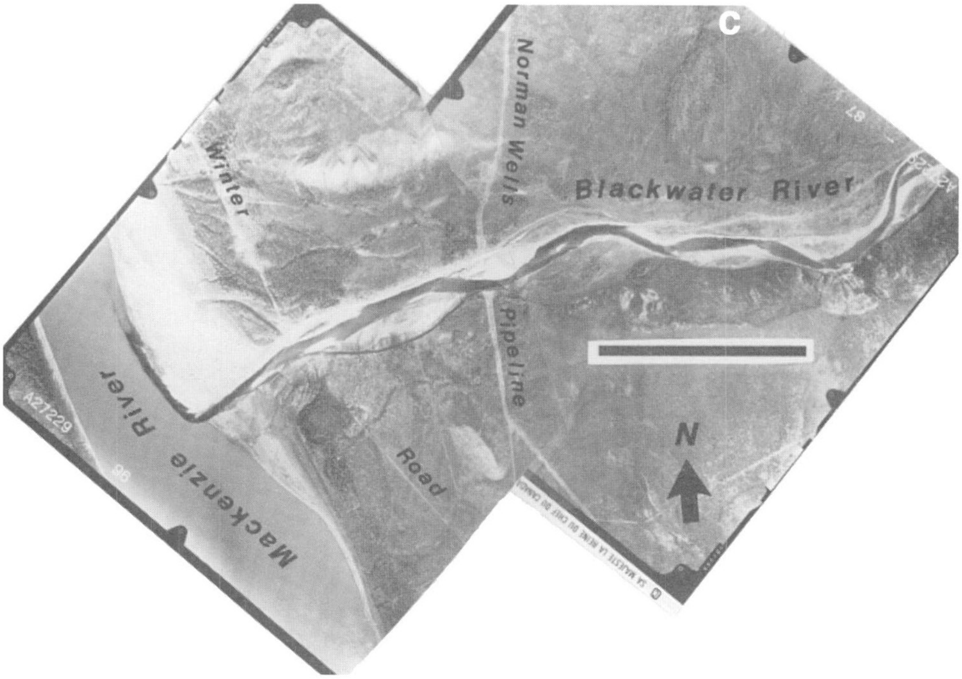


Figure D2c.

Mackenzie River valley, beginning from about the lower 2 km of Blackwater Valley (Fig. D1). It is interpreted as relating to Mackenzie River. Equivalent surfaces relating directly to Blackwater River are not present along the study reach.

Along Blackwater Valley upstream of the study reach, terrace fragments, including a well-developed meander cutoff, occur at least two levels above the floodplain. The correlation of these terraces to any other levels along the study reach is not known.

HYDROLOGY

The streamflow of Blackwater River was measured between 1983 to 1985 at a station located 'near the mouth'. In 1986, this station was moved to the 'outlet of Blackwater Lake' situated about 60 km upstream of the river mouth (Water Survey of Canada, 1992a).

From the 1986 to 1992 record of the 'Blackwater River at outlet of Blackwater Lake' station, mean annual discharge was 47 $m^3 \cdot s^{-1}$ (Fig. D5). The maximum mean monthly discharge was 181 $m^3 \cdot s^{-1}$ occurring in June, the product of the spring melt (Fig. D5; C. Brumwell, written comm., September 27, 1993). The maximum daily discharge in the record is 573 $m^3 \cdot s^{-1}$ recorded on June 1, 1992. Since this discharge is not excessively greater than the maximum mean monthly discharge, Blackwater River probably dampens the discharge, limiting the magnitude of extreme flows. The minimum mean monthly discharge is about 3 $m^3 \cdot s^{-1}$, occurring in March; this figure does not differ significantly from the minimum historical daily discharge of 0.6 $m^3 \cdot s^{-1}$ recorded at the 'near the mouth' station on March 25, 1984.

Along the study reach, the bouldery bed and insignificant lateral channel change over the past about 40 years (see section on Lateral channel change, below) suggests that bed-material transport rates are relatively low. Concurring with this, P. Wood reported that very little sediment is transported by Blackwater River (pers. comm., January 13, 1994).

Suspended sediment load along Blackwater River is not monitored. The waters in Blackwater River are stained brown by organic acids originating from extensive wetlands within the drainage basin; the river's name undoubtedly refers to this staining. Despite the staining, the river waters at the time of observation (August 1, 1992) were clear; they also appear clear in the three sets of aerial photographs (Fig. D2) and were reported clear by Camsell and Malcolm (1921). Blackwater Lake undoubtedly functions as a major sediment trap within the drainage basin, thereby limiting the suspended sediment load at the river mouth. The dark and clear waters of Blackwater River form an obvious plume in Mackenzie River that extends downstream from the tributary mouth (Fig. D2).

CHANNEL CHARACTERISTICS

Along the study reach, Blackwater River is a single channel stream with a gravel bed, primarily consisting of a boulder lag (Fig. D6). The unvegetated channel zone in which the river flows, ranges from 75 to 175 m wide. During the site visit (August 2, 1992), discharge at the 'Blackwater River at outlet of Blackwater Lake' station was 52 $m^3 \cdot s^{-1}$ (D. Anderson, written comm., February 3, 1994). Flow was swift and alternating between pools and riffles. Between about 2.5 and 5 km above the river mouth, valley slope averages 0.006, estimated from 1:50 000 scale NTS map 95N/16. From data in UMA-Canuck-Hardy (1983b), channel slope between 500 m upstream and 400 m downstream of the Norman Wells pipeline is estimated to be 0.005.

The channel planform along the study reach is relatively straight with a sinuosity of only 1.06. Above the study reach, however, the river exhibits irregular meanders (sinuosity 1.3) that are entrenched in the Mackenzie Lowland. The control upon the river causing this major change in sinuosity is not known.

Typically, the river banks are composed of a boulder lag (Fig. D4 and D6). Fresh cutbanks are relatively uncommon, reflecting the stability of the channel (see section on Lateral channel change, below).

A number of point and side bars occur along the river, imparting a slight sinuosity to the channel within the unvegetated channel zone (Fig. D2a). These bars generally are low-angled, sloping gently from the floodplain to the channel. Several mid-channel bars are also present, causing the channel to split in places. Typically, the mid-channel bars have a low relief above the water surface (less than 1 m), but a bar located about 500 m above the river mouth is 2 to 3 m above the river and likely represents dissected floodplain. At the river mouth, a large channel junction bar is splayed into the Mackenzie River channel (Fig. D2b).

Along the study reach, the surface of the bars generally consists of gravel (boulders and cobbles). Within 500 m of the river mouth, pebbles and sand are present amongst the boulders and cobbles, and as sheets on the floodplain. At the river mouth, sand sheets form a discontinuous veneer over large parts of the channel junction bar (Fig. D7). The occurrence of these finer sediments along the lower end of the study reach probably reflects inundation by backwater from Mackenzie River. The sand sheets on the channel junction bar probably have originated from the trunk stream rather than Blackwater River since similar deposits are present on the eastern bank of Mackenzie River, 1 to 2 km upstream of the Blackwater confluence.

Figure D3.

Relatively fresh wood debris, sand, and gravel deposits on the contemporary floodplain (Ap surface) of Blackwater River. GSC 1993-177B

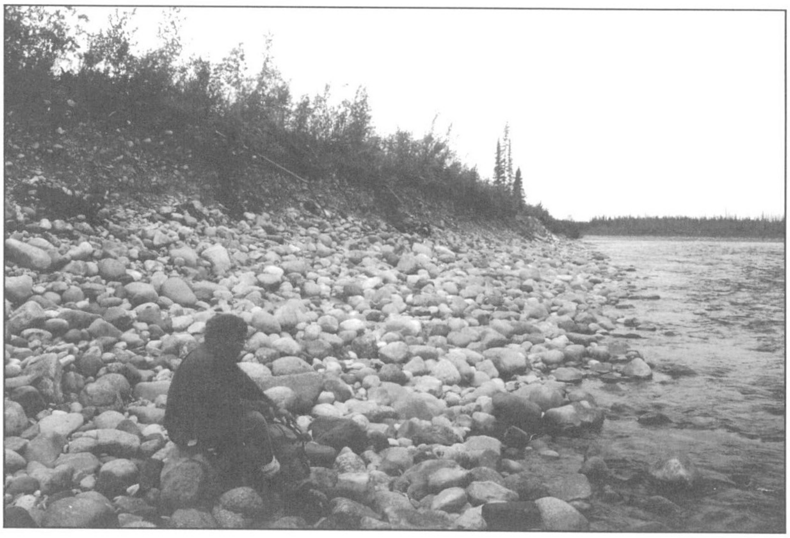


Figure D4.

Bouldery bank of Blackwater River. An exposure of the At1 surface along the top of the bank reveals a unit of poorly sorted gravel. GSC 1993-177U

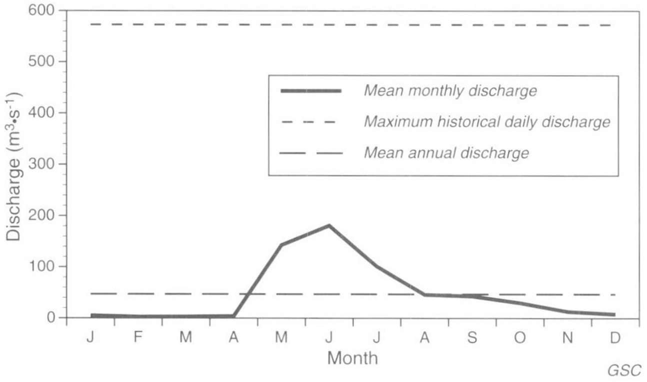


Figure D5. *Hydrograph of the Blackwater River streamflow, 1986-1992, 'Blackwater River at outlet of Blackwater Lake' station (Water Survey of Canada, unpub. data).*

No ice-push features were observed along Blackwater River, but a line of driftwood, 4 to 5 m above the observed river surface that was located within 500 m of the river mouth probably marks the level of 'recent' high backwater flooding from Mackenzie River.

LATERAL CHANNEL CHANGE

Aerial photograph comparison (Fig. D8) suggests that there was some lateral migration to the unvegetated channel zone along Blackwater River between 1945 and 1987. Close inspection of the aerial photographs, however, reveals that there was little change in the position of the river banks relative to static features on the floodplain (Fig. D2a, b, c). Some of the apparent change in Figure D8 may be due to error associated with the aerial photograph comparison and/or to shifting in the vegetation line along the river that is independent of any lateral channel migration. Overall, there appears to have been little significant major lateral migration of Blackwater River along the study reach between 1945 and 1987.

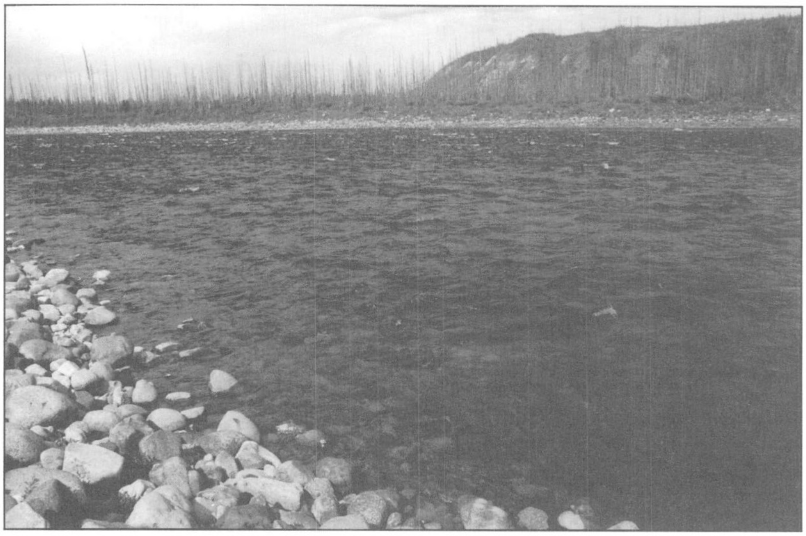


Figure D6.

The gravel bed channel and swift, clear waters of Blackwater River. Note the dead trees on the opposite bank in the background, killed by a large forest fire in July 1979. GSC 1993-177Z

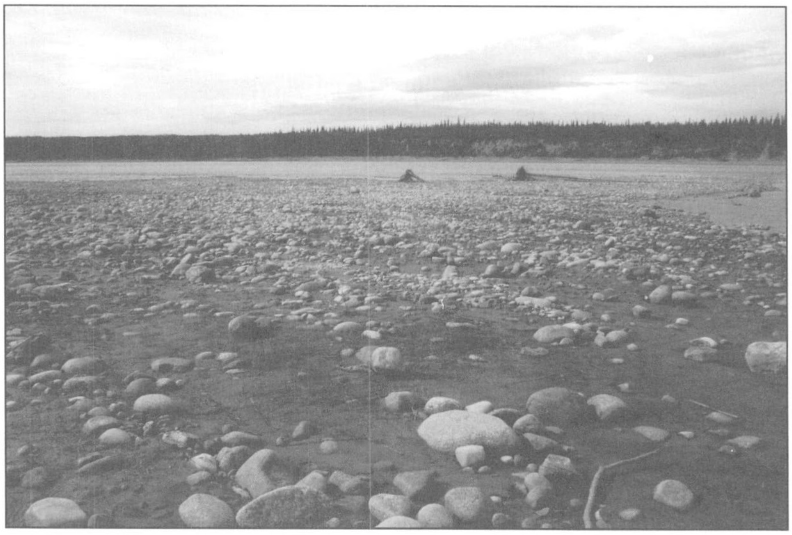


Figure D7.

Discontinuous sand sheets on an exposed channel junction bar at the Blackwater River mouth. GSC 1992-177BB

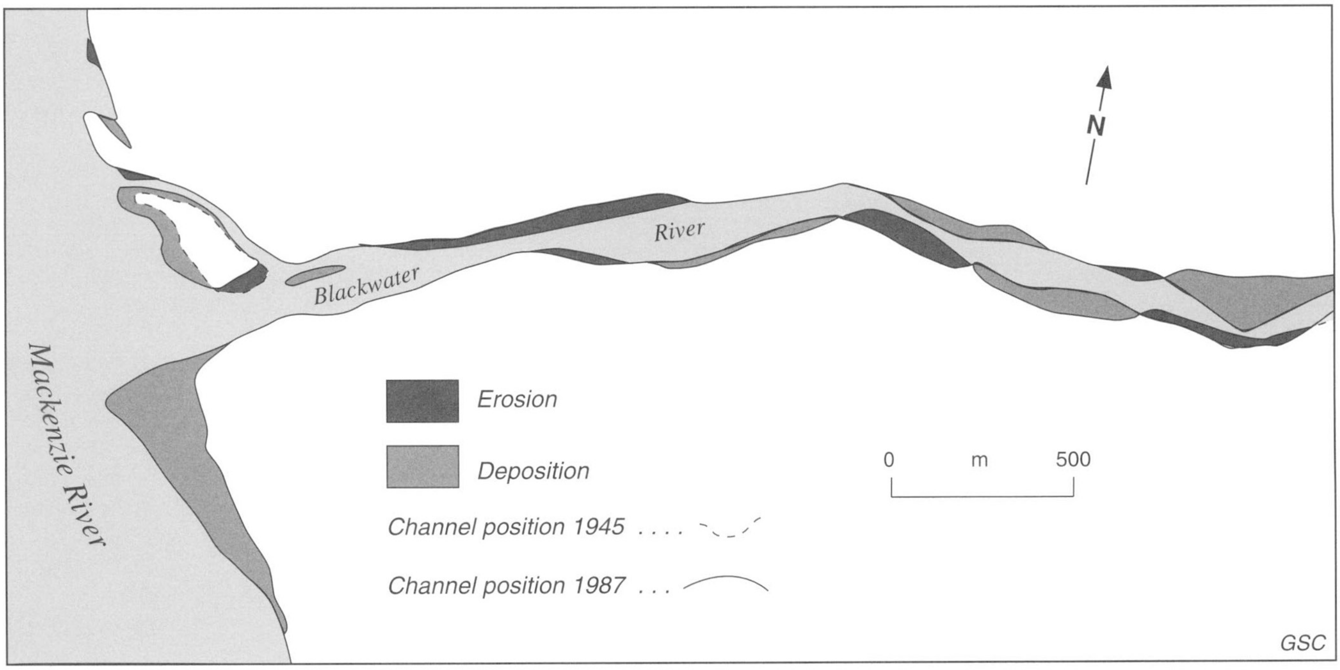


Figure D8. *Apparent channel change along the Blackwater River study area between 1945 and 1987.*

Within the unvegetated channel zone along the river, 'real' change to the river is difficult to detect because of river stage differences between the three sets of aerial photographs. The only obvious change concerns the location of mid-channel bars (which cause the splitting of the channel) in the 1972 photographs which differs from that of the 1945 and 1987 photography (Fig. D2a, b, c). However, this may only reflect changes in river stage since the discharge in the 1945 and 1987 photographs appears to be much lower than that in 1972 (as revealed by the relative size of the channel junction bar at the river mouth). It is possible that avulsions of the river cause the shifting of the main channel from one side of a mid-channel bar to the other, but without major displacement of the river banks.

Site inspection of Blackwater River did not reveal any significant changes to the river with respect to the 1987 photography. The coarse nature of the channel materials undoubtedly contributes to the lateral channel stability of Blackwater River. The attenuation of the discharge regime by water storage in Blackwater Lake (see section on Hydrology, above) may also be a factor in limiting the channel change because the river does not experience extreme discharges which may cause significant erosion of the river banks.

The existence of abandoned channels on the floodplain and the channel scars on the At1 terrace indicates that major changes to the lateral position of the river have occurred in the past. These changes have occurred presumably through the progressive lateral migration of the channel and by avulsions. Given the present morphology of the valley bottom (see section on Valley characteristics, above), a similar change to the river could occur within the narrow zone of the valley bottom formed by the Ap surface (floodplain). Since 1945, however, there has been no significant lateral migration and avulsions of the channel.

BLACKWATER-MACKENZIE INTERACTION

At the Blackwater-Mackenzie confluence, the presence of the Ap surface on either side of Blackwater Valley indicates that the river mouth has shifted laterally within a 600 m wide corridor relative to Mackenzie River (Fig. D1). The present trend of migration, however, is not obvious in Figure D8.

Because of its relatively steep gradient and swift flow, Blackwater River appears to be affected little by backwater except during relatively high Mackenzie River stages. The most obvious influence arising from backwater conditions is the presence of finer gravel and sand on the river bars and floodplain within the lower 500 m of the river.

At the river mouth, a large channel junction bar is splayed 500 m into and about 3000 m along Mackenzie River (Fig. D2a). This bar has formed despite relatively low bed-material transport rates from Blackwater River (see section on Hydrology, above). It causes constriction of the adjacent Mackenzie River channel (particularly at low river stages) and very slight deflection of the opposite river bank (Fig. D2b). The bar, however, is a moribund feature at the river mouth. It undoubtedly is the product of a higher bed-material transport in the distant(?) past.

