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Flow modelling to estimate suspended sediment travel times for two Canadian Deltas

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Abstract

The approximate travel times for suspended sediment transport through two multi-channel networks are estimated using flow modelling. The focus is on the movement of high sediment concentrations that travel rapidly downstream. Since suspended sediment transport through river confluences and bifurcation movement is poorly understood, it is assumed that the sediment moves at approximately the average channel velocity during periods of high sediment load movement. Calibration of the flow model is discussed, with an emphasis on the incorporation of cross-section data, that are not referenced to a datum, using a continuous water surface profile. Various flow regimes are examined for the Mackenzie and the Slave River Deltas in the Northwest Territories, Canada, and a significant variation in travel times is illustrated. One set of continuous daily sediment measurements throughout the Mackenzie Delta is used to demonstrate that the travel time estimates are reasonable.

Keywords: suspended sediment; multi-channel river systems; flow modelling; sediment transport

Introduction

The movement of fine grained suspended sediment particles often becomes dominant over bed load sediment in the downstream sections of riverine systems that carry a substantial sediment load, with the concentrations transported usually varying as a function of the discharge rate (Asselman, 2000). Such a sediment regime is often established in the middle reaches of a system whose terminus is an alluvial delta, and the delta becomes the sink for a majority of the suspended load. Since an understanding of the transported suspended sediment is very important to assess movement of nutrients and contaminants at moderate to high suspended sediment loads (Helmer, 1994), monitoring sediment load into and through a delta is crucial to understanding the fate of contaminants. Furthermore, deltaic systems are very sensitive environments that are often home to numerous flora and fauna, especially for the breeding of bird species (e.g. Gratto-Trevor, 1997), and thus changes to nutrient and contaminant inputs into such an environment can be very detrimental.

The understanding of sediment transport in streams and rivers is extensive, yet not complete (Shen and Julien, 1993). For suspended sediment transport in a river reach, some form of the advection-dispersion equation is typically used for modelling sediment movement (e.g. Lau and Krishnappan, 1981; Alonso, 1981; Krishnappan, 1990; Ziegler and Nisbet, 1994). However, little is known about the movement of fine grained particles through multi-channel systems. Pickup and Higgins (1979) investigated sediment transport in a braided river by treating the system as a multi-channel network; but, their work was limited to bed-load transport. However, Fassnacht (1997) has examined the suspended sediment transport through multi-channel systems, using a mass balance at bifurcations and confluences. Equations that model the physical movement of suspended sediment through bifurcations and confluences are not available.

For depositional areas, such as estuaries and deltas, a minimum rate of sediment influx is usually maintained throughout the open-water season (Henderson, 1997). Significant quantities of sediment are brought into these systems, or taken out, by high flow events accompanied by substantially increased sediment concentrations. The periods of high flow are often induced by upstream precipitation events, or snowmelt for rivers in cold climates. During these peak flows, suspended sediment concentrations usually resemble a slug (Jasper and Kerr, 1992) since peak flows are rarely sustained for long time periods. Attenuation occurs as the slug travels downstream. It is important to consider the sediment travel time such that sampling of the same location on the suspended sediment hydrograph (called a pycnograph) occurs, that is, sampling the same point on the pycnograph at different locations down the river, or throughout a bifurcating system.

To date suspended sediment travel times are based solely on field expertise and for practical purposes, considered static. These times are used to design sampling schedules. Suspended sediment travel times have also been used to determine the relationship of sediment concentrations between upstream and downstream sampling locations (e.g. Carson, 1994). A constant time or a time range has been used to lag sediment movement between locations due to the limitation of available data.

To examine the impacts on water quality across an entire basin, a snapshot approach was used by Grayson *et al.* (1997). This approach collected samples throughout a river system at one instant in time. Grayson *et al.* (1997) examined water quality during low flow periods over a 4 day period, and the snapshot approach examined the state of the basin when little change in quantity or quality occurred. One of their main focuses was to provide a spatial coverage of the study basin to complement long term point data.

While the low flow water snapshot approach is the same as the suspended sediment sampling schedule derived from travel time estimates, the travel time estimates will vary with the flow regime. In particular, sampling during periods of large suspended sediment loads requires an understanding of the sediment movement rates at high flow rates. To illustrate this importance of appropriate timing, five rapid changes in suspended sediment load, concentration and discharge on the Slave River at Fitzgerald are presented in Figs. 1a, b, and c, respectively. In each instance, there was a substantial increase in sediment load, as the increased flows transported higher concentrations of suspended sediment. The largest suspended sediment slug was observed in June of 1990 when 33.3 Mt were transported over a 14 day period (Fig. 1d), with a daily maximum of 6.67 Mt transported on June 19th, 1990. Considering the inflow to the Mackenzie Delta, the large sediment slug was observed in mid-August 1974 on the Mackenzie River at Arctic Red River (Fig. 2). Over a 14 day period 101 Mt of suspended sediment were transported and the largest observed daily sediment load was 23.3 Mt observed on August 12th, 1974. Due to the rapid rise in the pycnograph, sampling to develop a temporal snapshot of sediment flow must consider the travel time and attenuation as a suspended sediment slug flows downstream.

To address the difficulties in determining the movement rates of suspended sediment, travel times estimates are derived for two multi-channel river systems. As equations for suspended sediment movement through bifurcations and confluences are not available, equations for water flow will be used instead, based on the assumption that the particles move as water. Alonso (1981) agrees with this assumption by stating that particles carried in suspension move at a rate close to the stream velocity. However, this does not hold true at all times due to deposition and/or resuspension, especially at confluences and bifurcations (Krishnappan, pers. comm., 1994).

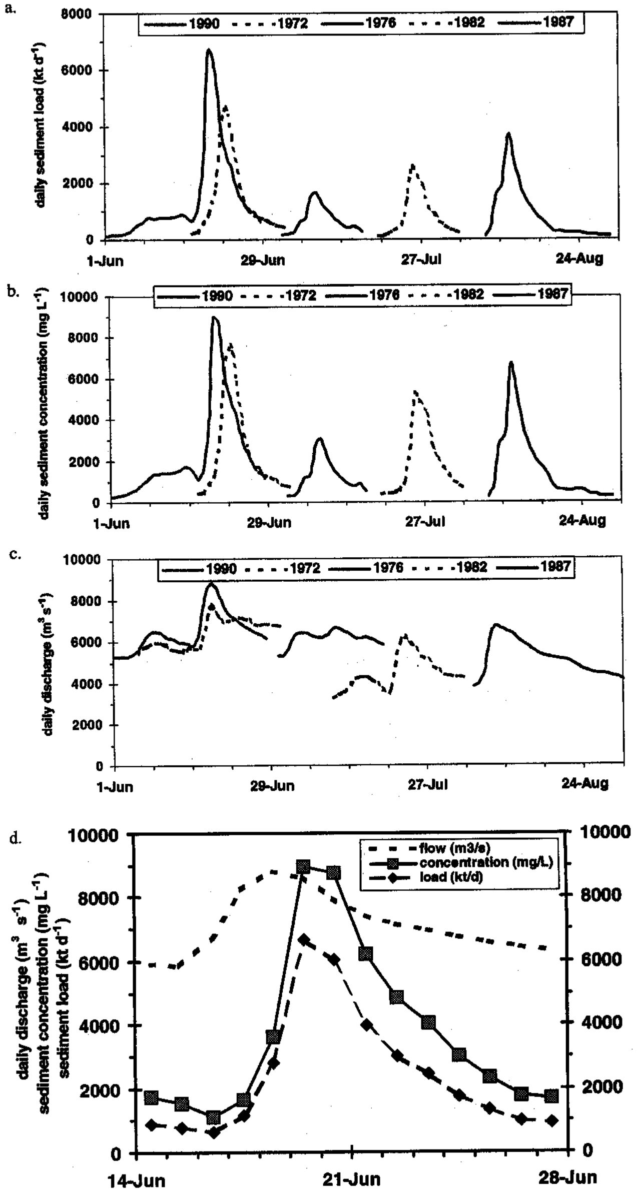

Fig. 1. *(a) The five largest daily sediment load peaks, (b) the corresponding daily sediment concentrations, (c) the corresponding daily discharges, for the Slave River at Fitzgerald, upstream of the Slave River Delta, for the years from 1971 through 1991 (data from Environment Canada, 1997), (d) The largest sediment load peak (in* $kt\ d^{-1}$*) observed between 1971 and 1991 on the Slave River at Fitzgerald occurred in 1990. The corresponding daily suspended sediment concentration (in* $mg\ L^{-1}$*) and discharge (in* $m^3\ s^{-1}$*) are also included (data from Environment Canada, 1997).*

Study sites

The Mackenzie River Basin covers an area of approximately

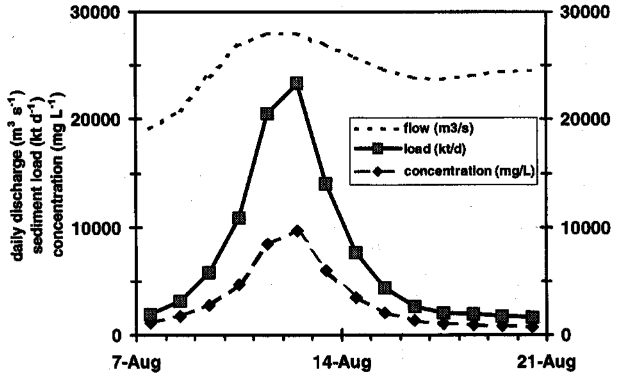

Fig. 2. *The largest sediment load peak (in kt d^{-1}) observed between 1972 and 1991 on the Mackenzie River at Arctic Red River, and the corresponding suspended sediment concentration (in mg L^{-1}) and discharge (in $m^3 s^{-1}$) (data from Environment Canada, 1997).*

1.8 million square kilometres in northwestern Canada (see Fig. 3a). Within the basin there are three deltas of varying size (Mackenzie, Peace-Athabasca, and Slave) that, except for flowing channels, consist of large wetland and slough areas. Since most portions of the various rivers within the Mackenzie basin are north flowing, and the basin is snow-covered for an extended period of the year, peak streamflows and water levels are related to snowmelt and ice jams as warm north-flowing water melts the ice cover. However, the peak suspended sediment loads occur after the river ice-cover has been melted. Thus, only open water periods for the deltas will be considered in this study.