Upstream of Blackwater confluence, the Mackenzie River channel is single channelled and relatively straight. Downstream, beginning between Blackwater and Dahadinni confluences, the channel widens and bars and islands become more prevalent in response to an increase in valley gradient and supply of bed material from Dahadinni River and from cutbank erosion and slope failures of the Mackenzie River valley sides. The influence of Blackwater River in this channel change is minor because its bed-material transport to Mackenzie River is low.

APPENDIX E

Dahadinni River

STUDY REACH DESCRIPTION

Dahadinni River is 125 km long and drains an area of about 2700 km^2 (Table 1). The river flows initially along a northerly course, beginning from its headwaters in the Redstone Range of the Mackenzie Mountains. Prior to exiting the mountains, the river course shifts towards the northeast, a direction that the river follows out of the mountains, across the Mackenzie Lowland, where it merges with Mackenzie River (Fig. 2).

The study reach is located along the lowest 6 km of Dahadinni River (Fig. E1). Along this reach, the river flows within a valley incised roughly 90 m into the Mackenzie Lowland. The lower 1 km of the river flows across a low-angled alluvial fan splayed into Mackenzie River valley (Fig. E1).

Bedrock underlying the study reach is Cretaceous sandstone and shale (Douglas, 1973). Bedrock is reported to outcrop along the north side of the valley about 5 km above the river mouth (Hume, 1924). Downstream of this location,

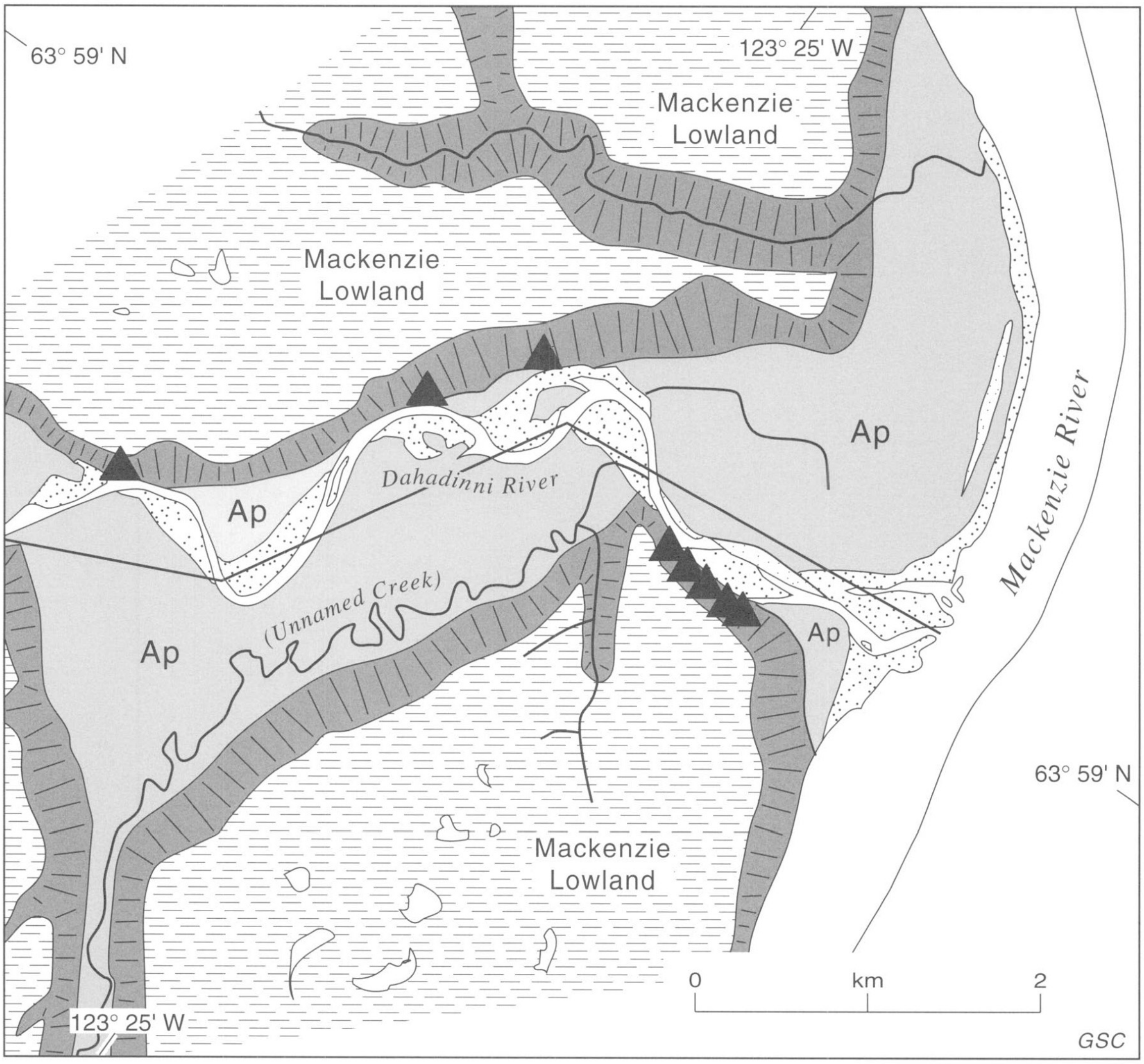
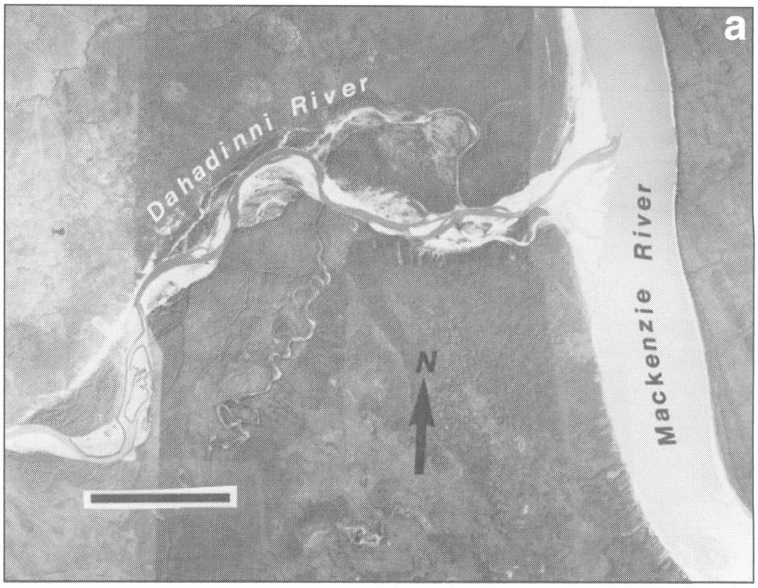


Figure E1. Physiographic map of the Dahadinni River study area (uncorrected from aerial photograph NAPL A22427-52). Refer to Figure A1 for legend.

Figure E2.

*Sequence of aerial photographs of the Dahadinni River study reach **a**) 1945 (NAPL A8717-58, -59, -60), **b**) 1971 (NAPL A22427-52), and **c**) 1981 (NAPL A25821-168); the black bar on each photograph represents one kilometre. In a) and c), the river bars have been outlined and shaded to enhance their appearance.*



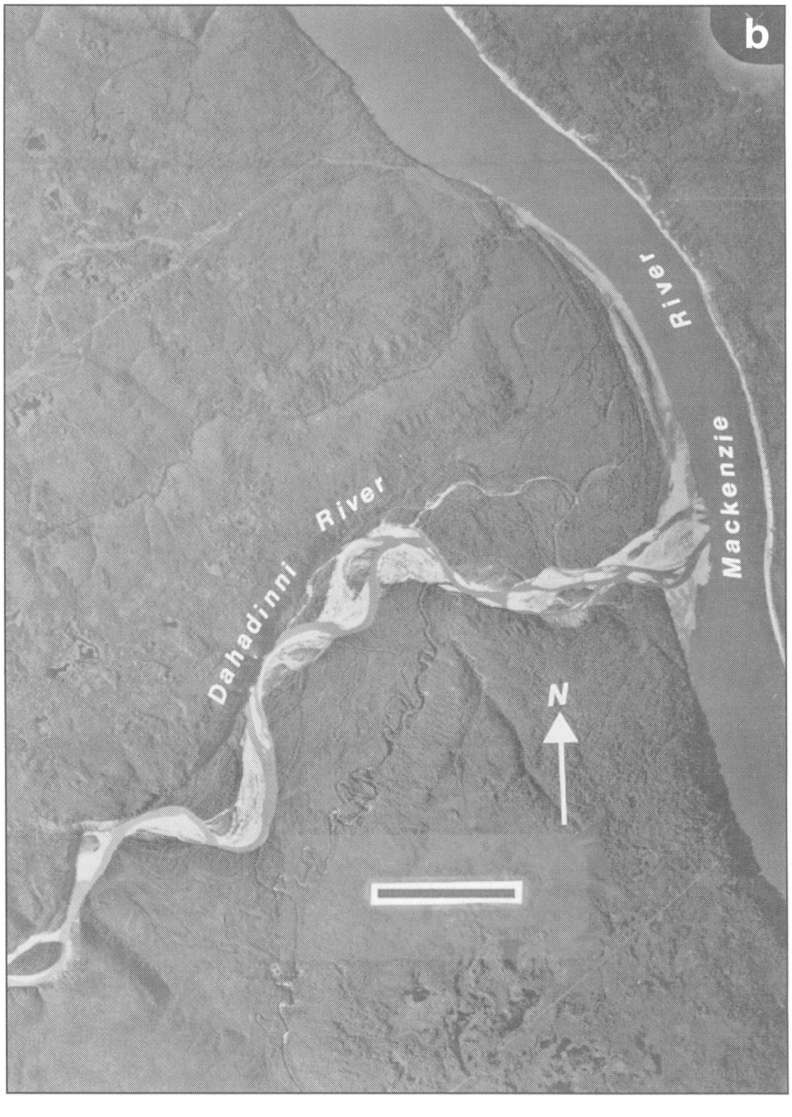


Figure E2b.

the valley sides are composed entirely of Quaternary sediments (Hume, 1954); an exposure about 90 m high occurs at a large cutbank along the southern side of the valley near the river mouth (Fig. E1). Basal sediments, 15 to 20 m thick, along this exposure consist of stratified gravel with sand lenses.

Rutter and Boydell (1972) mapped the surficial geology of the Mackenzie Lowland adjacent to the study area as morainic till plain and wetland (bog and fen). Smith (1992, Fig. 9), however, shows this area inundated beneath glacial Lake Mackenzie during the waning of the late Wisconsinan Glaciation suggesting that glaciolacustrine and/or related deposits form at least a portion of the surficial geology. Numerous small lakes are present within the wetland areas of the Mackenzie Lowland; some of the wetlands occupy thermokarst depressions (Rutter and Boydell, 1972).

The postglacial history of Dahadinni River incision into the Mackenzie Lowland is not known.

VALLEY CHARACTERISTICS

Along the lowest 15 km of Dahadinni Valley, the valley bottom generally ranges from 1000 to 1500 m wide. Locally it narrows to 300 m and may be up to 2000 m wide at the junctions of major creek valleys. At the very narrow sections of the valley, the active channel zone width is approximately equal to that of the valley bottom suggesting that the valley is the product of Dahadinni River incision. The wider sections of the valley probably are a result of lateral channel migration.

Along the study reach, the valley bottom consists of large tracts of contemporary floodplain up to five times the active channel zone width (Ap in Fig. E1). The floodplain is nearly continuous along both sides of the river, being absent only for short sections where the river is confined against a valley side. A dense coniferous forest cover grows upon the valley bottom; recently accreted floodplain or abandoned channels are covered with deciduous forest. As observed at fresh cutbanks along the

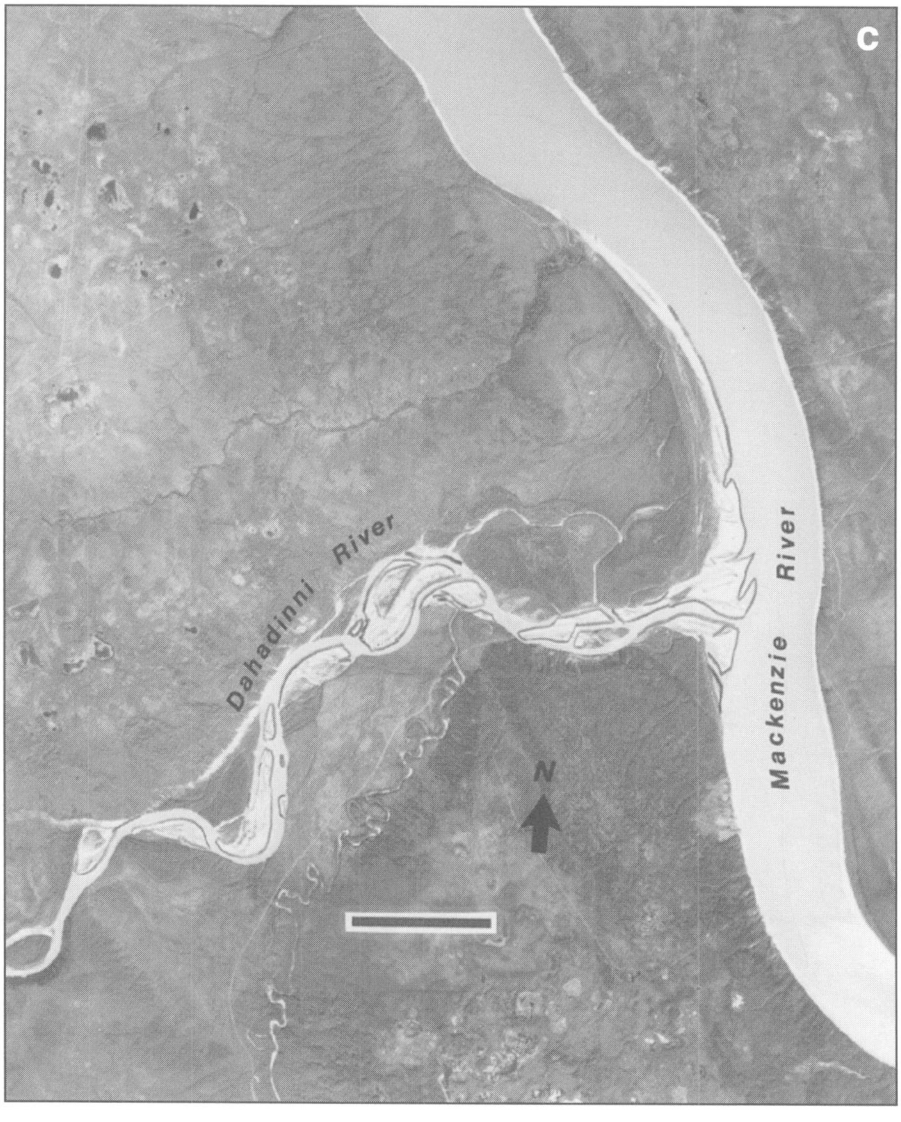


Figure E2c.

lower 2 km of the study reach, floodplain deposits are 2 to 4 m thick, consisting of 1 to 2 m of channel gravel overlain by 1 to 3 m of interbedded silt and sand overbank sediments.

The valley bottom has formed primarily from the lateral migration of Dahadinni River as is evident from the numerous channel scars on all areas of the floodplain (Fig. E2b). An exception to this is a narrow strip of floodplain deposits along the southern side of the valley that has originated from the major unnamed creek entering from the south (Fig. E1). This strip follows the creek course as it flows for a short distance along the valley bottom before joining Dahadinni River.

No alluvial terraces are present along the study reach despite Dahadinni River being incised roughly 90 m into the Mackenzie Lowland. Along Dahadinni Valley just upstream of the study reach, however, two isolated terrace fragments are present approximately 6.25 and 7.25 km from the river mouth. Along the eastern side of Mackenzie River valley opposite the mouth of Dahadinni River, a bench is situated just below the Mackenzie Lowland the formation of which is related to Mackenzie River incision.

In some parts of the study reach, Dahadinni River is confined directly against the valley sides (Fig. E1). The proportion of this confinement to the total length of valley side is about 22%. At several locations of direct confinement, the presence of large scars suggests that cutbank erosion has precipitated failure of the valley sides (Fig. E1). Major failures along the valley sides, however, are not contingent exclusively upon undercutting of the basal slope by the river, as several fresh scars (formed in spring 1992?) were observed well away from the active channel zone on the southern side of the valley near the river mouth. Failure at these locations appears to have occurred primarily through detachment block sliding and flowing, a mechanism commonly associated with slopes containing permafrost.

HYDROLOGY

The streamflow of Dahadinni River is ungauged. The discharge regime likely is similar to Redstone River in the adjacent watershed to north (see section on Redstone River-Hydrology, Appendix F). At moderate discharges, the active channel zone is very wide relative to the active channel width (Figs. E2a, E3, and E4; see section on Channel characteristics, below) suggesting that the river periodically experiences extreme discharges, probably the result of summer rain storms (see Jasper and Kerr, 1992).

Dahadinni River has a relatively high bed-material transport rate as indicated by the considerable amount of lateral channel change along the study reach (see section on Lateral channel change, below). The suspended sediment load is not monitored. When visited (August 4, 1992), the waters were relatively clear. Presumably, the river experiences relatively high suspended sediment concentrations in the spring which decrease over the summer, analogous with Redstone River (see section on Redstone River-Hydrology, Appendix F).

CHANNEL CHARACTERISTICS

Dahadinni River is an alluvial stream with a gravel bed (Fig. E3 and E4). At moderate discharges, flow is relatively swift and alternates between riffles and pools. As estimated from 1:50 000 scale NTS maps 95N/15 and 95N/16, the valley slope averages 0.0045, between 3.25 to 10 km above the river mouth.

Channel planform is variable depending upon the river stage. At low to moderate discharges, the channel is predominantly single and meanders within a wide active channel zone (Fig E2b); mid-channel bars do occur, however, causing some splitting of the channel, particularly along approximately the lower 2 km of the study reach. At higher stages, the inundation of inactive channels within the active channel zone creates a multi-channelled morphology more characteristic of a braided planform. The general river planform is considered

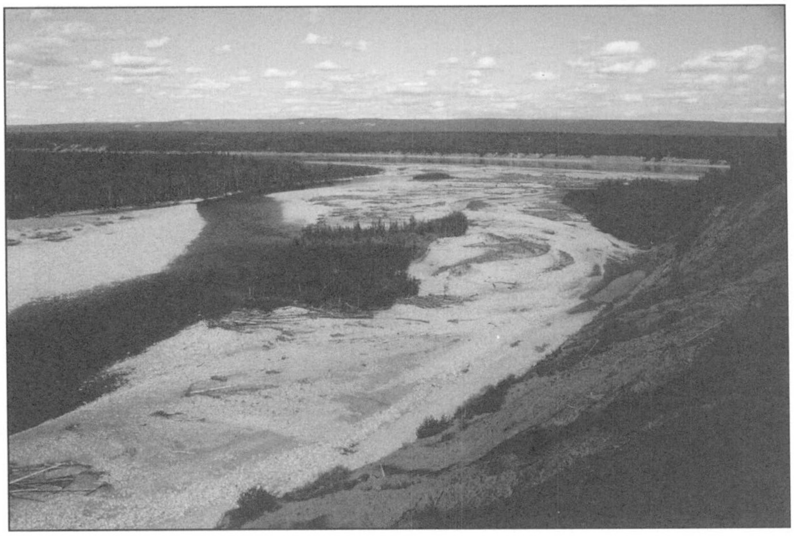


Figure E3.

Dahadinni River viewed towards the river mouth from the edge of the Mackenzie Lowland. Note that the active channel zone is much wider than the river channel at this stage. GSC 1993-177T to be transitional meandering-braided and probably falls within the wandering gravel-bed river morphology (see Desloges and Church, 1989).

The width of the active channel zone ranges from 50 to 450 m. As seen in Figures E2b, E3, and E4, up to 80% of the active channel zone width consists of unvegetated bars. The large size of this unvegetated area suggests that the active channel zone has been subject to very recent fluvial activity, possibly during spring 1992, but almost certainly during a July 1988 flood (see Jasper and Kerr, 1992).

Point bars are the most common type of bar along the study reach (Fig. E2b). Side and mid-channel bars are also relatively common and there are several vegetated islands.

During the site inspection (August 4, 1992), the subaerial portions of the river bars were composed of gravel with large areas covered with sand sheets, up to several tens of centimetres thick. The sand sheets were dissected by inactive channels with gravel-bottoms, that sweep across the bar surface and which would carry discharge at higher river stages (Fig. E4).

Near the river mouth, exposed bars and inactive channels were covered with a thin drape of fine sand and silt (up to several centimetres thick) that has settled within a low-energy depositional environment formed by backwater from Mackenzie River (Fig. E5).

Numerous isolated logs and small log jams are present on the bar surfaces throughout the active channel zone (Fig. E3, E4, and E5); several large log jams were present at the river mouth. The abundance of logs and log jams on the bars suggests that a high degree of concave bank erosion is occurring along the margins of the active channel zone and is introducing trees to the river both within and upstream of the study reach. The log jams represent relatively minor to moderate obstructions of flow, but these may influence channel avulsion processes, particularly near the river mouth. Minor obstructions to flow are also caused by several anomalous, large boulders (up to several metres in diameter) that are present within the river channel about 2 km above the river mouth.

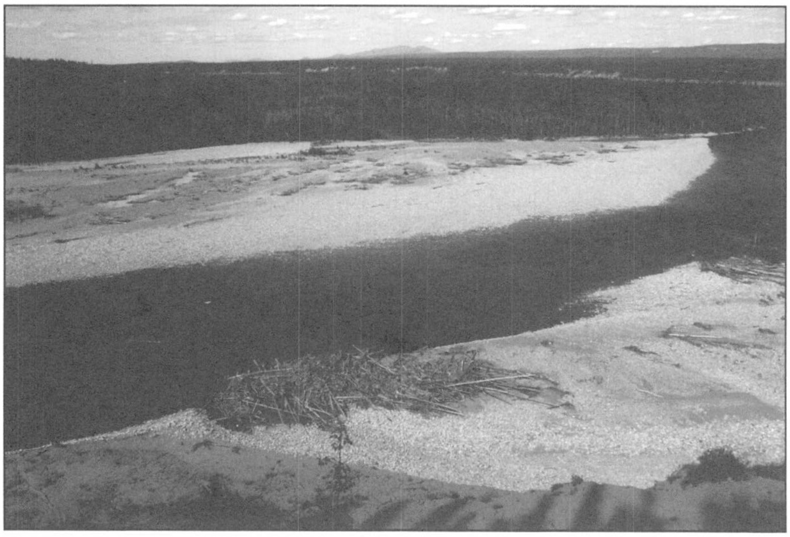


Figure E4.

The active channel zone of Dahadinni River, the reach immediately above that shown in Figure E3. Note, the gravel channel bed, the log jam, and the large subaerial bar surfaces that are capped with sand sheets. GSC 1993-177R

Figure E5.

Dried and cracked fine sand and silt sediments forming a veneer on the surface of an exposed bar near the Dahadinni River mouth. Several small log jams are also present on the bar surface. GSC 1993-177C

No ice-push features were observed along Dahadinni River study reach.

LATERAL CHANNEL CHANGE

Along the Dahadinni River study reach, lateral migration of the active channel zone is occurring primarily through concave bank erosion associated with the progressive expansion of the meandering channel (Fig. E6) and by avulsions.

Comparison of aerial photographs taken between 1945 and 1981 reveals that progressive lateral channel migration is occurring along eight zones of the study reach which correspond roughly to the meander bends (labeled A to H in Fig. E6). The maximum erosion along each zone generally ranges from about 1 to 4 m.a^{-1} (Table E1). At zone E, however, the amount of erosion is about 9 m·a^{-1}, the product of both concave bank erosion and an avulsion across the point bar located opposite zone F which occurred sometime between

Table E1. Maximum rates of bank retreat along Dahadinni River study reach between 1945 and 1981 (refer to Fig. E6).

Zone of erosion	Amount of erosion (m)	Rate of erosion (m·a^{-1})	Comments
A	45[a]	1.3	
B	90	2.5	
C	90	2.5	
D	124	0.9	
E	338	9.4	- combination of concave bank erosion and channel avulsion
F	68	1.9	
G	90	2.5	
H	135	3.8	

[a] amount of erosion is less than ±50 m error of the aerial photograph comparison.

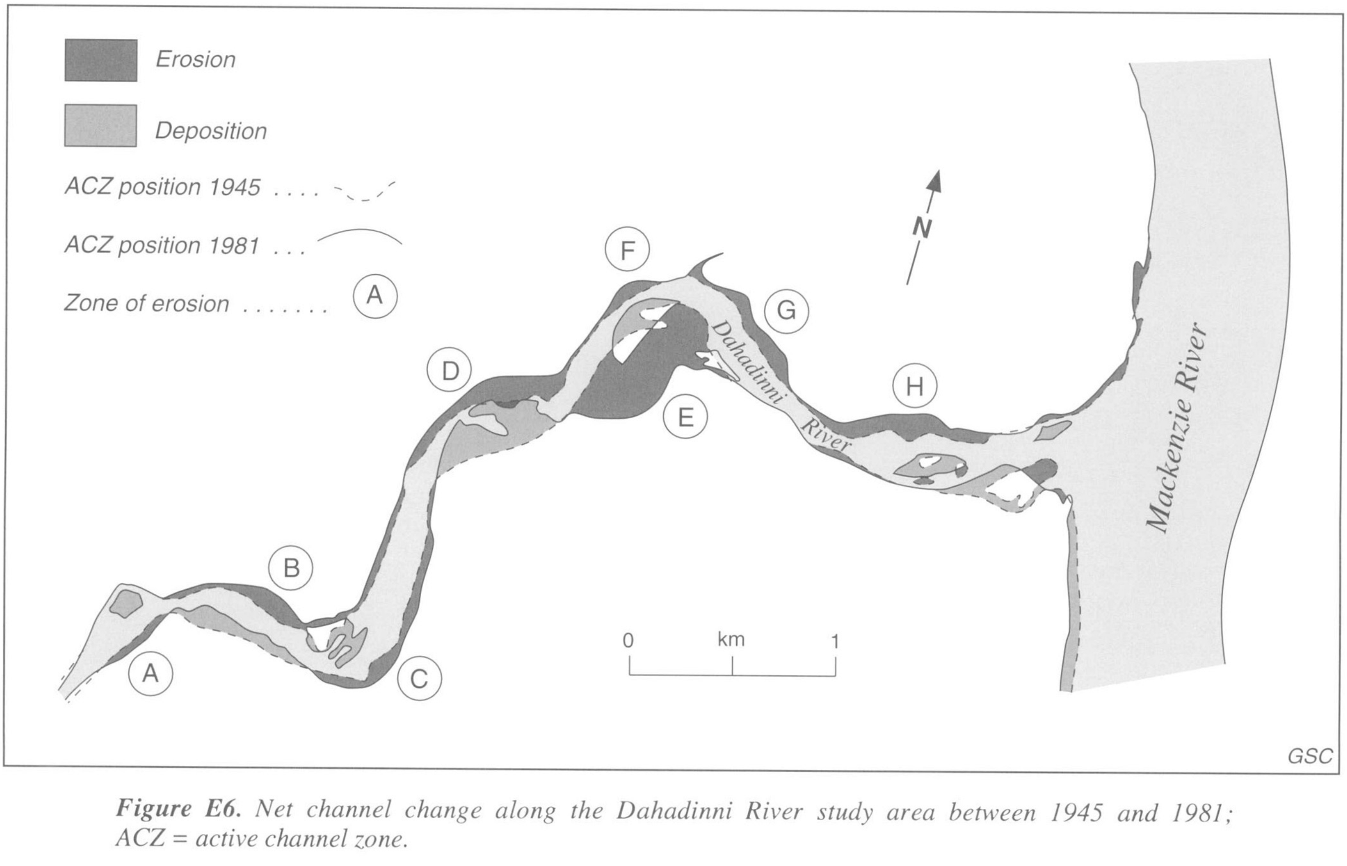


Figure E6. Net channel change along the Dahadinni River study area between 1945 and 1981; ACZ = active channel zone.

1945 and 1971 (see section on Dahadinni-Mackenzie interaction, below; compare Fig. E2a and b). Floodplain deposits form the river banks at all of the locations experiencing measurable concave bank retreat. Erosion of the valley side is occurring opposite zone H where the river is confined directly against the Mackenzie Lowland, but lateral channel migration here is limited by the valley side which is 90 m high.

Concave bank erosion is complimented by deposition along the convex side of the meanders. This process is not very apparent in Figure E6 because this diagram is based upon the vegetated boundary along the river. Inspection of the aerial photographs (Fig. E2a, b, and c) does, however, reveal accretion to unvegetated point bars and mid-channel bars.

A significant channel avulsion occurred sometime between 1945 and 1971 across the point bar at zone E (as mentioned above). Since this involved the removal of a vegetative cover, the avulsion probably was associated with a high to extreme discharge of Dahadinni River. An indication that avulsions are a relatively common process along the river is apparent from the floodplain, where there are several abandoned channels; a particularly prominent abandoned channel is present along the northern side of the study reach near the river mouth (Fig. E2a). Although an avulsion results in a major division of the active channel zone forming an island, this may be only temporary as one branch may become inactive and eventually abandoned and vegetated, attaching the island to the floodplain.

Floodplain construction along the study reach is occurring through the progressive lateral migration of the channel, whereby, point bar accretion is followed by colonization of vegetation. A second process relates to the attachment of unvegetated islands to the floodplain as mention above.

Within the active channel zone, channel change is occurring several ways. Changes to the morphology of point, side, and mid-channel bars are apparent in the aerial photograph sequence (Fig. E2), despite the differences in river stage between the photographs. Erosion and deposition of the bars has resulted in varying degrees of modification to bar morphology (including destruction and creation) causing lateral shifting of the river channel(s), and minor channel avulsions.

DAHADINNI-MACKENZIE INTERACTION

Along the lower part of the study reach, the presence of the floodplain (Ap surface) to the north of the active channel zone indicates that the river mouth has shifted laterally within a 2500 m corridor relative to Mackenzie River (Fig. E1). The recent trend of active channel zone migration is not apparent in Figure E6. Inspection of the aerial photograph sequence in Figure E2, however, reveals that the main channel at the tributary mouth has migrated within the active channel zone as exemplified by an avulsion occurring sometime between 1945 and 1971.

Dahadinni River probably delivers a relatively high amount of bed-material into Mackenzie River (see section on Hydrology, above). As a result of this bed-material supply, a low-angled alluvial fan is splayed from the mouth of Dahadinni Valley 1000 m into, and 4400 m downstream along Mackenzie River valley. This fan confines Mackenzie River against the opposite side of Mackenzie River valley, causing a slight narrowing of the Mackenzie River channel and a marked deflection of the eastern valley side (Fig. E2c). Control of the lateral position of Mackenzie River by Dahadinni River is notable because of the considerable difference in size between the two rivers.

The supply of bed-material from Dahadinni River appears to cause a downstream morphological change to Mackenzie River. Comparison of the reach of Mackenzie River below the Dahadinni confluence with that above the nearby Blackwater confluence reveals that Mackenzie River increases in average width, gravel point bars cause the channel thalweg to meander, and several islands and mid-channel bars are present. These channel characteristics extend downstream to the Redstone confluence where they become accentuated in response to an increase in valley gradient, and the combined supply of bed-material from the Redstone River and cutbank erosion and bank failures along the Mackenzie River valley sides.

APPENDIX F

Redstone River

STUDY REACH DESCRIPTION

Redstone River is 310 km long and drains an area of about 16 400 km^2 (Table 1). Originating within the Backbone Range of the Mackenzie Mountains, the river follows a northeasterly course through the Canyon and Redstone ranges, across the Mackenzie Lowland, and into Mackenzie River (Fig. 2).

The study reach extends along the lowest 6.5 km of Redstone River (Fig. F1). Over the upper 3.5 km of this reach, the river is contained within the lower end of Redstone Valley. From the mouth of Redstone Valley to the confluence with Mackenzie River, the river flows roughly perpendicular to and across the bottom of Mackenzie River valley.

Figure F1. Physiographic map of the Redstone River study area (uncorrected from aerial photograph NAPL A23038-131). Refer to Figure A1 for legend.

Cretaceous bedrock underlies the study reach, consisting of predominantly Slater River Formation (marine shale and minor sandstone), although the Little Bear Formation (marine and nonmarine cherty sandstone and minor shale) is present in the extreme upper part of the study reach (Cook and Aitken, 1976). An outcrop of bedrock is reported to occur along Redstone Valley about 8 km from the river mouth (Hume, 1954, Fig. 11), but it is not clear if bedrock is exposed along the valley sides downstream as far as the study reach. Upstream of the study reach, the river is confined against the Cretaceous bedrock (Hume, 1954). Quaternary sediments probably form the valley sides along the lower portion of Redstone Valley since these deposits are present along the eastern side of Mackenzie River valley directly opposite the Redstone River mouth.

Redstone River is incised 50 to 75 m into the Mackenzie Lowland. The surficial geology of the adjacent lowland surface is mapped as glaciolacustrine plain composed of silt and clay with areas of morainic till plain and glaciofluvial gravel plain (Hanley and Hughes, 1973). Several small lakes and wetlands are present on the lowland, particularly to the west of the study area, some of which occupy thermokarst depressions (Hanley and Hughes, 1973). The lowland surface is densely covered with a coniferous forest.

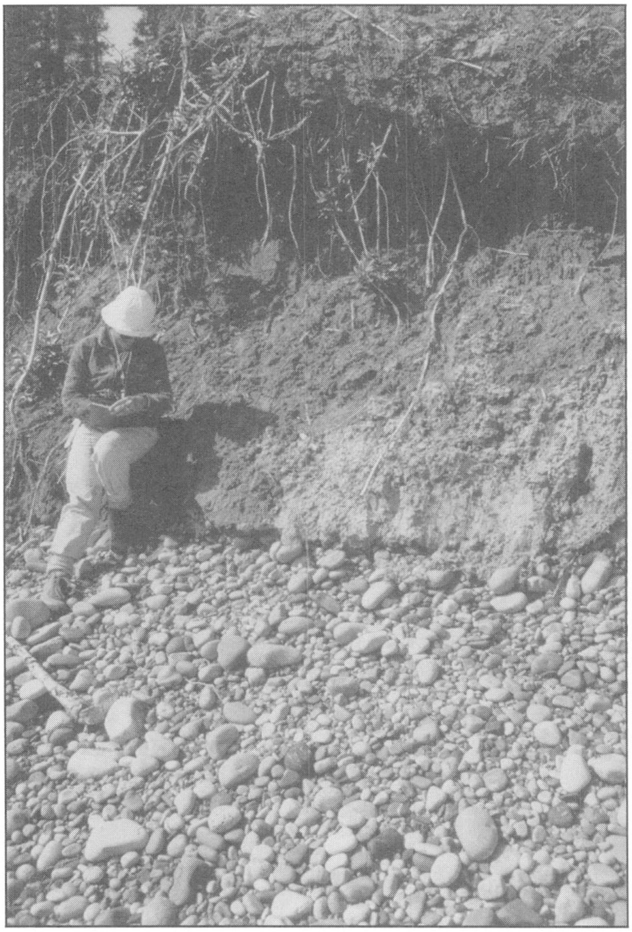


Figure F2. *Typical contemporary flood plain deposits (Ap surface) of Redstone River exposed at a fresh cutbank exposure; overbank sand and silt overlie channel gravel. GSC 1993-177O*

VALLEY CHARACTERISTICS

Along the study reach, Redstone Valley gradually widens from 1000 to 4000 m, then opens into Mackenzie River valley about 3 km from the river mouth (Fig. F1). This widening is part of a regular oscillation of valley width, ranging between 300 and 2500 m, that occurs along at least the lower 15 km of Redstone Valley and which is the product of lateral channel migration. The narrower reaches of valley are of similar width to the active channel zone, indicating that Redstone River is fit to the valley width.

No major slope failures along the valley sides are apparent in the aerial photographs, probably because the river is not confined directly against the valley sides.

Along the study reach, three alluvial surfaces occur beneath the level of the Mackenzie Lowland (Ap, At1, and At2 in Fig. F1). The lowest surface (Ap) is 2 to 5 m above the river and consists of 1 to 2 m of channel gravel overlain by 1 to 3 m of interbedded silt and sand overbank deposits (Fig. F2). This surface is forested with dense, coniferous trees, but there are distinct tracts of deciduous forest (the lighter toned forest in Fig. F3a) that branch from the active channel zone and meander through the floodplain. These deciduous forest tracts undoubtedly delineate abandoned channels. Several wetlands and small lakes are present on the Ap surface within old channel scars (Fig. F3a). On the north side of the river, the Ap surface forms an extensive area of valley bottom, but only two comparatively small parcels are present on the south side (Fig. F1). The Ap surface is interpreted as the contemporary floodplain of Redstone River. In the Mackenzie River valley north of Redstone River, the Ap surface becomes indistinguishable from the Mackenzie River floodplain.

The At1 surface is about 10 m above Redstone River. It is present only along the southern side of the study reach where it extends upstream along the bottom of Mackenzie River valley (Fig. F1). Very generally, it is composed of stratified alluvium (the deposits were viewed only from a distance). Hanley and Hughes (1973) mapped the At1 surface as an alluvial terrace consisting of silt overlying sand and gravel. The surface is covered with a dense, mature coniferous forest. The At1 surface is interpreted as an alluvial terrace of Redstone River.