The deltas are breeding, rearing and feeding habitats for numerous migratory birds and other wildlife (Mackenzie River Basin Committee, 1981), making them biologically sensitive areas that can be affected by the influx of contaminants, human influences, such as the impoundment of Williston Lake on the Peace River, as well as the influences of climate change (Mackenzie Basin Impact Study, 1997). Future development of Beaufort Sea oil and gas reserves will also influence the Mackenzie basin. For example, pipeline or tanker accidents can contribute hydrocarbons to the riverine environment; petroleum products are hydrophobic and adsorb to sediment particles.

Within the deltas, sediment is transported primarily in suspension (Carson *et al.*, 1998). This is mainly a result of the high discharges and flow velocities into and through the deltas, and the dominance of fine-grained particles in the transported sediment. These suspended sediment particles can act as media of transport for contaminants from upstream fluvial and upwind aeolian sources. To support sediment sampling, which is a step towards understanding the sediment regime through the Mackenzie Basin river system, travel times have been estimated for the Mackenzie and Slave River deltas.

Mackenzie river delta

Emptying the entire basin waters into the Beaufort Sea, the Mackenzie Delta is the second largest arctic delta in the world, covering an area of 13 000 km^2 (Fig. 3b). At its inflow the mean annual discharge of the Mackenzie River from 1973 to 1995 was 8980 $m^3 s^{-1}$ (Environment Canada, 1997), with a peak of more than double the yearly average occurring in late May or early June due to snowmelt. The delta also receives flow and sediment from the 70 600 km^2 Peel River, and the 18 600 km^2 Arctic Red River. The Peel River contributes on average 680 $m^3 s^{-1}$ annual or 7% of the delta inflow, and the Arctic Red River contributes on average 155 $m^3 s^{-1}$ annual or 1.6% of the delta inflow (Environment Canada, 1997). Carson *et al.* (1998) estimate the fine-grained sediment fluxes into the Mackenzie Delta to be approximately 103 Mt yr^{-1} from the Mackenzie River and 21 Mt yr^{-1} from the Peel River. The Arctic Red River contributes in the order of 4 Mt yr^{-1} (Carson *et al.*, 1998).

Numerous hydrometric studies have been undertaken in the Mackenzie Delta, including investigations by the oil and gas industry, prompted by the discovery of hydrocarbon reserves in the Beaufort Sea, and by various Canadian government agencies. The Northern Oil and Gas Action Program prompted Environment Canada to model the delta hydraulics. The Mackenzie Delta travel time estimates were performed in conjunction with a flow modelling project coordinated by Environment Canada that used the ONE-D flow model (see Jasper and Kerr, 1994).

Slave river delta

Although the entire Slave Delta deposits are 8300 km^2, the active delta covers only 5% of this area, or approximately 400 km^2 (English *et al.*, 1997). The channels of the active delta are illustrated in Fig. 3c. Entering its delta, the Slave River drains 606 000 km^2 and carries a mean annual discharge of approximately 3400 $m^3 s^{-1}$ (Environment Canada, 1997). Although the Slave Delta is almost 1000 km south of the Mackenzie delta, the annual peak, which is of the order of 6000 $m^3 s^{-1}$, occurs later. The contribution of mountain meltwaters from British Columbia are more significant in the late June high flows of the Slave River than in the Mackenzie Delta.

The hydrometric studies in the Slave Delta have been less extensive than in the Mackenzie. The most comprehensive study occurred during the Mackenzie River Basin Committee Study from 1978 to 1981. Flow modelling of the Slave River delta using the ONE-D model is a new application.