The At2 surface occurs to the south of Redstone River mouth (Fig. F1) and can be traced readily upstream along Mackenzie River. In places, the At2 surface has been dissected by small streams. Its height above the river was not measured, but lies between that of At1 and the Mackenzie Lowland. Hanley and Hughes (1973) mapped the surface as an alluvial terrace consisting of sand and gravel. The At2 surface is interpreted as an alluvial terrace relating to Mackenzie River.

Figure F3.

*Sequence of aerial photographs of the Redstone River study reach **a**) 1949 (NAPL A11974-221); **b**) 1972 (NAPL A23038-131); and **c**) 1981 (NAPL A25822-24); the black bar on each photograph represents one kilometre. In c), the bars have been outlined and shaded to enhance their profiles.*

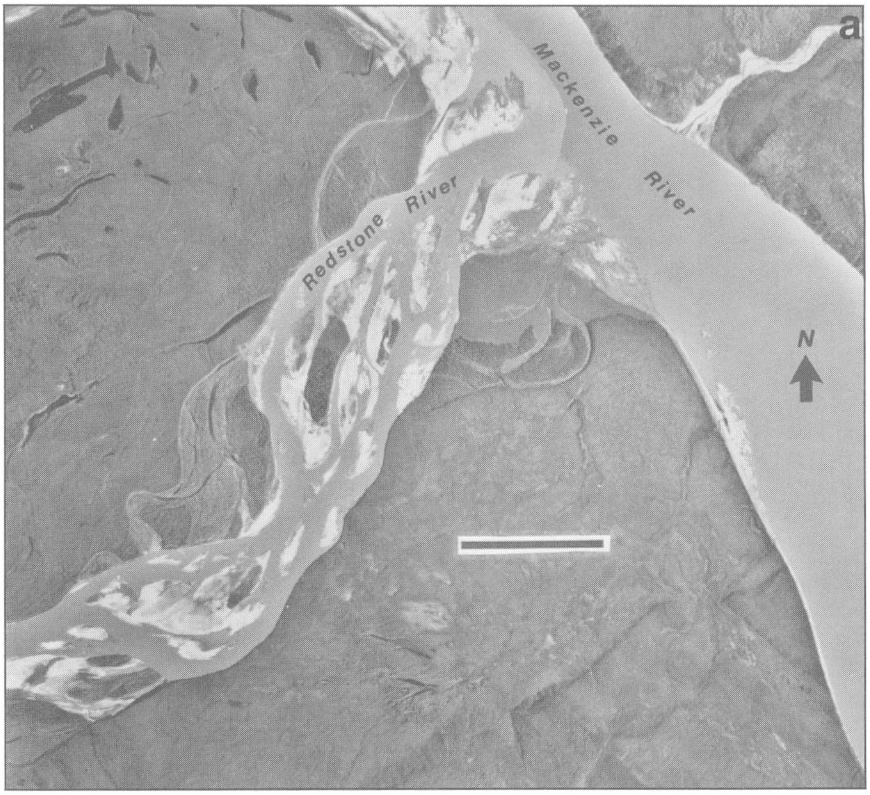
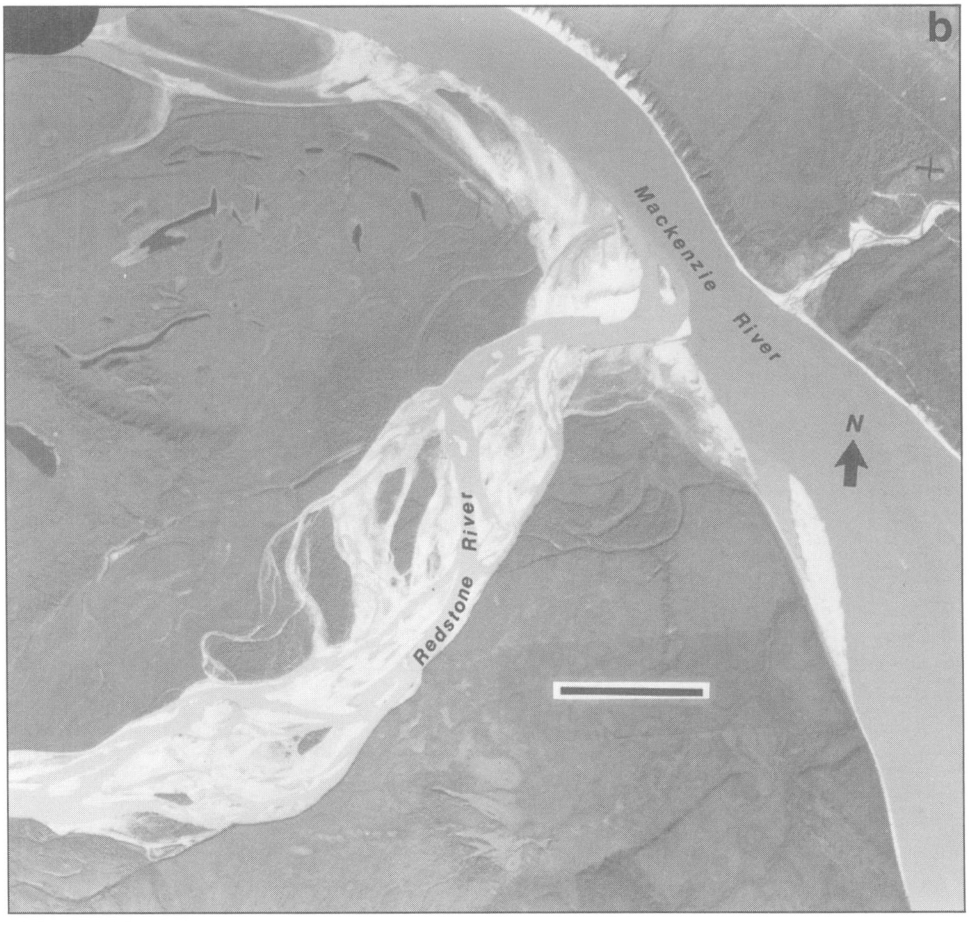


Figure F3b.



Upstream of the study reach, numerous levels of discontinuous alluvial surfaces are present along Redstone Valley in the form of large tracts of valley bottom, abandoned meander loops, and various levels of 'slip-off' slopes. (The slip-off slopes form on the inner side of entrenched meanders, the result of concomitant incision and outward migration of a channel.) Some of these alluvial surfaces undoubtedly correlate with the Ap and At1 surfaces, and possibly the At2 surface, along the study reach.

HYDROLOGY

Streamflow of Redstone River was monitored 'near the mouth' for the period 1963 to 1974 (Water Survey of Canada, 1992a). In 1974, the station was moved to '63 km above the mouth' and has remained there ever since (Water Survey of Canada, 1992a). Based upon the 1974 to 1991 record (C. Brumwell, written comm., September 27, 1993), mean annual discharge of Redstone River is 181 $m^3 \cdot s^{-1}$ with the maximum and minimum mean monthly discharges being 495 (July) and 18 (March) $m^3 \cdot s^{-1}$, respectively (Fig. F4). The maximum monthly discharge, however, commonly occurs in June rather than July. The minimum mean monthly discharge (18 $m^3 \cdot s^{-1}$) is only slightly higher than the minimum historic daily discharge of 9 $m^3 \cdot s^{-1}$ recorded on March 22, 1979.

The maximum historic daily discharge in the 1974 to 1991 record is 3750 $m^3 \cdot s^{-1}$ recorded on July 28, 1991. This discharge is far in excess of the maximum mean monthly discharge (Fig. F4) and clearly shows that Redstone River occasionally experiences very large flows. An unrecorded

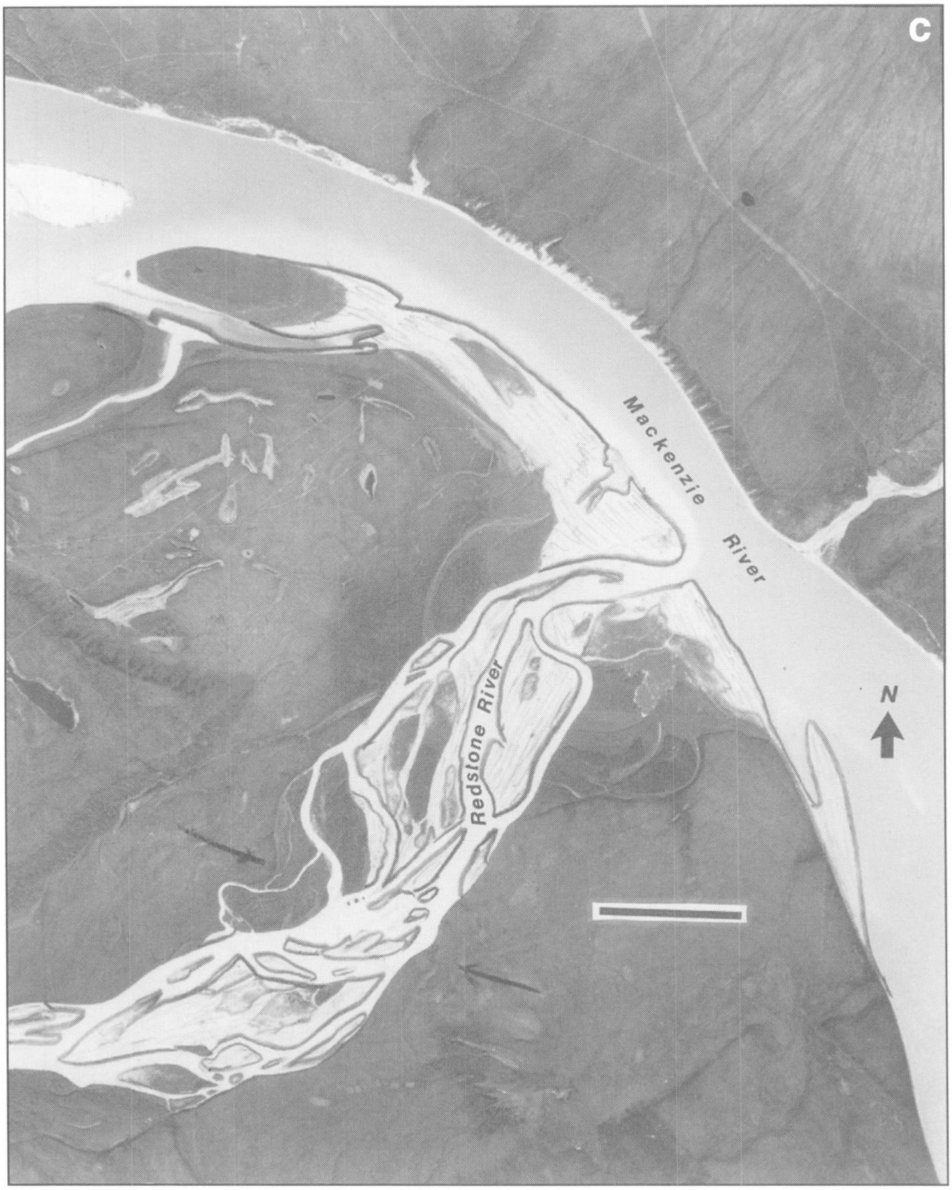


Figure F3c.

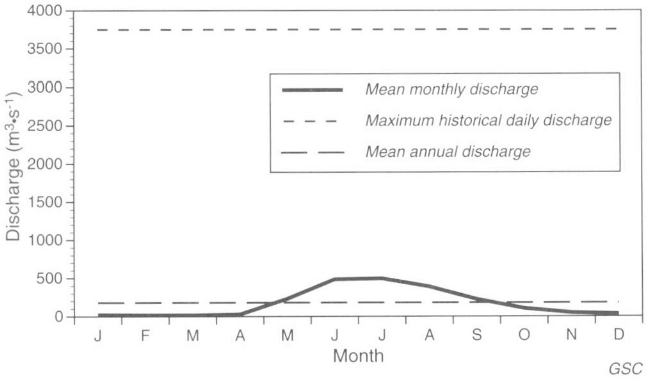


***Figure F4.** Hydrograph of the Redstone River streamflow, 1974-1991, 'Redstone River 63 km above the mouth' station (Water Survey of Canada, unpub. data).*

extreme flood occurred in July 1970 caused by a severe rain storm in the Mackenzie Mountains (see MacKay et al., 1973). In general, the river regime is 'flashy'; subject to sudden and significant rises in stage caused by summer rain storms and diurnal spring melt.

The rate of bed-material transport along Redstone River is relatively high as indicated by the considerable lateral channel change occurring along the study reach (see section on Lateral channel change, below). Suspended sediment load of Redstone River varies seasonally. Dryden et al. (1973) describe river waters as silty in the spring and summer months, but becoming clear gradually by late September. A partial record of suspended load exists for 1973, and 1987 to 1989 (Water Survey of Canada, 1992b); maximum and minimum historical concentrations are 1960 $mg \cdot l^{-1}$ (June 6, 1989) and 21 $mg \cdot l^{-1}$ (September 25, 1987), respectively.

Figure F5.

Exposed bar surface along Redstone River; in places, the gravel bar is capped with sand. GSC 1993-177J

Figure F6.

Sand deposits on an inactive bar surface of Redstone River which is in an early stage of being colonized by vegetation. GSC 1993-177G

CHANNEL CHARACTERISTICS

Along the study reach, Redstone River is an alluvial stream with a gravel bed. During the site visit (August 6, 1992), the river discharge at the '63 km above the mouth' station unfortunately was not measured (D. Anderson, written comm., February 3, 1994). Flow was observed to be swift and alternating from pools and riffles. As estimated from the contour lines of 1:50 000 scale NTS maps 96C/2 and 96C/7, the average valley slope is 0.0027, between 4 and 9.5 km above the river mouth.

Over the study reach, the active channel zone ranges from 300 to 1250 m wide. Numerous bars and islands divide the river into multiple branches forming a braided planform. Upstream of the study reach, side, mid-channel, and point bars are common, but occur with a much lower frequency causing the channel to split only rarely. This upstream reach consequently has a narrower active channel zone and does not exhibit the same degree of channel division. The reason for the increased braiding towards the river mouth is not known.

A number of different types of bars are present within the active channel zone, including mid-channel, diagonal, and side bars (e.g., Fig. F3b). The bars exposed at moderate and low discharges are composed of gravel that is in some places capped with a veneer of sand (Fig. F5). Some of these bar surfaces are in the early stages of colonization by vegetation (Fig. F6). Channels which were not inundated during the 1992 freshet generally were sand-bottomed and had a sporadic cover of herbaceous vegetation. The downstream ends of these inactive channels were covered with a thin drape of silt (up to several centimetres thick) that settled from suspension in slack waters resulting from backwater which originated from the 1992 Redstone River freshet (Fig. F7). A similar drape of silt occurs on some bar surfaces at the river mouth, which has originated from Mackenzie River backwater.

Along any given cross-section of the active channel zone, bars and channels occur at varying heights, reflecting the river stage at which they formed. When the site was inspected (August 6, 1992), discharge was moderate and a large tract of the northern active channel zone along the lower third of the study reach was inactive. A significant portion of this area was in the early stages of vegetative succession suggesting that no

Figure F8. *Silt and fine sand sediments deposited to the lee of an isolated log stranded on the surface of an exposed bar along the Redstone River study reach. GSC 1993-177Q*

Figure F7.

Drape of fine sand and silt overlying an inactive channel bottom along the Redstone River study reach. GSC 1993-177F

Figure F9.

*Area of forest at the edge of the Redstone River floodplain (Ap surface) damaged by ice thrusting during spring break-up **a**) flattened trees and shrubs (GSC 1993-177E); and **b**) a fresh impact scar on a tree (GSC 1993-177Y)*

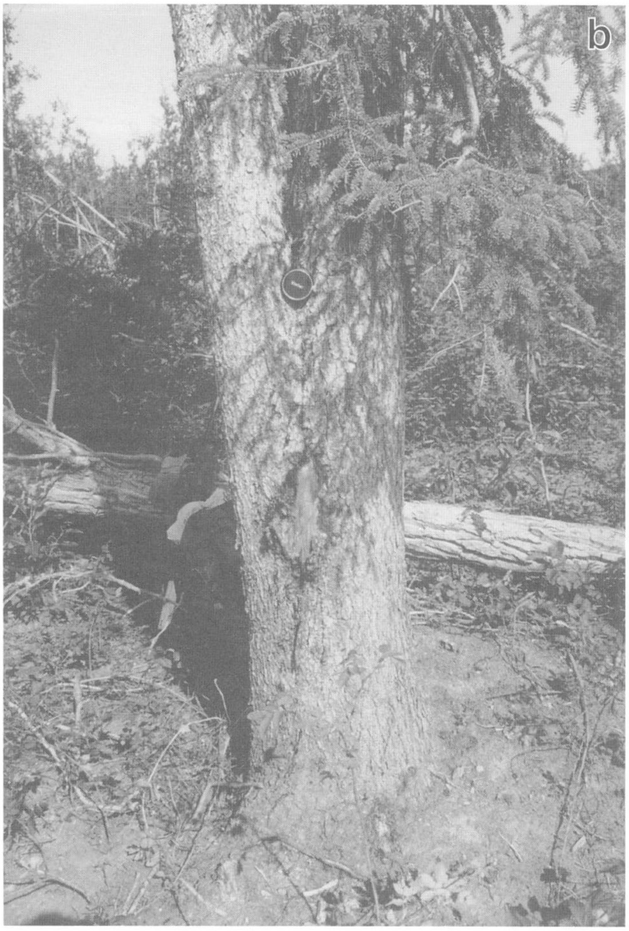


Figure F9b.

major deposition or erosion had occurred for several years. These areas may have been active during the large flood of July 1, 1988. Because the Redstone River experiences a wide fluctuation of annual flows, the size of active channel zone likely reflects the fluvial activity of the most recent extreme discharge. At any given time, large tracts of the active channel zone are inactive, with the bars and channels in various stages of vegetative succession. These features are vulnerable to reactivation during the next extreme discharge event.

A typical active cutbank along the north side of the active channel zone is shown in Figure F2. Basal materials of the active cutbanks are gravel. Cutbanks on the south side of the active channel zone were observed only from a distance, but the basal material there also appears to be gravel. Along former cutbanks next to abandoned channels, the overbank deposits have wasted to produce angle of repose slopes that are being colonized by vegetation. The vegetation cover on these slopes, even if well developed (i.e., mature deciduous or coniferous trees), probably offers negligible protection from erosion should the river once again attack the bank. In general, vegetation does not appear to offer the banks significant protection from river erosion.

Isolated logs and small log jams are scattered sporadically upon the surface of exposed bars and shallow channels. Fine sediments accumulate commonly on the lee side of this debris (Fig. F8). Overall, logs and log jams represent only very minor obstructions to Redstone River.