Methodology

The estimation of sediment travel times is derived from flow

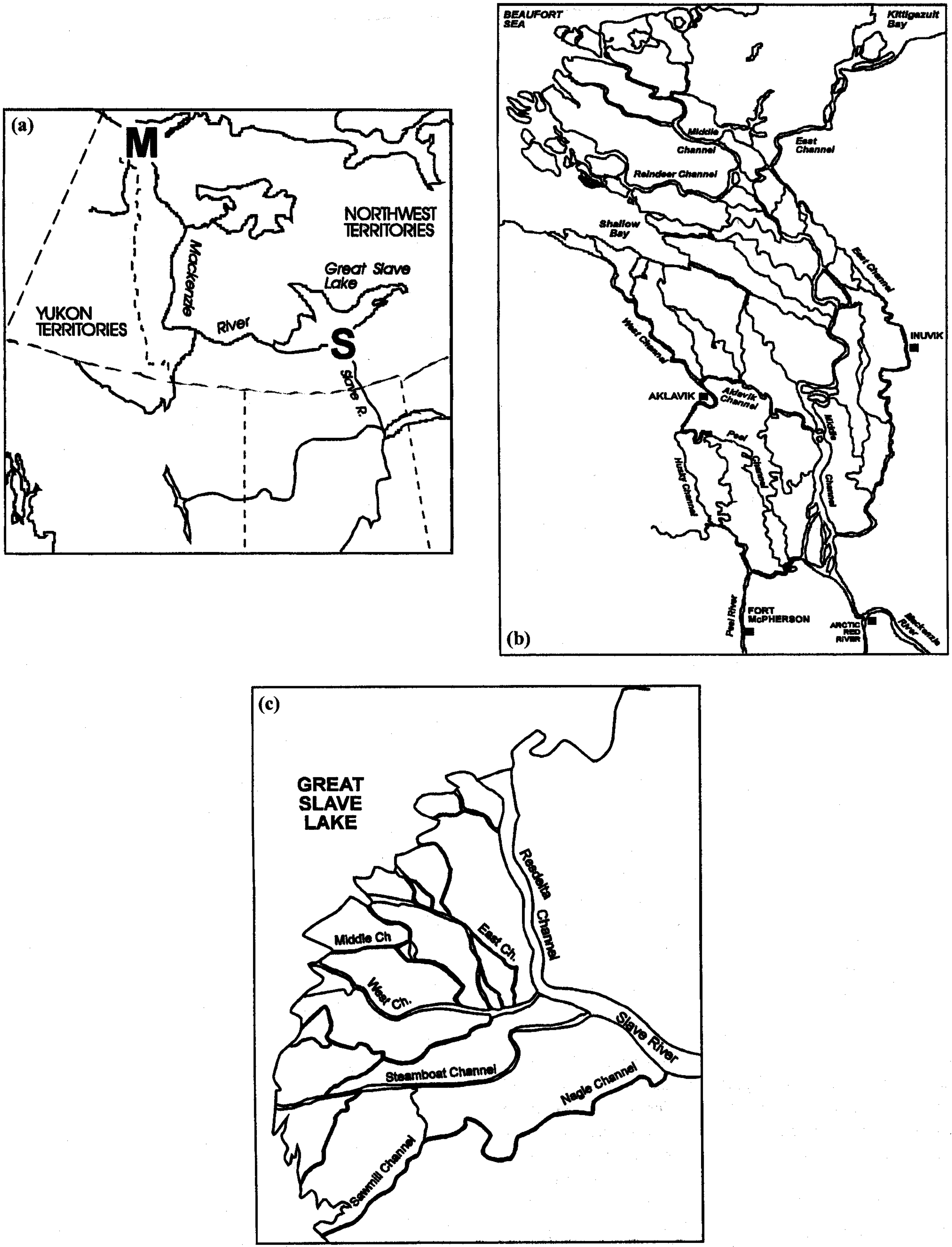

Fig. 3. *(a) Location map of the study areas (M and S indicate the location of the Mackenzie and Slave Deltas, respectively), (b) Map of the Mackenzie River Delta, (c) Map of the Slave River Delta.*

modelling results using the Environment Canada (1988) ONE-D hydrodynamic flow model. The travel times are based on the assumption that suspended sediment moves at approximately the same velocity as the water in which it is transported. The ONE-D model implicitly solves the flows in each reach and the water levels at each node of a multichannel network.

The ONE-D model has been applied to numerous river regimes throughout Canada. The model is capable of simulating flows in the unsteady state for river networks with rigid beds. It is a finite difference scheme formulated from the St. Venant equations. The scheme was obtained by applying a weighted residual method of optimisation to a linearised version of the governing equations and the discrete approximations (CSCE Task Group on River Models, 1987). The model uses water levels or flows as the upstream boundary conditions and water levels at the downstream boundary. The input parameters are the river topology network and the channel hydraulic properties; and the output file provides water levels or hydrographs at the locations within the network specified in the input file (Environment Canada, 1988).

The Mackenzie Delta flow regime was modelled using a topology of 85 reaches, and was supported by data from 10 hydrometric stations (Fig. 4a). For the Slave River Delta, 31 reaches were chosen to determine the suspended sediment travel times (Fig. 4b).

The channel hydraulic properties required by the ONE-D model are based on the characteristics of a cross-section at either end of each channel reach within the modelling topology. It is preferable that a representative channel cross-section is measured at the upstream and downstream sections of each channel reach, and that all the cross-sections are referenced to a standard datum. Unfortunately, both the Mackenzie and Slave River Deltas are large systems in remote areas, and representative cross-sections have not been taken on all channels. Furthermore, few of the measured cross-sections have been referenced to a standard datum, as only a small network of benchmarks exists. Most benchmarks are situated at the upstream and downstream boundaries of the two deltas. A geodetic tie-in of the town of Aklavik from the town of Inuvik (see Fig. 3b) has provided a series of referenced benchmarks across a transect in the middle of the Mackenzie Delta (Fassnacht, 1993).