Ice-push features are not common along Redstone River. The general lack of ice-push features along the river may reflect the high amount of deposition and erosion that is occurring within the active channel zone (see section on Lateral channel change, below). Trees knocked over in areas extending 10 to 20 m into the floodplain from the river bank were observed locally along the northern side of the river between 1 to 2 km above the river mouth (Fig. F9a). This probably occurred due to the thrusting of ice into the forest because of jamming during the break-up. Scars on some trees were very fresh, likely having formed during the 1992 spring break-up (Fig. F9b).

LATERAL CHANNEL CHANGE

Lateral channel change within the study reach has occurred on both sides of the active channel zone (Fig. F10). Virtually the entire north side of the study reach has experienced erosion while accretion has occurred predominately along the southern side (except along the lower 1000 m). Inspection of the aerial photograph sequence (Fig. F3a, b, and c) reveals that lateral change is occurring through two main processes: channel avulsions causing the dissection of the floodplain through the formation of new channels (or reactivation of abandoned channels); and the progressive erosion of the river bank where a major channel is positioned against the margin of the active channel zone. Overall, both processes cause the widening of the active channel zone (Fig. F10).

The significance of the avulsion process is readily apparent in the island development that occurred along the northern side of the middle part of the study reach between 1949 and 1972 (Fig. F3a and b). Close inspection of this area of the floodplain in the 1949 photograph (Fig. F3a) reveals several tracts of light-coloured deciduous forest around several isolated stands of dark-coloured coniferous forest. The coniferous stands probably represent old islands that have been attached to the floodplain. After the 1949 photography, Redstone River has reactivated some parts of the abandoned channels within the deciduous forest, thus, creating 'new' islands and active channels. Since this process involves the erosion of relatively stable vegetated surfaces, reactivation likely is associated with a high or extreme discharge of Redstone River.

Changes to the active channel zone boundaries apparent in the comparison of aerial photographs taken between 1949 to 1981 are listed in Table F1. Channel change was measured from Figure F10 at regular intervals perpendicular to the valley axis with positive and negative rates indicating erosion and accretion, respectively. Erosion typically ranges from about 1 to 5 $\mathrm{m \cdot a^{-1}}$ with higher rates of about 5 to 11 $\mathrm{m \cdot a^{-1}}$ occurring locally at the mouths of reactivated channels. The higher rates of bank retreat have occurred along the northern side of the active channel zone probably reflecting differences in the bank heights of the active channel zone boundaries (Table F1). The northern boundary is formed by the Ap surface (2 to 5 m high), while the southern boundary consists of At1 surface (10 m high; Fig. F1). Also of importance are channel avulsions which can cause a major retreat of the active channel zone boundary. These avulsions have occurred only along the northern side of the active channel zone.

The north side of the lower half of the study reach was inspected on August 6, 1992. In general, much like the circumstance depicted in Figure F3c, a major channel was confined against the northern side of the active channel zone along the lower third of the study reach and along (at least) the middle third of the southern side; active cutbank erosion was occurring at both zones of confinement.

The presence of numerous channel scars upon the Ap surface to the north of the active channel zone (Fig. F3a) indicates that Redstone River once occupied these back areas of the floodplain. Although faint, these scars appear to delineate a network of interbranching channels analogous to those

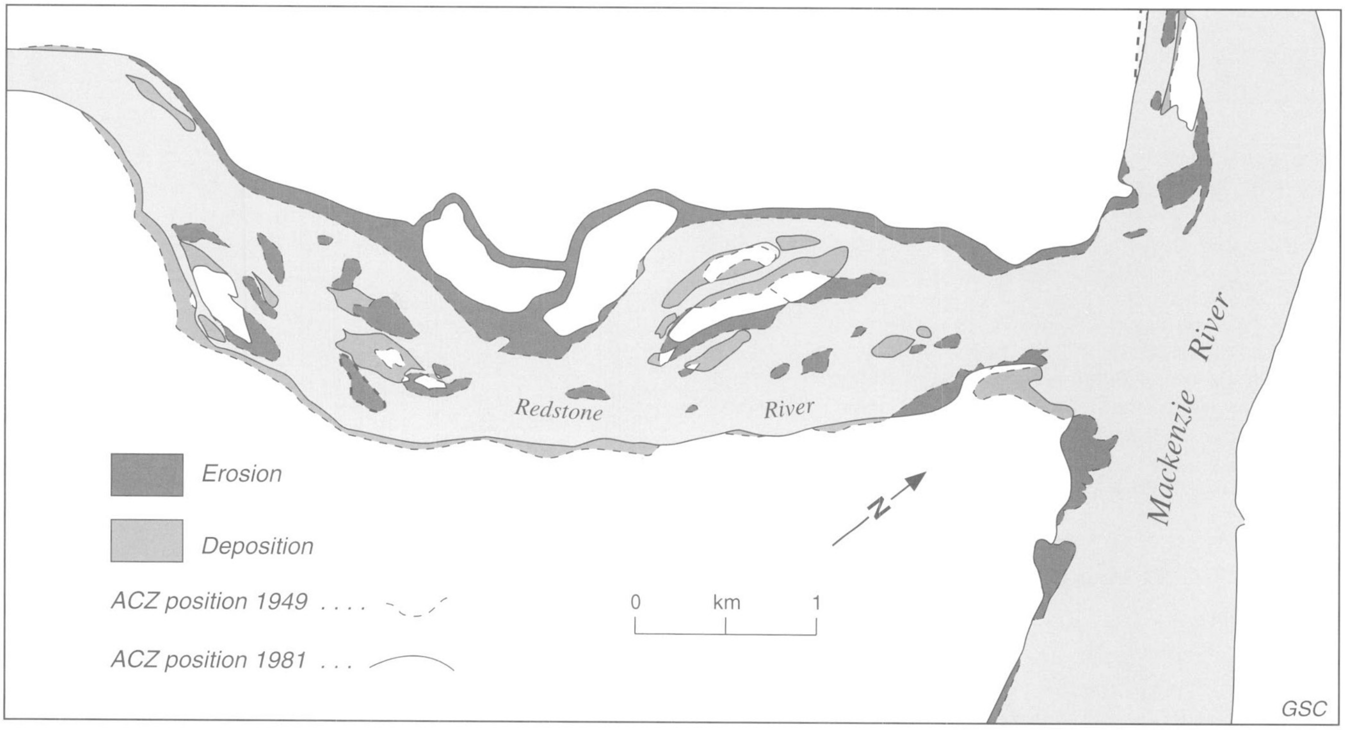


Figure F10. Net channel change along the Redstone River study area between 1949 and 1981; ACZ = active channel zone.

Table F1. Lateral migration along the active channel zone of Redstone River between 1949 and 1981 (refer to Fig. F10).

Distance above river mouth (m)[a]	Amount of erosion south side (m)	Rate of erosion south side of active channel zone ($m\cdot a^{-1}$)	Amount of erosion north side (m)	Rate of erosion north side of active channel zone ($m\cdot a^{-1}$)
0	0[b]	0	34[b]	1.1
250	68	2.1	34[b]	1.1
500	0[b]	0	136	4.3
750	51	1.6	68	2.1
1000	68	2.1	85	2.7
1250	0[b]	0	68	2.1
1500	0[b]	0	68	2.1
1750	0[b]	0	51	1.6
2000	0[b]	0	85	2.7
2250	0[b]	0	34[b]	1.1
2500	-51	-1.6	51	1.6
2750	-34[b]	-1.1	102	3.2
3000	-68	-2.1	238	7.4
3250	0[b]	0	340	10.6
3500	-34[b]	-1.1	136	4.3
3750	0[b]	0	102	3.2
4000	-34[b]	-1.1	170	5.3
4250	-51	-1.6	102	3.2
4500	-34[b]	-1.1	102	3.2
4750	-68	-2.1	85	2.7
5000	-102	-3.2	51	1.6
5250	-51	-1.6	68	2.1
5500	-34[b]	-1.1	34[b]	1.1
5750	-34[b]	-1.1	34[b]	1.1
6000	0[b]	0	0[b]	0
6250	0[b]	0	0[b]	0
6500	0[b]	0	0[b]	0

[a] Bank erosion was measured perpendicular to the channel axis. It encompasses lateral displacement to the margins of the active channel zone and the construction/reactivation of channel on the flood plain; change in area to islands within the active channel zone is ignored. A positive rate refers to bank erosion with a negative representing bank accretion.

[b] note that amount of erosion is below ±50 m error of the aerial photograph comparison.

in the contemporary active channel zone. The floodplain appears to have been created as the active channel zone migrated laterally across the valley bottom probably through a sequence involving the stabilization of bars forming islands, followed by channel abandonment and infilling, and eventually colonization by vegetation which has 'attached' the islands to the floodplain.

Within the active channel zone, erosion and deposition to the margins of the numerous islands and active bars has caused modification to the channel network. This change is apparent in Figure F3 despite differences in river stage between the aerial photographs.

REDSTONE-MACKENZIE INTERACTION

The presence of the Ap surface indicates that Redstone River has shifted laterally within a 4 km wide corridor relative to Mackenzie River. The present trend of lateral shifting for the Redstone River mouth is not obvious from Figure F10.

The supply of bed material from Redstone River into Mackenzie River is relatively high (see section on Hydrology, above). As a result of this, a large, low-angled alluvial fan is splayed outwards from the mouth of Redstone Valley into and across Mackenzie River valley. This fan confines the Mackenzie River channel against the eastern side of Mackenzie River valley (Fig. F3c). At a smaller scale, a large channel junction bar that is part of the low-angled fan, extends from the mouth of Redstone River roughly 1 km into and 3 km downstream along Mackenzie River (Fig. F3c). This bar locally constricts the Mackenzie River channel to a minimum width of 650 m and causes a slight deflection of the eastern valley side (Fig. F3c). Redstone River, thus, controls the lateral position of Mackenzie River within the valley bottom opposite the tributary mouth.

Bed-material supply from Redstone River appears to have an effect upon the downstream morphology of Mackenzie River, as the frequency of bars and islands is significantly greater below the Redstone confluence than above it. This characteristic is, however, part of the general morphological pattern of Mackenzie River, beginning between the Blackwater and Dahadinni confluences and extending to about 55 km below Keele River. It probably is the result of combined bed-material supply from tributaries and erosion of the Mackenzie River valley sides (see section on Overview-Interaction between tributaries and Mackenzie River).

APPENDIX G

Keele River

STUDY REACH DESCRIPTION

Keele River[1] is 420 km long and drains an area of about 26 800 km^2 (Table 1). The river originates within the Backbone Range of the Mackenzie Mountains and flows eastwards through the Canyon and Redstone ranges, across the Mackenzie Lowland and finally into Mackenzie River valley (Fig. 2).

The study reach extends over the lower 7.5 km of Keele River and is contained partially within a stream-cut valley (Keele Valley) incised into the Mackenzie Lowland (Fig. G1). About 4 km from its mouth, the river emerges from Keele Valley and flows diagonally across the bottom of Mackenzie River valley, then merges with Mackenzie River.

Two formations of Cretaceous bedrock underlie the study reach, although neither outcrops. Beneath the lower one-third of the study reach is the Slater Formation, consisting of marine shale with a minor occurrence of sandstone. The Little Bear Formation underlies the upper two-thirds of the study reach and is composed of marine and nonmarine cherty sandstone with a minor occurrence of shale (Cook and Aitken, 1976).

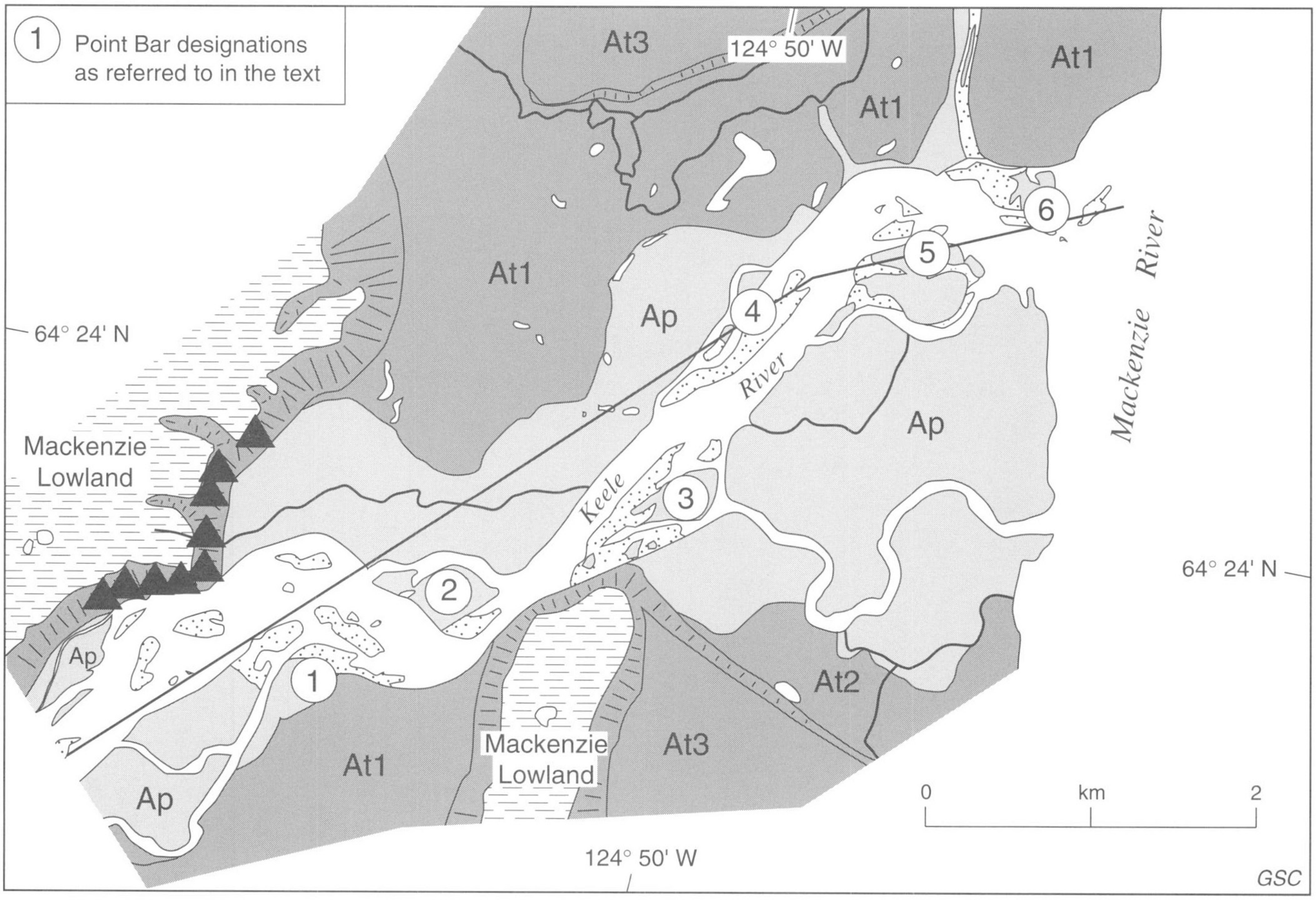


Figure G1. *Physiographic map of the Keele River study area (uncorrected from aerial photograph NAPL A11973-219). Refer to Figure A1 for legend.*

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[1] In the early literature, the river was named 'Rivière du Gravais' or more commonly 'Gravel River' (e.g., Richardson, 1851; Petitot, 1891; McConnell, 1891; Keele, 1910; Camsell and Malcolm, 1921), a name originating from fur-traders and which refers to the frequency and extent of gravel bars along the lower reaches of the river (Keele, 1910). Ogilvie (1890) reports the name 'Pecat-ah-zah', which translates into Gravel River, was given to him by local Indians for this river. In 1924, it was officially renamed 'Keele River' after J. Keele, an officer of the Geological Survey of Canada who descended the river as part of an expedition in the District of Mackenzie (Files of the Canadian Permanent Committee on Geographical Names, pers. comm., December 8, 1993).

Along the study reach, Keele River is incised about 60 m into the Mackenzie Lowland (Keele, 1910). The surficial geology of the Mackenzie Lowland to the north of Keele Valley consists of morainic till plain with eolian sands, while to the south it is glaciolacustrine plain (Hanley and Hughes, 1973). This area was inundated by glacial Lake Mackenzie during the waning of the late Wisconsinan Glaciation (Smith, 1992). The lowland surface is densely covered with a mature coniferous forest; several small lakes and wetlands are present, some of which occupy thermokarst depressions (Hanley and Hughes, 1973; Fig. G2a).

The exposures of the sides of Keele Valley were not examined, but are believed to consist of Quaternary sediments. Just upstream of the study area, a 60 m bank along the north side of the river reportedly consists of 45 m of stratified clay overlain by 15 m of clay containing pebbles (Keele, 1910). Along the eastern side of Mackenzie River directly opposite Keele River, the valley side is composed entirely of Quaternary deposits with at least the lower 15 m of the bank consisting of massive, matrix-supported diamicton (see Brooks, 1993).

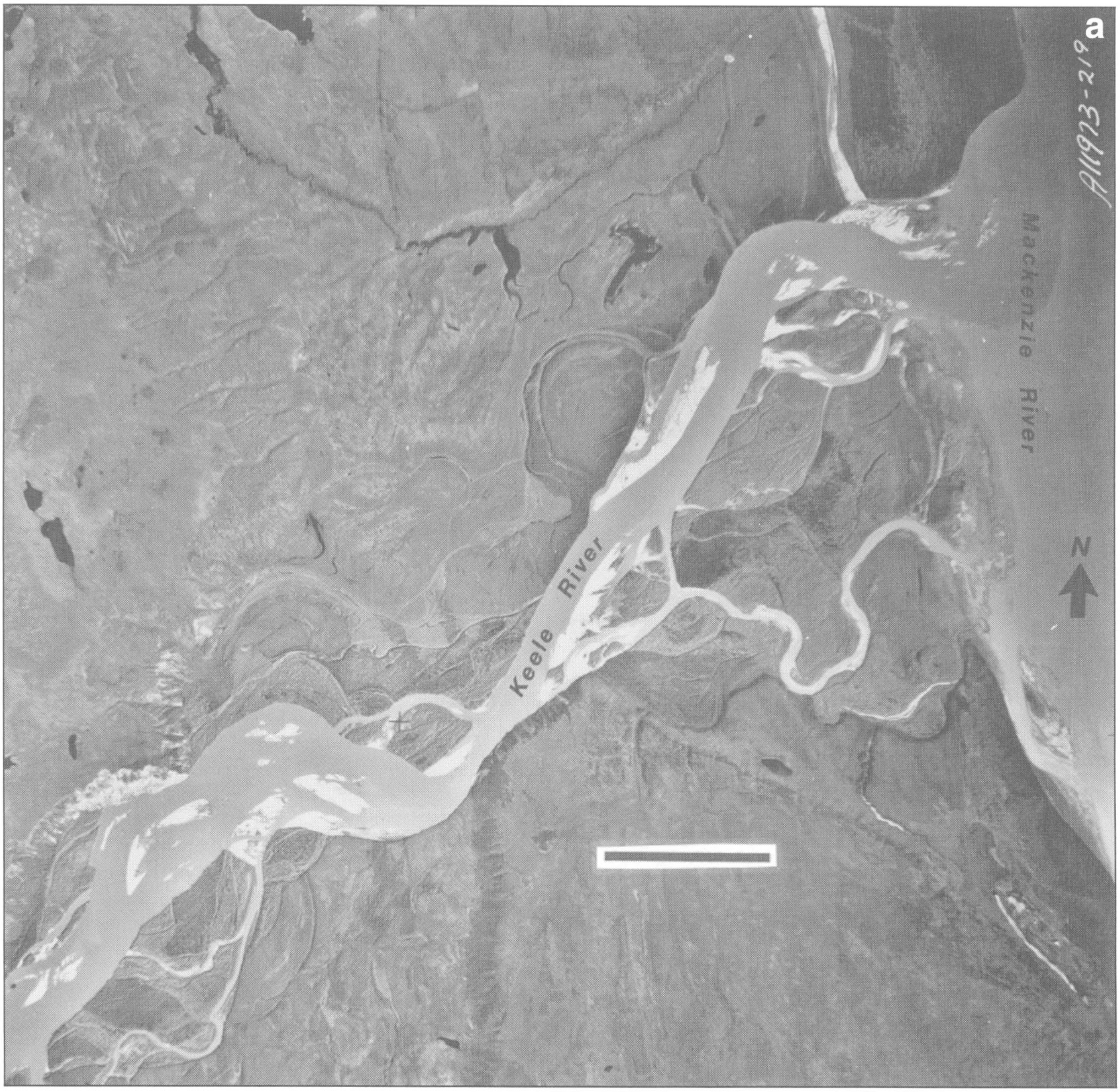


*Figure G2. Sequence of aerial photographs of the Keele River study reach **a**) 1949 (NAPL A11973-219); **b**) 1972 (NAPL A22973-15); and **c**) 1981 (NAPL A25822-42). The black bar on each photograph represents one kilometre. In b), the bars have been outlined and shaded to enhance their profile.*

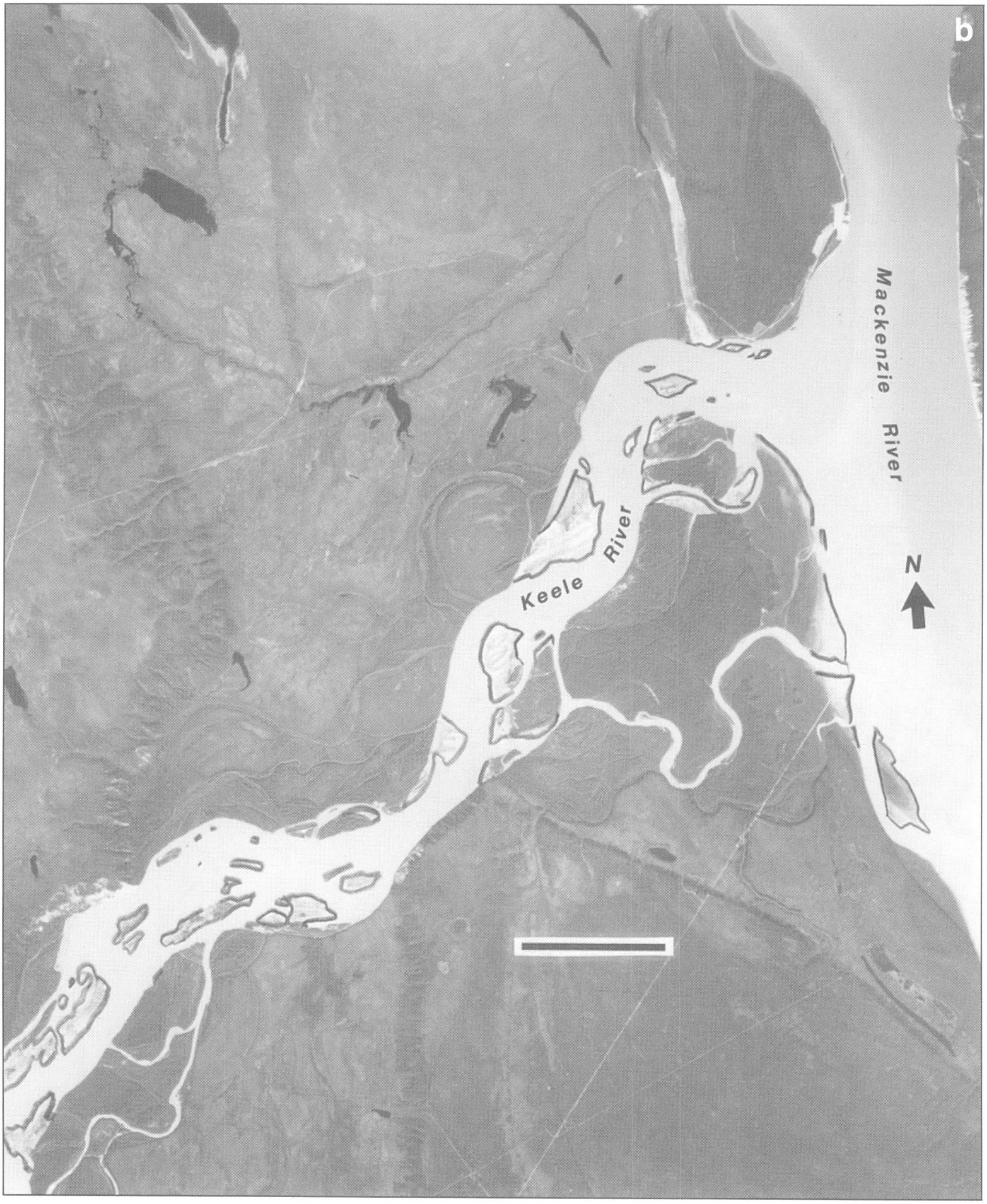


Figure G2b.

The postglacial history of Keele River incision into the Mackenzie Lowland is not well understood. Incision presumably began after 10 600 BP with the drainage of glacial Lake Mackenzie (see section on Great Bear River-study reach description in Appendix H). A radiocarbon age of 8510 ± 280 BP (GSC 1471) obtained from a peat bog opposite the Keele River mouth, which is situated upon glaciolacustrine deposits, indicates that Mackenzie River was within 35 m of its present level at about 8500 BP (Lowden and Blake, 1979). It is not known when the river attained its present level.

VALLEY CHARACTERISTICS

Along the study reach, Keele River is confined directly along about 10% of the valley sides. River erosion of the valley sides has produced a large cutbank along the upper 1.5 km of the study reach (Fig. G1).

Along the study reach, four levels of alluvial surface occur below the Mackenzie Lowland (Ap, At1, At2, and At3 in Fig. G1). The lowest surface (Ap in Fig. G1) is 2 to 4 m above the river. It is composed of about 2 m of channel gravel

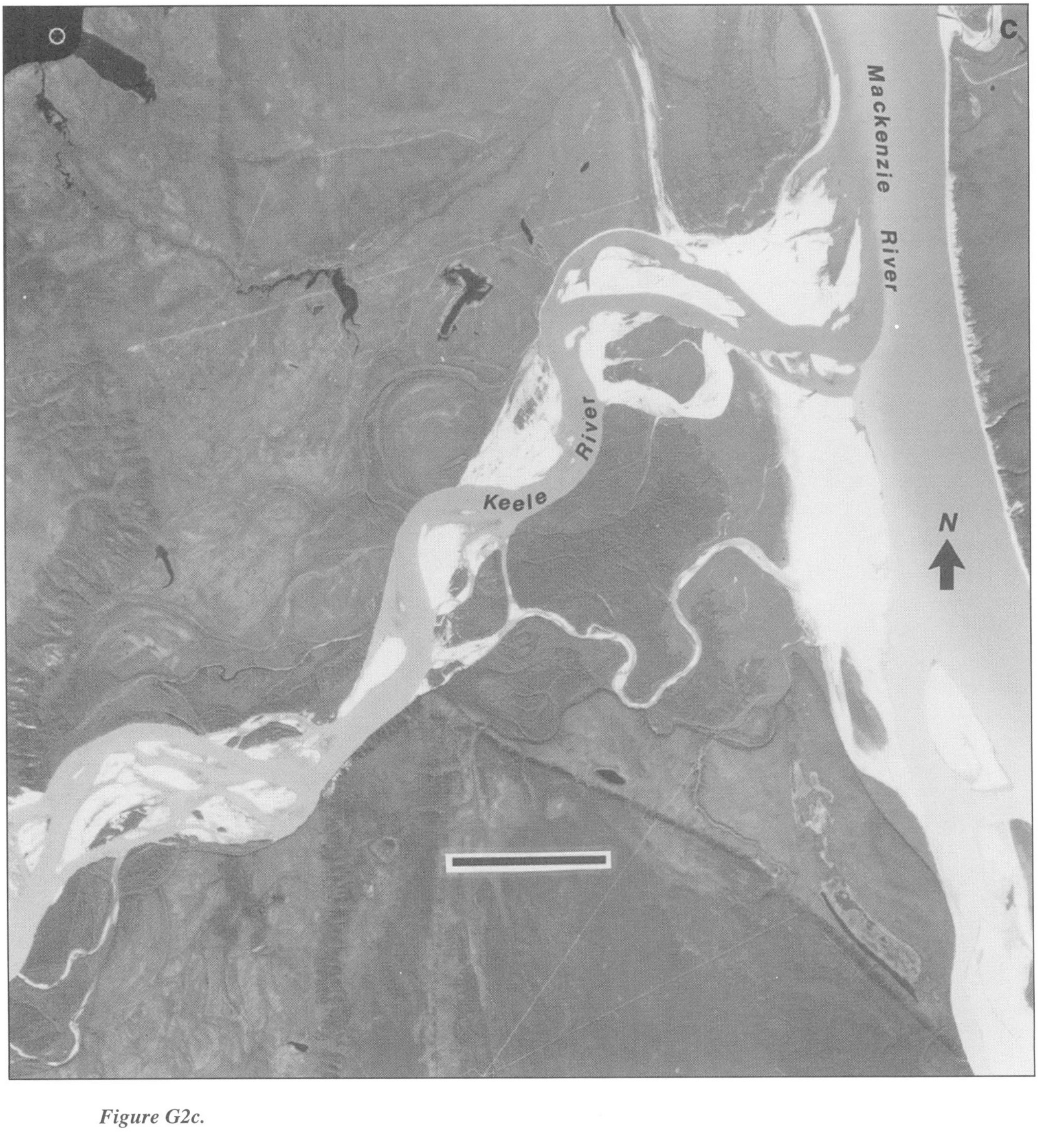


Figure G2c.

underlying up to 3 m of interbedded silt and sand overbank deposits (Fig. G3). The Ap surface is densely vegetated with a mosaic of different-aged deciduous and coniferous forests reflecting various stages of vegetative succession (Fig. G2a). Narrow forest tracts delineate channel scars that branch from and rejoin the active channel zone (Fig. G2a). Elongated lakes are present within some of these scars. The Ap surface is interpreted as the contemporary floodplain of Keele River.

The At1 surface is 5 to 10 m above the river and is composed of 2 to 4 m of channel gravel overlain by up to 6 m of interbedded silt and sand overbank deposits. The surface is covered with mature coniferous forest and forms large tracts of the valley bottom. It includes the surface of the valley bottom extending to the north of the study reach between the western side of Mackenzie River valley and the At3 surface. On the At1 surface, the texture of the forest in the upper part of the study reach to south of the river delineates a braided network of channel scars, while faint channel scars are present to the north of the river in the middle part of the study reach (Fig. G2a). All of these paleochannels are approximately parallel to and interpreted as having originated from Keele River. Near the river mouth, the At1 surface is subject to backwater effects from Mackenzie River as is apparent by ice-push damage and discontinuous driftwood lines in the forest along the lower 2 km of the study reach. The At1 surface is interpreted as a terrace of Keele River. However, to the north of the study reach along Mackenzie River valley, the At1 surface grades into and becomes indistinguishable from the Mackenzie River floodplain. Along Keele Valley, it is not clear if the At1 surface represents a period of vertical stability followed by incision or an episode of aggradation which was followed by incision.

Figure G3. Contemporary flood plain deposits (Ap surface) of Keele River exposed at a fresh cutbank. The coarse channel lag in the foreground is the bottom of an inactive channel. GSC 1993-177X

Together, the Ap and At1 surfaces form the valley bottom of Keele Valley. The valley bottom is present along both sides of the river, being absent only where the river is confined directly against the valley sides. Upstream of the study reach, the valley bottom ranges from 500 to 4000 m wide. The width of the narrower sections is approximately that of the active channel zone, suggesting that Keele River is fit to the valley. The wider areas of the valley are interpreted to be the product of lateral channel migration.

The exact height of the At2 surface above Keele River is not known (the site was not visited, but the height probably lies within the 10 to 20 m range, as defined by the heights of the At1 and At3 surfaces). Viewed stereographically on aerial photographs, the At2 surface appears higher than both Ap and At1, and thus is identified as a separate surface in the valley. It is densely covered with a mature coniferous forest and is mapped as an alluvial terrace consisting of sand and gravel (Hanley and Hughes, 1973). The At2 surface is present only to the south of Keele River mouth; no equivalent surface is apparent upstream along Keele Valley. Since it extends to the south (upstream) along Mackenzie River valley, the At2 surface is interpreted as a terrace relating to Mackenzie River rather than Keele River.

The At3 surface is present to the north and south of the study reach at two locations (Fig. G1). Both are roughly 20 m above the Keele River water surface and are correlated on this basis. To the south of Keele River, the At3 surface forms a large 'bench' with an arcuate backwall cut into the Mackenzie Lowland. The orientation of the backwall is roughly parallel with Mackenzie River valley indicating that the surface was formed by Mackenzie River. To the north of Keele River, the At3 surface occurs as an isolated feature within Mackenzie River valley that is separated from the western valley side by a northward branch of the At1 surface. Since this At3 surface extends downstream (to the north) along Mackenzie River valley for about 6 km, it relates to Mackenzie River and not Keele River. Both At3 surfaces consist of sand and gravel (Hanley and Hughes, 1973) and are interpreted as alluvial terraces. There is no equivalent At3 surface along Keele Valley.

HYDROLOGY

The streamflow of Keele River is not gauged, but the regime likely is similar to Redstone River, which drains a similar region immediately to the south (see section on Redstone River-Hydrology, Appendix F). Of note, MacKay et al. (1973)

document a June 19 to 21, 1970 storm that produced the highest river stage known to have occurred on the Keele River (at least up to that time); the previous high was observed in 1926. At 'Keele River below Nainlin Creek', discharge from the 1970 event was estimated to be 4530 $m^3 \cdot s^{-1}$ (MacKay et al., 1973), but undoubtedly was considerably higher at the river mouth.

Bed-material transport rates along Keele River are relatively high as indicated by the considerable amount of lateral channel change occurring along the study reach (see section on Lateral channel change, below). Suspended sediment load fluctuates seasonally as the river reportedly is very silty in the spring and summer months, becoming clear around mid-August (Dryden et al., 1973). When observed (August 8, 1992), suspended sediment gave the river a milky appearance, but the turbidity was lower than that of Mackenzie River.

CHANNEL CHARACTERISTICS

Along the study reach, the Keele River is an alluvial, gravel-bed stream. The river flow is swift and alternates through sequences of riffles and pools. The valley gradient over the study reach is not known; between about 13.5 and 17 km above the river mouth, the valley slope averages 0.003 (estimated from 1:50 000 scale NTS map 96C/7).

The active channel zone ranges from 240 to 800 m wide (Fig. G1). Channel planform is transitional braided-meandering, probably falling within the wandering gravel-bed river morphology. The river is dominated by a single sinuous major channel that is divided to a degree by small islands and bars, particularly along the upper part of the study reach (Fig. G2a). Several minor channels branch from the major channel and delineate large islands (Fig. G2a).

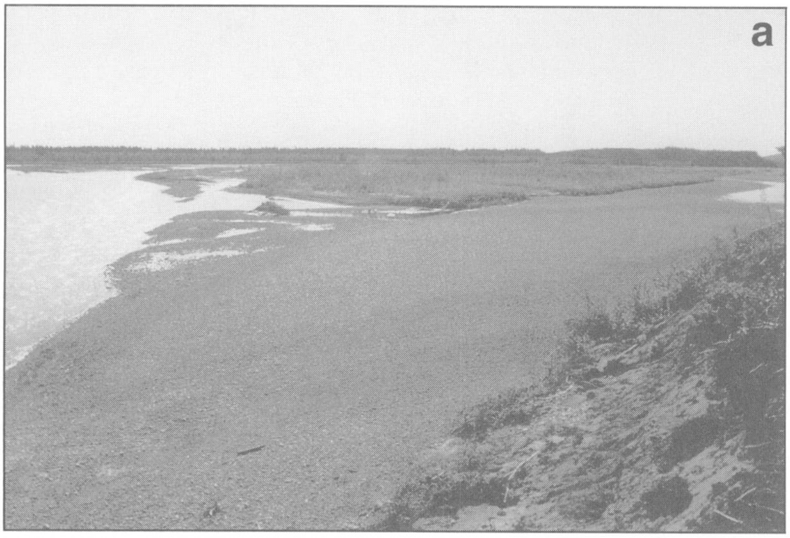
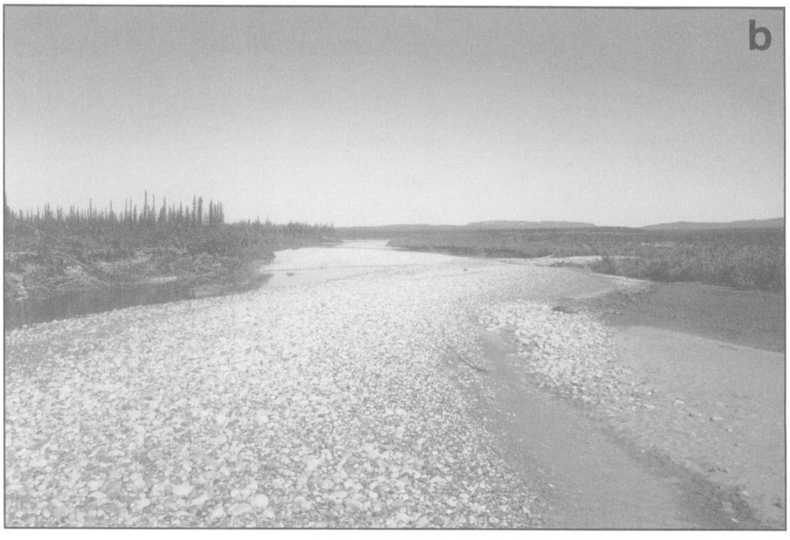


Figure G4.