Since the location of each cross-section within a channel is known, a longitudinal profile has been used to estimate the water surface elevation. Figure 5 illustrates an example of three longitudinal profiles for the different days on which cross-sections were measured. (The cross-sectional data were collected as part of the Canadian hydrometric monitoring network. These particular data are archived by Environment Canada-Yellowknife and were used to derive the streamflow, water level, and sediment discharge record published in Environment Canada, 1997.) There were four locations where the water surface elevations were known for each cross-section survey date (Fassnacht, 1993). A curve

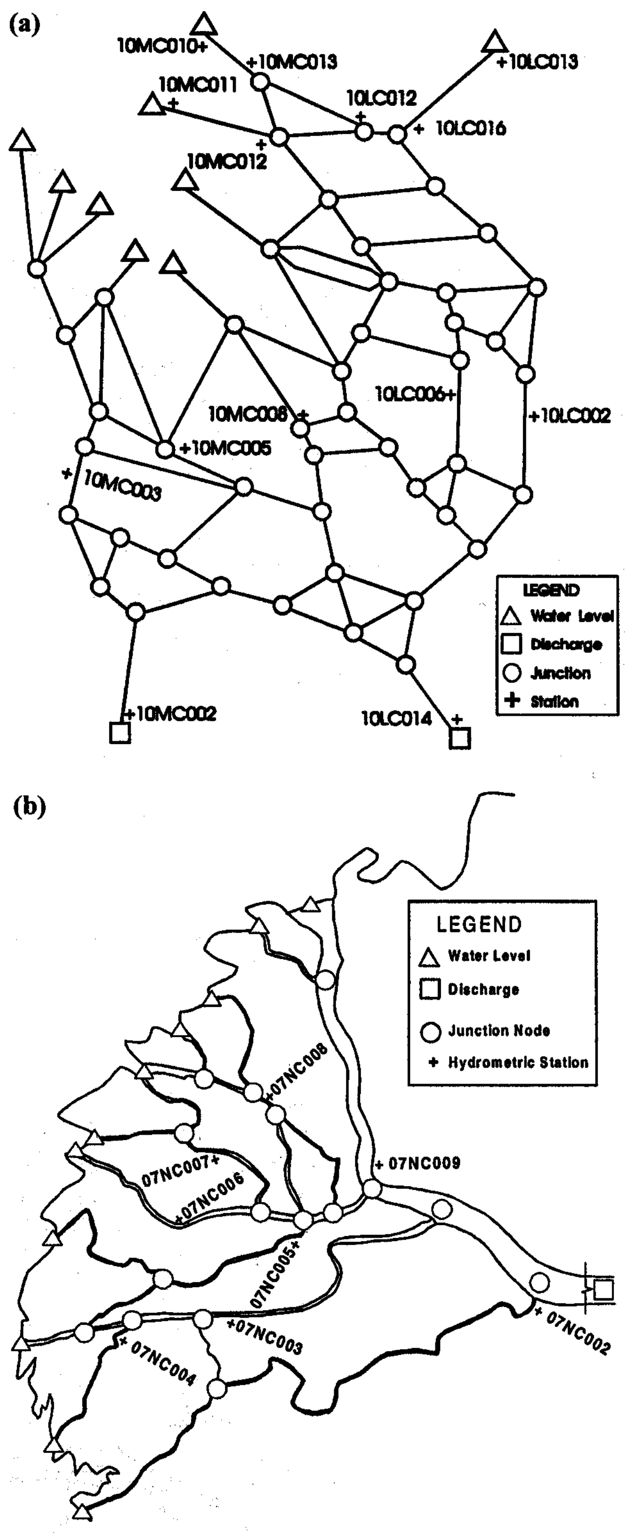

Fig. 4. *(a) Mackenzie River Delta modelling schematic, (b) Slave River Delta modelling schematic.*

was drawn between each set of points with the intent of forming a continuous curve. This method builds upon the longitudinal stream profile reported in various US Geological Survey reports (e.g. Hack, 1957; Brush, 1961).

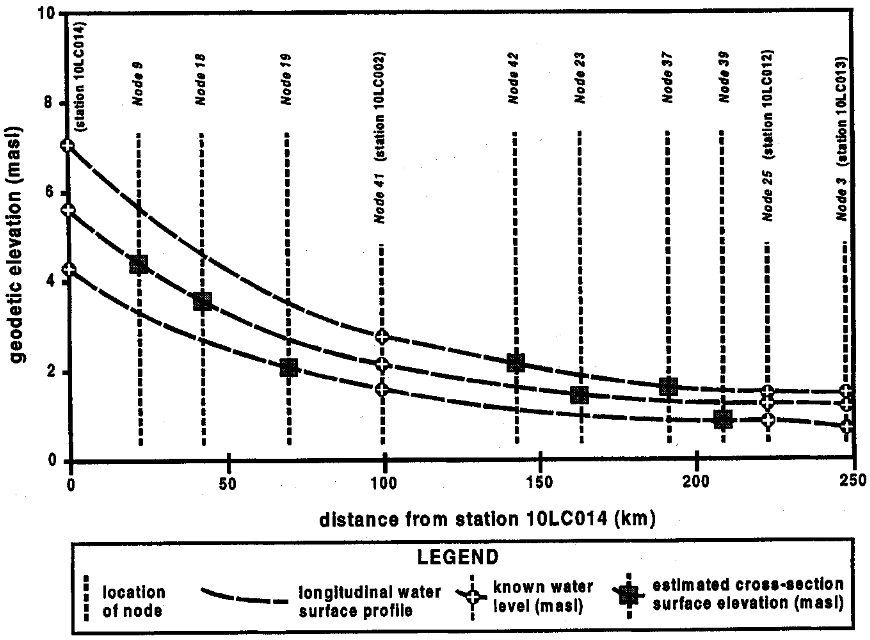

Fig. 5. *Longitudinal water surface profile through the Mackenzie Delta from station 10LC014 through stations 10LC002 (at node 41)and 10LC012 (at node 25) to the downstream station 10LC013 (at node 3).*