*Gravel bed chute channel along Keele River extending across the back of 'point' bar 2 (see Fig. G1); **a**) the downstream end of the chute channel (GSC 1993-177W), and **b**) looking downstream from the chute channel entrance (GSC 1993-177I).*

Figure G4b.



A number of different types of bars are present within the active channel zone, including channel side, mid-channel, diagonal, and 'point' bars. The bars are composed of gravel with minor accumulations of sand and shrubs present on the bar surfaces. Vegetated islands also are present, representing stabilized bars and pieces of remnant floodplain (Fig. G2a).

Along the study reach, six large quasi-flat 'point' bars (marked 1 to 6 in Fig. G1) project into the channel around which the major channel meanders. The middle and back areas of the 'point' bar surfaces are vegetated with a thin to moderately dense cover of shrubs and small trees; mature deciduous trees are present on the back areas beside the floodplain. Cutting across the back area of each 'point' bar is a chute channel which is active at moderate to high discharges (Fig. G4). Of note, a large area of trees in the back area of 'point' bar 4 had been knocked over, probably during the large flood of July 1988.

At the sides of the active channel zone near the river mouth, a drape of silt and sand (up to 30 cm thick) covers large parts of the exposed bars and inactive channel bottoms (Fig. G5). These fine sediments have accumulated in a low energy depositional environment formed by backwater originating from Mackenzie River.

Cutbanks are present opposite each point bar (except for 'point' bar 6 situated immediately at the river mouth; Fig. G1) These cutbanks are eroding actively and subject to high rates of retreat (see section on Lateral channel change, below). Basal sediments along the cutbanks consist of gravel which represent river bars that have been incorporated into the floodplain (Ap surface; Fig. G3).

Isolated logs and small log jams occur sporadically in the shallow waters and on exposed bar surfaces. Large log jams occur at the heads of several chute channels and inactive channels (Fig. G6). Overall, logs and log jams represent minor obstructions to the river flow, although they do partially obstruct some inactive and abandoned channels.

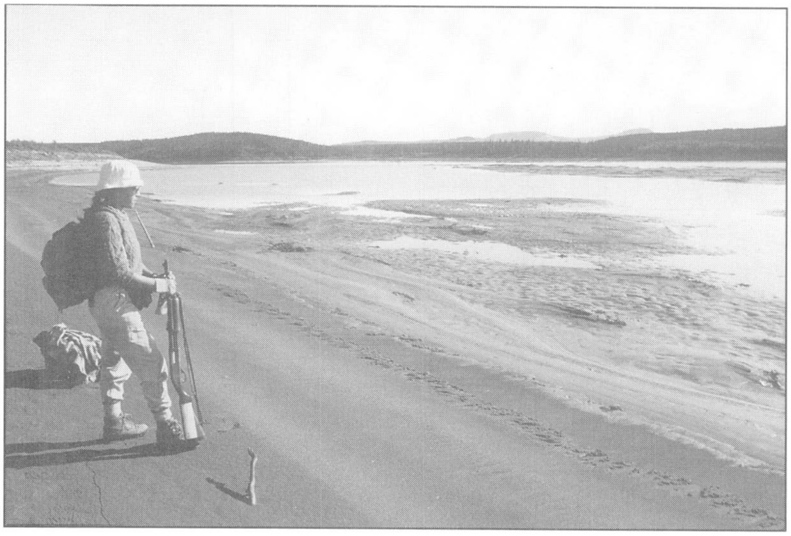


Figure G5.

A veneer of fine sand and silt sediments on the bottom of an inactive channel bottom along the Keele River study reach. GSC 1993-177N

Figure G6.

Log jam across the mouth of an abandoned Keele River channel. GSC 1993-177P

Ice-push features are not common along Keele River probably because of the high amount of deposition and erosion that occurs along the active channel zone (see section on Lateral channel change, below). Between 1 to 1.5 km above the river mouth, there are isolated areas of knocked over trees opposite point bar 5 which extend 10 to 20 m into the Ap and At1 surfaces (Fig. G7). These trees were probably knocked over by ice which was thrust onto the Ap and At1 surface because of jamming in the river during spring break-up.

LATERAL CHANNEL CHANGE

Along the study reach, lateral channel change is occurring through two processes: the progressive lateral migration of the active channel zone and, to a lesser extent, by channel avulsions (Fig. G8). Comparison of aerial photographs reveals that major active channel zone retreat between 1949 and 1981 occurred within five discrete zones of erosion (designated A to E in Fig. G8). Zones A and D are located along the southern bank of Keele River while B, C, and E occur along the northern side. These zones generally alternate from one side of the active channel zone to the other and occur where the floodplain forms the outer bank of meanders in the major channel. This alternating pattern is disrupted where the active channel zone is confined directly against the high sides of the Mackenzie Lowland on the south side of the river (Fig. G1) between zones B and C (Fig. G8).

Between 1949 and 1981, the rate of maximum erosion along zones A to E averaged from about 4 to 6 m·a^{-1} (Table G1). The net effect of this erosion has been to increase the sinuosity of the major channel within the active channel zone. Site inspection on August 8, 1992 revealed that there has not been significant alteration to the general location of active channel zone erosion along at least the lower 3 km of the study reach.

Erosion of the active channel zone boundary is being complimented by deposition within the channel, although this is not apparent everywhere in Fig. G8 (but compare Fig. G2a and c). Along zones A and B, this deposition is occurring

Figure G7.

Area along the edge of the At1 surface that has been affected by ice thrusting during the spring break-up of Keele River; ***a****) a severely abraded surface (GSC 1993-177H); and* ***b****) flattened trees (GSC 1993-177M).*

Figure G7b.

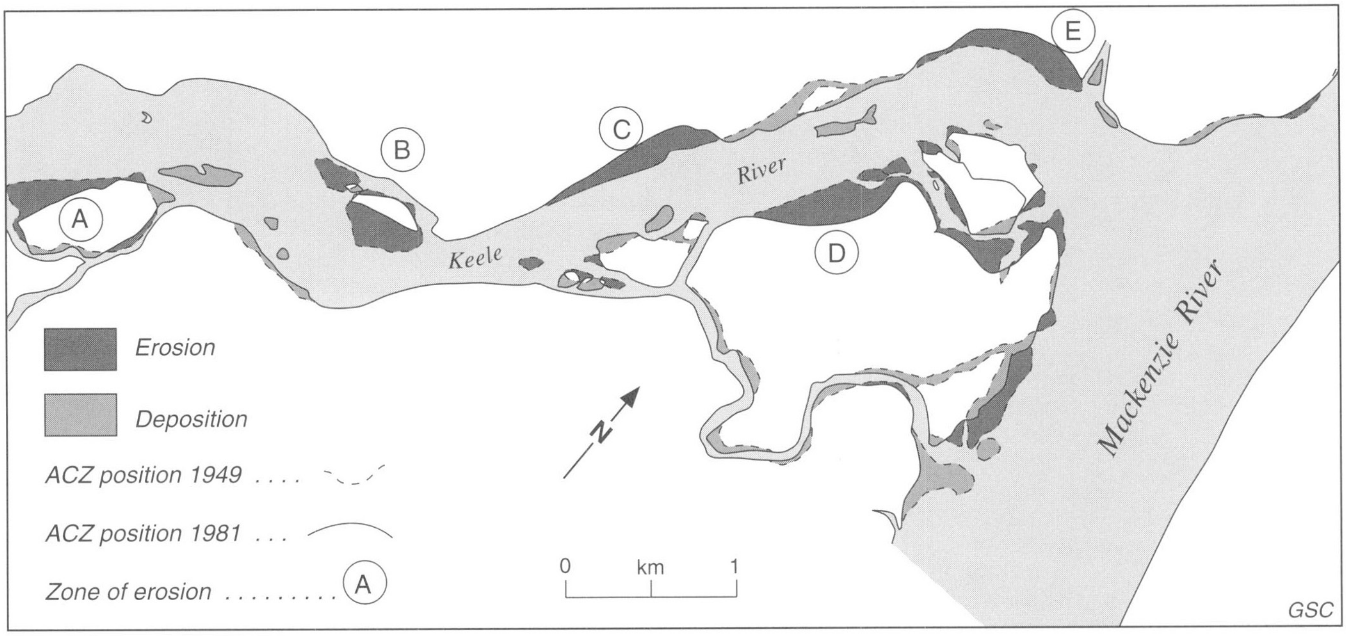


***Figure G8.** Net channel change along the Keele River study reach between 1949 and 1981; ACZ = active channel zone.*

through the growth of mid-channel and side bars while 'point' bars are developing opposite zones C, D, and E (compare the locations of 'point' bars 1 to 5 in Figure G1 with the zones of erosion in Fig. G8).

Within the active channel zone, the bars and islands are subject to both accretion and erosion resulting in some modification to the channel network (Fig. G2a and b).

KEELE-MACKENZIE INTERACTION

The presence of the Ap surface along the southern side of the tributary mouth indicates that Keele River has shifted laterally relative to Mackenzie River within a corridor about 4 km wide. The present trend of lateral migration of the river mouth is not obvious from Figure G8.

Emerging from Keele Valley about 4 km above the river mouth, Keele River has constructed a low-angled alluvial fan that splays across the bottom of Mackenzie River valley. The fan is the product of bed-material transport from Keele River into Mackenzie River. It controls the lateral position of Mackenzie River, confining it against the eastern side of Mackenzie River valley. A channel junction bar at the river mouth constricts the adjacent Mackenzie River channel which cause the channel to narrow from 1250 m upstream to a minimum of 650 m (Fig. G4b).

Table G1. Maximum erosion along the bank segments of Keele River between 1949 and 1981 (refer to Fig. G8).

Bank segment	Retreat of bank (m)	Rate of retreat ($m \cdot a^{-1}$)
A	189	5.9
B	189	5.9
C	145	4.5
D	203	6.3
E	145	4.5

Bed-material transport from Keele River into Mackenzie River is relatively high (see section on Hydrology, above). As a result of this, numerous islands and bars are present downstream along Mackenzie River for some 55 km below the tributary mouth. The presence of these features, however, is only partially attributable to Keele River sediment supply. The modified character of Mackenzie River begins between the Blackwater and Dahadinni confluences and probably reflects sediment supply from Dahadinni and Redstone rivers and from cutbank erosion and slope failures along Mackenzie River valley sides, and an increase in valley gradient.

APPENDIX H

Great Bear River

STUDY REACH DESCRIPTION

Great Bear River is 115 km long and drains an area of 158 000 km^2 (Table 1). The river originates from Keith Arm in the southwestern corner of Great Bear Lake and flows westward over the Great Bear Plain, across the Mackenzie Lowland and into Mackenzie River valley (Fig. 2). The southern end of the Norman Range of the Franklin Mountains occurs northwest of the river mouth, but does not encroach upon the river (Fig. 2).

The study reach extends along the lowest 5.5 km of Great Bear River (Fig. H1). Along this reach, the river occupies a narrow, steep sided valley incised into the Mackenzie Lowland. Tertiary bedrock underlies the Mackenzie Lowland (Yorath, 1970; Savigny, 1989) and is well exposed along the study reach. These rocks are comprised of two units (Savigny, 1989). The lower unit consists generally of a complex sequence of shale and siltstone overlain by sandstone and conglomerate (Savigny, 1989). This unit is exposed only along the lower 4 km of the study reach (Savigny, 1989). The upper unit is formed by interbedded bentonitic siltstone and coal (lignite to subbituminous). Both units are weakly indurated and easily excavated by a hand shovel (Savigny, 1989). Both units are, however, capable of supporting the high-angled slopes that have developed along some parts of Great Bear Valley.

The surficial geology of the Mackenzie Lowland to the south of the study reach is mapped as glaciolacustrine plain consisting of sand and silt (Hanley and Hughes, 1973). These deposits accumulated in lakes that occupied the Mackenzie Lowland during and after the waning of the late Wisconsinan Glaciation (Savigny, 1989; Smith, 1992). The area immediately north of the study reach is mapped as a morainic till plain (Hanley and Hughes, 1973; Savigny, 1989). Along the river, a vertical sequence of Quaternary deposits overlies the Tertiary bedrock and consists of (top to bottom) sand, clay, and till (diamicton?) (Savigny, 1989). These sediments generally thicken from about 20 to 45 m upstream along the study reach (Savigny, 1989).

The history of Great Bear River incision into the Mackenzie Lowland is known only generally. Associated with glacial Lake Mackenzie (Smith, 1992), deltaic sedimentation upon the lowland appears to have still been occurring at 10 600 BP as indicated by a radiocarbon age of 10 600 ± 260 BP (GSC 2328). This radiocarbon age is based upon

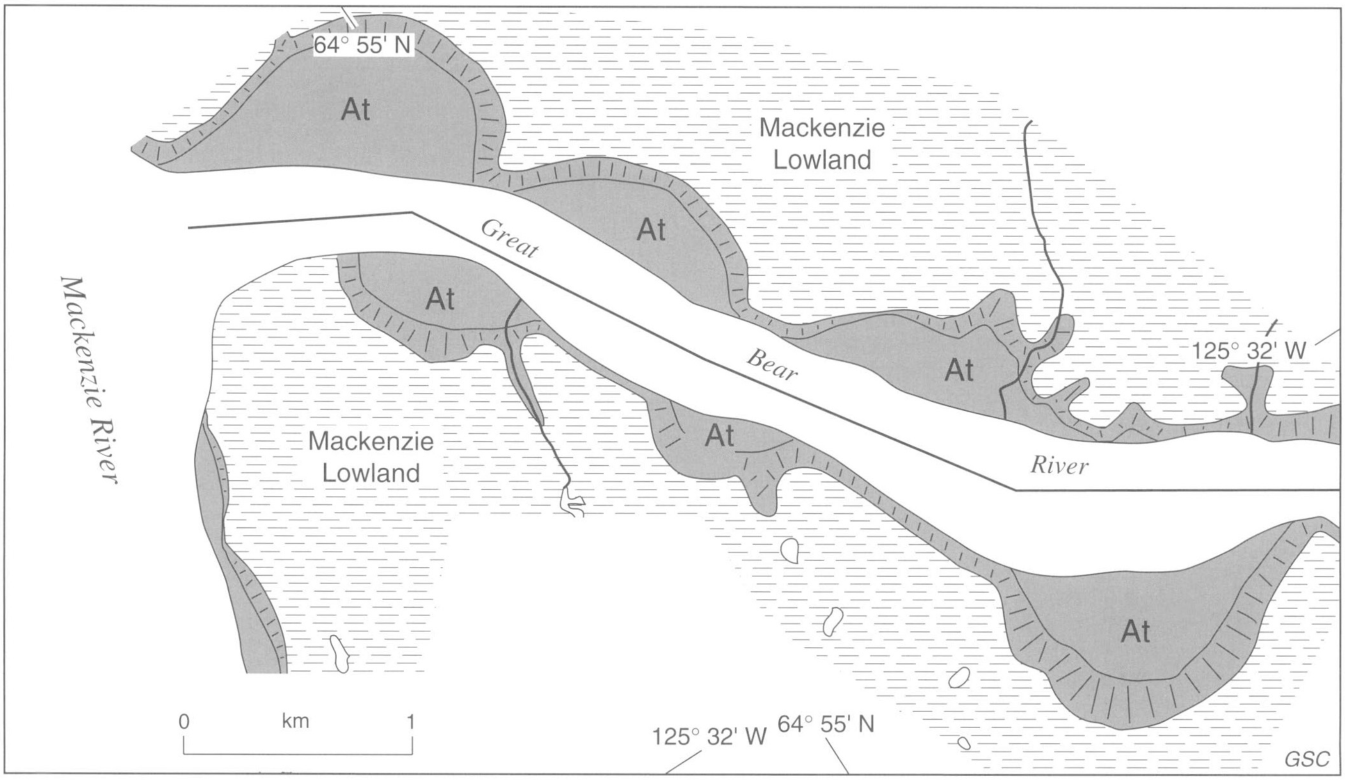


Figure H1. Physiographic map of the Great Bear River study area (uncorrected from aerial photographs NAPL A24089-87; A24089-98). Refer to Figure A1 for legend.

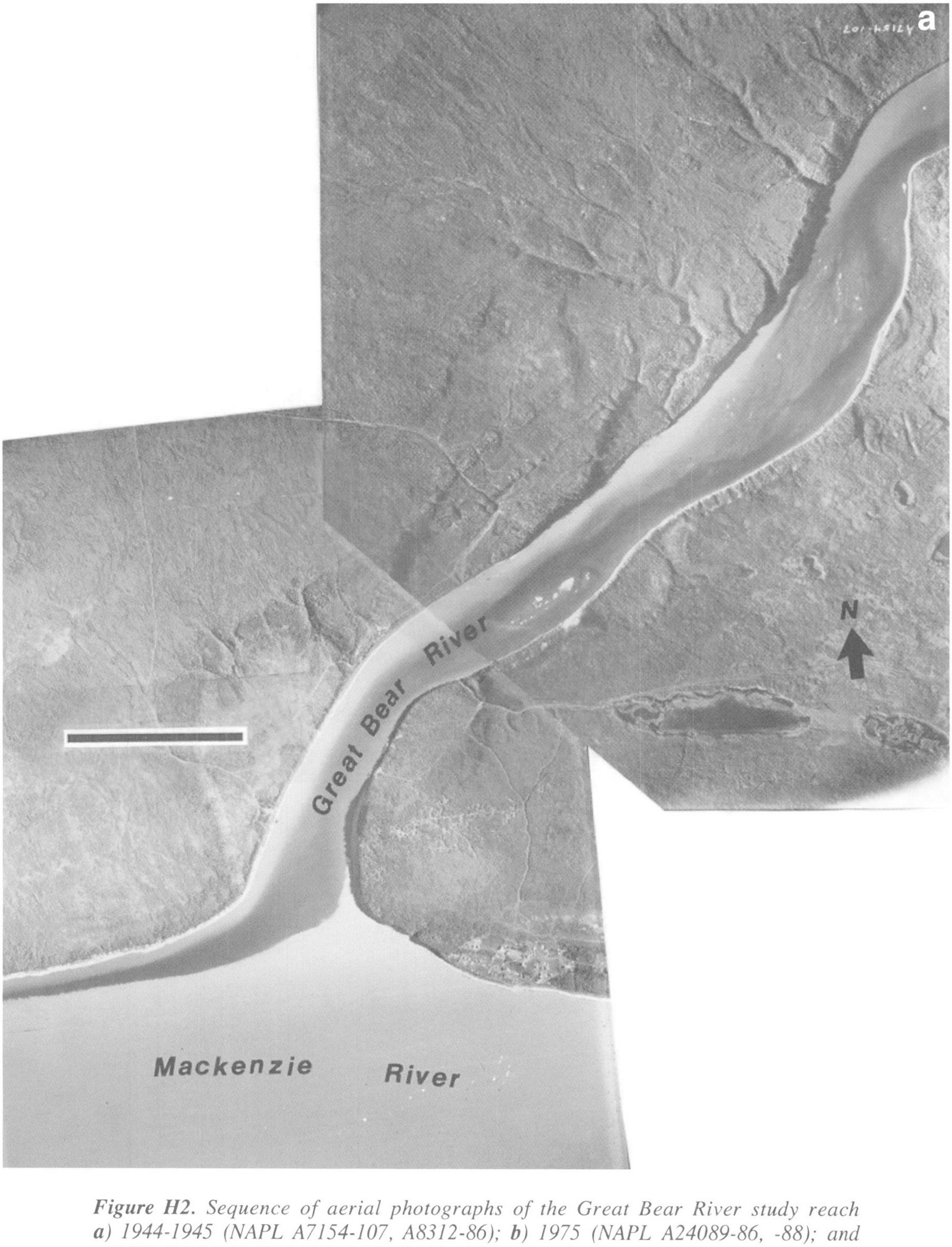


Figure H2. *Sequence of aerial photographs of the Great Bear River study reach* ***a****) 1944-1945 (NAPL A7154-107, A8312-86);* ***b****) 1975 (NAPL A24089-86, -88); and* ***c****) 1983 (NAPL A26354-134, -135); the black bar on each mosaic represents one kilometre.*

organic detritus that was obtained near the river mouth within tabular, crossbedded sands, which are situated about 5 m beneath the lowland surface (Lowden and Blake, 1979; Savigny, 1989). River incision thus began some time after 10 600 BP. The river was within 10 m of its present position after 2700 BP, as suggested by wood dated at 2670 ± 130 BP (GSC 2488; McNeely, 1989) obtained from colluvium about 7 km above the river mouth (Savigny, 1989).