Mackin (1948) stated that longitudinal profiles consisted of a number of differing segments, all parts of one system; as well, there was a decrease in slope in the downstream direction. Working upstream from the mouth of the delta, the initial slope is asymptotic to the horizon and then increases. Both Hack (1957) and Brush (1961) presented power and exponential functions to describe the shape of longitudinal profiles.

Functions were not fit through the data in Fig. 5 as different flow paths are available through the delta which can create discontinuities at bifurcations and confluences. For example, downstream of the Peel River, the streamflow is distributed to both the Peel and Husky Channels and subsequently the Husky Channel flows into Peel Channel. The Peel Channel route is 16.8 km (18%) longer, yet the upstream and downstream surface elevations are identical. This is possible due to the very gentle slope and the other confluences and bifurcations between the two locations. Since the slope in the delta is less than 0.1 m km^{-1} near the inflow and 0.005 m km^{-1} in the downstream sections, the errors in cross-section elevation associated with this method are considered to be less than 0.2 m. This is acceptable due to the uncertainty in the representativeness of the cross-section. However, it is important to minimize the elevation error to enable flow distribution.

The ONE-D model uses three sets of hydrometric stations that are operated by Water Survey of Canada (WSC), as summarized in Table 1a and 1b for the Mackenzie and Slave Deltas, respectively. The upstream flows and downstream water levels were used as boundary conditions for the model, and the mid-transect water levels were used for model calibration and verification. Kerr (1993) calibrated and verified the ONE-D model for the Mackenzie Delta for the period between 1982 and 1988. The Mackenzie Delta model was re-calibrated for the summer of 1993 since additional cross-sectional data were available for that period (in Fassnacht, 1994). The re-calibration adjusted the channel roughness values, depending upon the boundary conditions. Manning's roughness coefficients between 0.020 and 0.040 were estimated for each reach based on channel characteristics and bed material (fine sand, silt and clay). The model was subsequently verified for the late summer 1985. Fassnacht (1997) provides details of the calibration and verification.

Cross-sectional data were compiled from unpublished data collected by WSC in 1980 and by Wilfred Laurier University (WLU) in 1995. (The 1980 data were taken from field notes archived by Environment Canada in Yellowknife, NWT and the 1995 cross-sectional data were collected by the Cold Regions Research Centre at WLU). Since a flow station does not exist at the mouth of the Slave Delta, the Slave River at Fitzgerald station, located 262 kilometres upstream, was used as the upstream boundary. There are no water level gauges at the outlets of the delta on the Great Slave Lake, thus the gauging station at Fort Resolution was used as the primary downstream boundary. These data were supplemented, where necessary, by trends in water levels measured across the Great Slave Lake at Yellowknife. Only three complete datasets were collected for the Slave Delta. As part of this study, flow calibration was performed with the mid-delta flow dataset from May 19, 1980. Verification used the August 20, 1980 dataset.

Table 1a. Water Survey of Canada hydrometric stations in the Mackenzie Delta.

Station location	Station Name	WSC station
Upstream boundary	Mackenzie River at Arctic Red River	10LC014
	Peel River above Fort McPherson	10MC002
Mid-transect Aklavik to Inuvik	East Channel at Inuvik	10LC002
	Kalinek Channel above Oniak Channel	10LC006
	Middle Channel below Raymond Channel[1]	10MC008
	Aklavik Channel above Schooner Channel	10MC005
	Peel Channel above Aklavik	10MC003
	West Channel below Aklavik[2]	10MC004
Downstream boundary	Reindeer Channel below Lewis Channel	10MC012
	Middle Channel at Langley Island	10MC013
	East Channel below Tununuk Point	10LC016

[1] Station 10MC008 superceded 10LC008 (Middle Channel above Napoiak) in 1982.
[2] Station 10MC004 (West Channel below Aklavik) was discontinued in 1977.

Table 1b. Water Survey of Canada hydrometric stations in the Slave Delta.

Station location	Station Name	WSC station
Upstream boundary	Slave River at Fitzgerald	07NB001
Mid-delta transect	Nagle Channel below Slave River	07NC002
	Old Steamboat Channel above Connu Channel	07NC003
	Rosgen Channel below Steamboat Channel	07NC004
	4-Ways Channel below West Channel	07NC005
	West Channel below Middle Channel	07NC006
	Middle Channel above Split	07NC007
	East Channel above Beaver Dam Channel	07NC008
	Resdelta Channel below Middle Channel	07NC009
Downstream boundary	Great Slave Lake at Fort Resolution -OR- Great Slave Lake at Yellowknife	07PB001 07SB001

This study describes the completion of flow model calibration efforts for the Mackenzie River Delta and the application and calibration of the flow model for the Slave River Delta; the crux of this research is to use the calibrated models to estimate the suspended sediment travel times and to provide an evaluation of results. To date, no other efforts have been made to estimate suspended sediment travel times, and there has been limited work on flow modelling of multi-channel river systems. The specific procedure used in this study follows. Using initial water travel time estimates, mean reach velocities are computed, and then flow-weighted travel time averages are calculated. This procedure is iterated until the travel time estimates converge. A convergence criteria of 0.01 days or 15 minutes was used for the Mackenzie Delta simulations, and 5 minutes for the Slave Delta. This is approximately an order of magnitude better than is required for the flow model input. The time calculation using a flow-weighted average thus considers a nodal budget about confluences and bifurcations. The initial estimates of the water travel times through the Mackenzie Delta were produced based on generally accepted time lags; these derived from field measurements by WSC-Inuvik and Environment Canada-Yellowknife (Carson, 1994).

Results and discussion

The early July 1988, mid-August 1991 and mid-July 1993 suspended sediment travel time (isochrone) plots for the Mackenzie Delta illustrate significant differences for

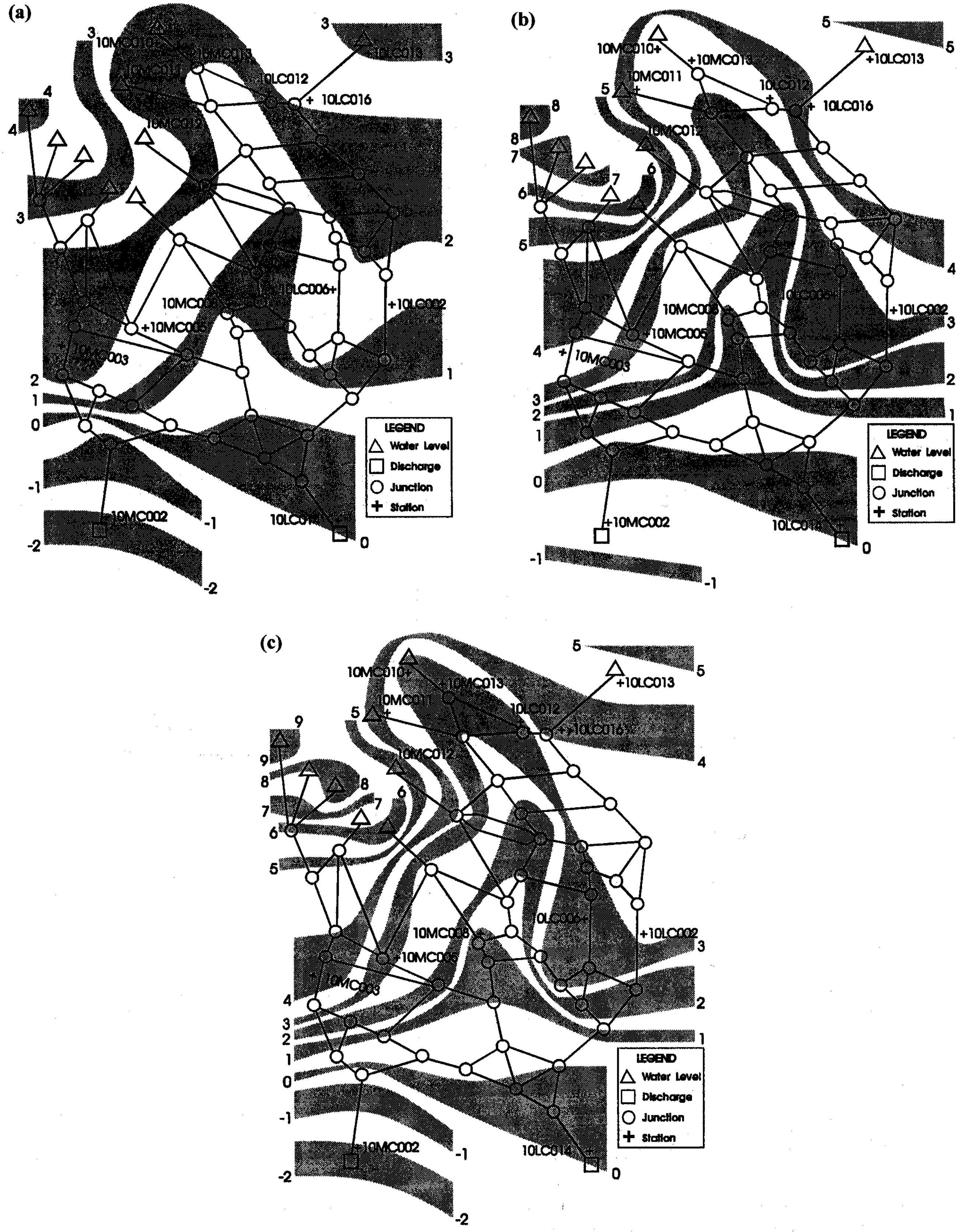

Fig. 6. *(a) Half day isochrones through the Mackenzie Delta for early July 1988, (b) Half day isochrones through the Mackenzie Delta for mid August 1991, (c) Half day isochrones through the Mackenzie Delta for mid July 1993.*