Of note, Savigny (1989) reports the presence of a narrow trough filled with Quaternary sediments that is situated about 7 km from the river mouth just above the study reach. The base of this trough extends below the present water surface of Great Bear River and is believed to represent part of the pre-late Wisconsinan drainage system, possibly being contiguous with the Hare-Mackenzie trench (see Mackay and Mathews, 1973).

The present surface of the Mackenzie Lowland is densely forested. Small lakes and wetlands are present on the lowland (Fig. H2c), some of which occupy thermokarst depressions (Hanley and Hughes, 1973). Fort Norman and associated clearings are located just south of the river mouth (Fig. H2c). The Norman Wells pipeline and several roads and cut-lines criss-cross the lowland surface in the area of the study reach (Fig. H2c; although pipeline construction postdates the aerial photography).

VALLEY CHARACTERISTICS

Along the study reach, Great Bear Valley decreases in depth towards the river mouth from 55 m to 40 m (Savigny, 1989). The valley bottom ranges from 600 to 1200 m wide; the wider areas correspond to terraces cut back into the valley sides (Fig. H1).

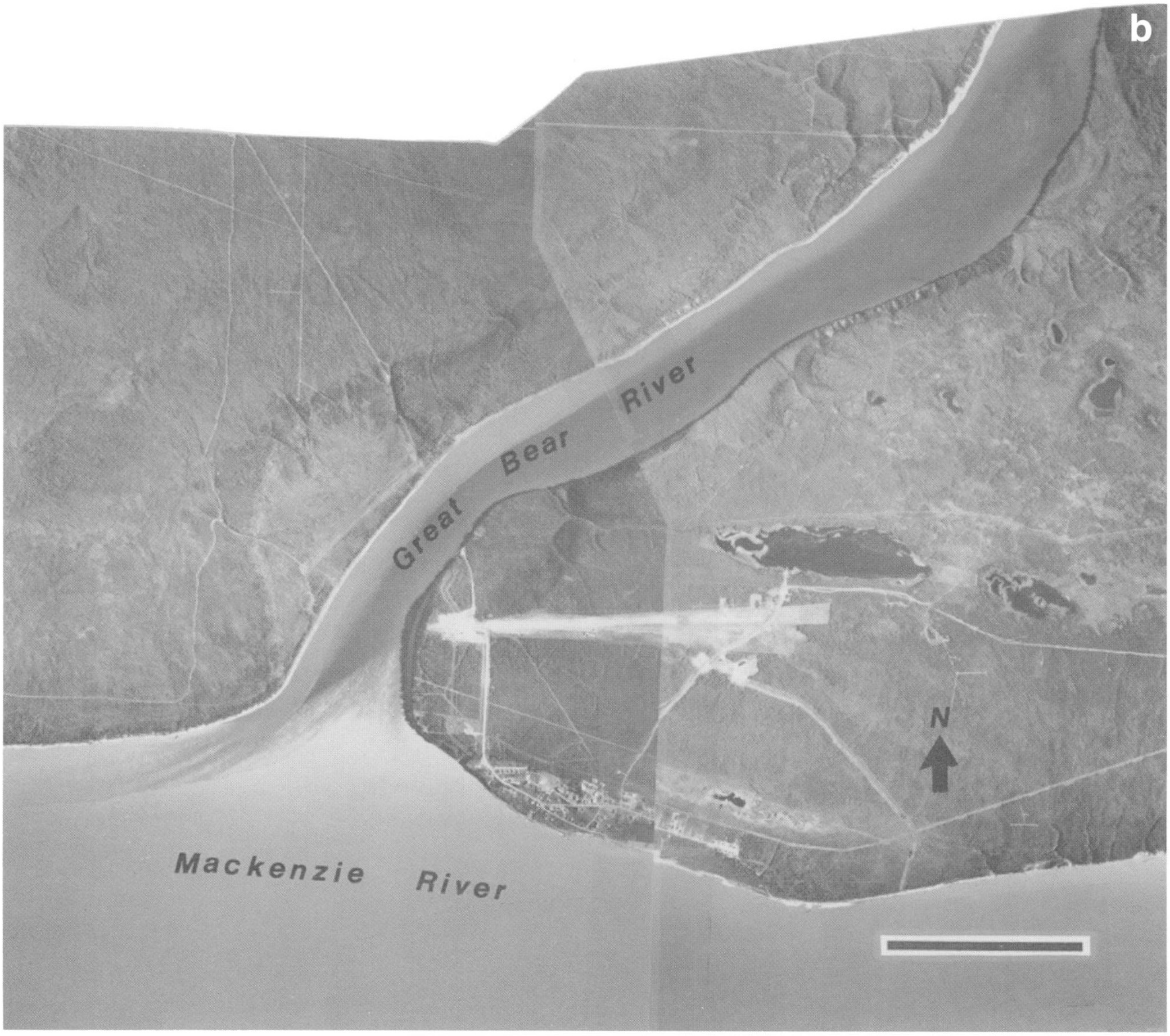


Figure H2b.

No major slope failures are apparent on the aerial photographs. However, minor and medium-sized failures occur where the river is confined directly against the valley side. This confinement occurs along about 35% of the total length of valley sides.

Site inspection revealed that the Tertiary bedrock forming the high-angled slopes generally is unvegetated and probably is subjected to minor mechanical weathering. The overlying Quaternary sediments commonly experience slope movement; the ice-rich glaciolacustrine sediments and, to a lesser extent, the diamicton are both prone to failure (Code, 1973; Hughes et al., 1973; Savigny, 1989). In places, failed Quaternary sediments have partially covered the Tertiary rocks. Savigny (1989) reported several major multiple retrogressive slides occurring upstream of the study area.

Six discontinuous alluvial terraces are present along the study reach below the Mackenzie Lowland (At in Fig. H1). The terraces have been mapped as sand and silt veneers (Hanley and Hughes, 1973), presumably of overbank origin. It is not clear if any of these terraces represent contemporary

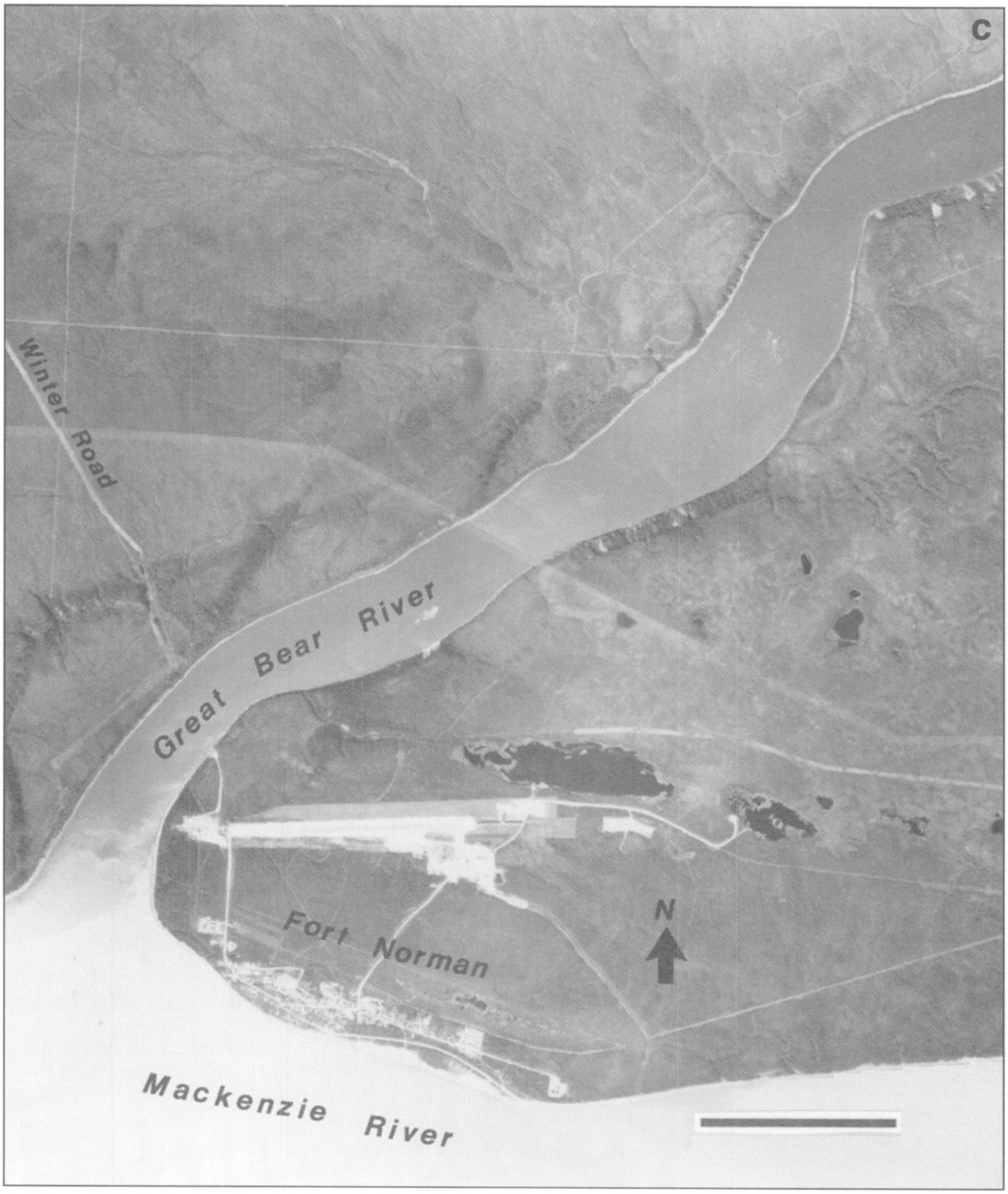


Figure H2c.

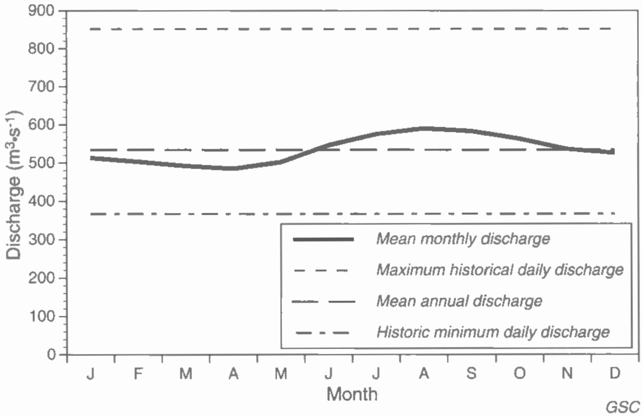


***Figure H3.** Hydrograph of the Great Bear River streamflow, 1961-1992, 'Great Bear River at outlet of Great Bear Lake station' (Water Survey of Canada, unpub. data).*

floodplain. The age and synchronicity of the surfaces is not known. The general outline of their backwalls suggests that several are contemporaneous, which implies that Great Bear River was more sinuous in the past.

HYDROLOGY

The streamflow of Great Bear River is monitored at the outlet on Great Bear Lake. Based upon the record for the period 1961 to 1992 (Table 3; C. Brumwell, written comm., September 27, 1993), mean annual discharge is 534 $m^3 \cdot s^{-1}$. Mean monthly discharge is very regular with the highest and lowest month varying by only 105 $m^3 \cdot s^{-1}$ (Fig. H3; August: 590 $m^3 \cdot s^{-1}$, April: 485 $m^3 \cdot s^{-1}$). There is also relatively little difference between the maximum (852 $m^3 \cdot s^{-1}$) and minimum historical daily discharges (367 $m^3 \cdot s^{-1}$; Fig. H3). This attenuated discharge regime is caused by water storage within Great Bear Lake which forms a major portion of the drainage basin[1]. The discharge regime at the study reach probably is only marginally different from that shown in Figure H3 since no major streams join Great Bear River along its 115 km course.

Along the study reach, high water marks up to 10 m above the observed river surface (August 10, 1992) reflect a level of backwater caused either by ice jamming in Mackenzie River, the Mackenzie River freshet, or both.

There is no published sediment load data for Great Bear River. As has been noted by early researchers (e.g., Mackenzie, 1801; McConnell, 1891; Bell, 1901b; Camsell and Malcolm, 1921), river waters are very clear suggesting that concentrations are low. The water is clear because Great Bear Lake functions as a major sediment trap within the drainage basin. These clear waters produce a noticeable plume in Mackenzie River (Fig. H2a and b) which can be readily followed up to 80 km below the confluence (Mackay, 1966). In Figure H2a and b, the obvious sediment plume along the north side of the Great Bear River originates from Brackett River, a small tributary which joins Great Bear River about 10 km above its mouth.

The clear waters and insignificant lateral channel migration suggests that bed-material transport rates along Great Bear River are very low (see section on Lateral channel change, below).

CHANNEL CHARACTERISTICS

Along the study reach, Great Bear River is relatively straight with a sinuosity of 1.03. The channel varies from 400 to 650 m wide. The observed streamflow was 605 $m^3 \cdot s^{-1}$ with a swift river current (August 10, 1992; D. Anderson, written comm., February 3, 1994). Shoals, exposed at low to moderate discharges, cause some shifting of the thalweg within the channel and present a hazard to navigation. Hardy Associates (1978) Ltd. (1982a) report a channel slope of 0.0006 along the river over a distance of 2.5 km upstream and 1.0 km downstream of the Norman Wells pipeline crossing.

The river bed consists of a coarse boulder lag. The river banks appear to be relatively stable, subject to little fluvial erosion and deposition. Areas where the banks are formed from Tertiary bedrock, the surfaces appear 'fresh', having been abraded by river ice during the spring break-up. Elsewhere, the banks are composed typically of boulder pavements and loose boulder pavements, the product of ice-push processes (Fig. H4). Both the pavements and the abraded areas extend 5 to 10 m above the observed river surface and form a distinct trimline.

LATERAL CHANNEL CHANGE

Inspection of the aerial photographs (Fig. H2) reveals little change of the channel boundaries relative to static features along or near the river banks. Thus, there has been little lateral channel change along the study reach between 1944/1945 and 1983. This inconsequential lateral change probably relates to the fact that the river occupies a narrow bedrock valley and has a very coarse bed. The attenuated discharge regime of Great Bear River may also have a role in the channel stability since the river is not subject to extreme floods which might initiate major bank erosion and deposition.

GREAT BEAR-MACKENZIE INTERACTION

The mouth of Great Bear River is laterally stable within its valley and has not migrated with respect to Mackenzie River.

The study reach is subject to high backwater conditions originating from Mackenzie River as shown by the occurrence of ice-push features up to 10 m above the observed river surface. This is well above the water level expected from Great Bear River with its very attenuated discharge regime. The high level of backwater likely occurs during the Mackenzie River freshet or when ice jamming occurs in Mackenzie River during the spring break-up.

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[1] With an area of 30 800 km^2, the surface of Great Bear Lake represents about 21% of the drainage basin.

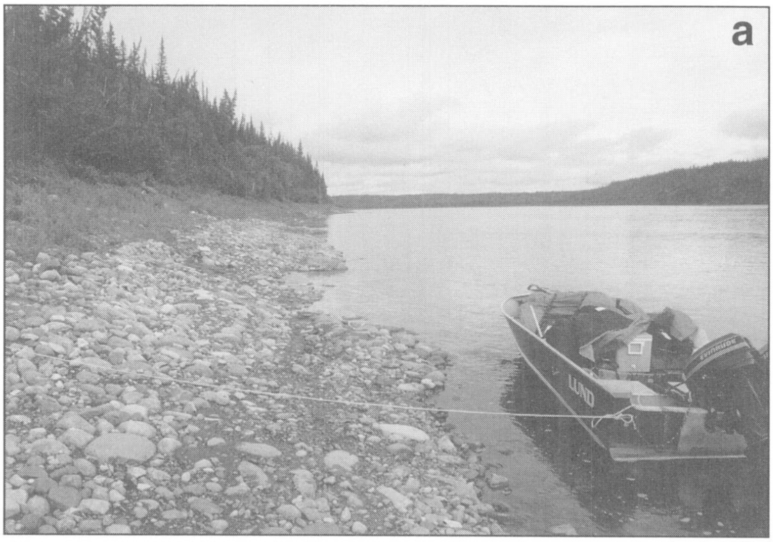

Figure H4.

*Typical river bank morphology along the Great Bear River study reach **a**) boulder pavement (GSC 1993-177V), and **b**) loose boulder pavement (GSC 1993-177L).*

Figure H4b.

Reflecting its relatively very low bed-material transport, there is no obvious morphological feature present at the mouth of Great Bear River.

At the Great Bear confluence, Mackenzie River is markedly wider than the immediate upstream and downstream reaches. This widening, however, begins 2 to 3 km upstream of the Great Bear River mouth and ends 8 km downstream. Associated with this channel widening, a 6 km long island (Windy Island) occurs mid-channel, beginning adjacent to the tributary mouth. The channel widening and the development of Windy Island may relate to the entrance of Great Bear River, perhaps related to the hydraulic deflection of Mackenzie River by the Great Bear River flow. The addition of Great Bear River discharge causes no persistent widening of the Mackenzie River channel below the Great Bear confluence.