Table 2. Approximate sediment travel times in days from station 10LC014 to Mackenzie Delta hydrometric stations for various flow events (except * 10MC003 from 10MC002), and average daily discharge at the inflow stations (from Fassnacht, 1997).

date station	July 6, 1988	July 24, 1988	July 25, 1991	July 29, 1991	Aug. 17, 1991	Aug. 26 1991	July 19, 1993	Aug. 17, 1993	Aug. 31, 1993
10LC014 flow ($m^3 s^{-1}$)	32 100	26 800	25 700	20 300	13 300	12 800	14 600	14 000	11 300
10MC002 flow ($m^3 s^{-1}$)	1210	1240	1210	908	1130	1560	822	720	680
10MC002	−1.9	−1.4	−1.9	−1.9	−0.4	−0.7	−1.8	−2.1	−2.6
10LC002	1.5	1.8	2.1	2.0	3.1	3.4	3.5	3.0	3.6
10LC006	1.9	2.2	2.5	2.3	3.3	3.6	3.2	3.2	3.7
10MC008	1.0	1.1	1.2	1.2	1.5	1.6	1.5	1.5	1.7
10MC005	1.8	2.0	2.7	2.3	3.3	3.8	3.1	3.2	1.8
10MC003*	2.4 + 1.9 = 4.3	2.8 + 1.4 = 4.2	3.5 + 1.9 = 5.4	3.3 + 1.9 = 5.2	4.1 + 0.4 = 4.5	5.0 + 0.7 = 5.7	4.5 + 1.8 = 6.3	4.9 + 2.1 = 7.0	2.5 + 2.6 = 5.1
10MC009	1.8	2.1	2.2	2.1	3.0	3.2	3.0	2.9	3.3
10MC012	1.9	2.2	2.4	2.3	3.2	3.4	3.6	3.0	3.5
10MC013	2.0	2.4	2.6	2.5	3.8	3.8	3.4	3.5	4.0
10LC016	2.5	2.9	3.2	3.0	4.2	4.5	4.1	4.1	4.8

different flow events (see Figs. 6a, b and c, respectively). The high inflows from the Mackenzie River during early July 1988 (of the order of 33 000 $m^3 s^{-1}$) are more than twice as large as the mid-July 1993 Mackenzie flows (approximately 14 500 $m^3 s^{-1}$), and the travel times are approximately one-half. However, the Peel River (see Fig. 1b) inflows were similar for these two events, and consequently the upper Peel travel times are in the same range. The mid-August 1991 Peel River flows were substantially larger than the mid-July 1993 Peel flows, but the Mackenzie flows were similar, so there is only a one day difference at the farthest downstream node in the Peel system. The Peel River travel times of 1.71 and 0.68 days for mid July 1993 and mid August 1991, respectively, illustrate this difference.

The travel times from the Mackenzie at Arctic Red River to the other hydrometric stations in the Mackenzie Delta are summarised in Table 2. These values are illustrated in Figs. 7a, b and c, for the outer, middle and upper Mackenzie Delta stations, respectively. An inverse exponential (decay) relationship exists between the travel times and flows in the Mackenzie River for all stations, except the Peel River station. All data points for each station illustrate the same

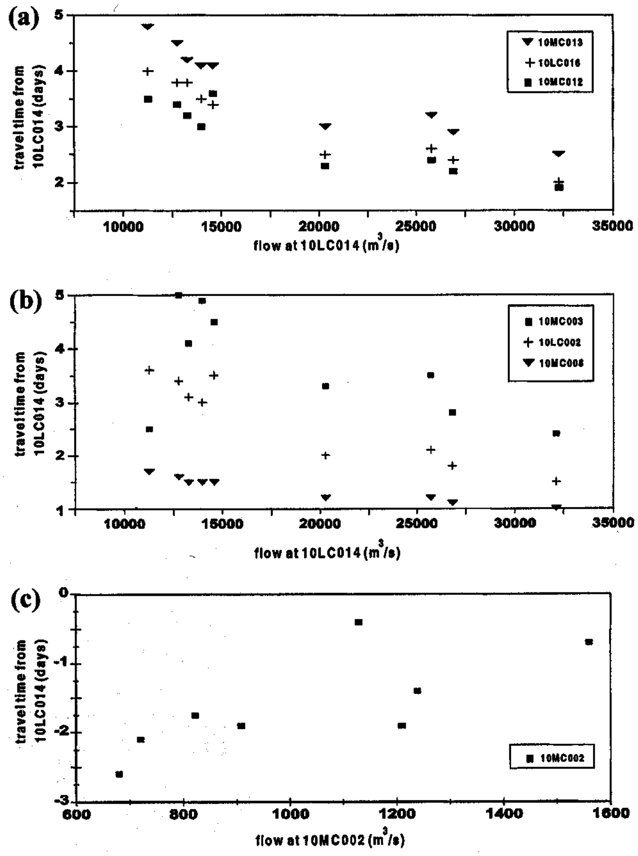

Fig. 7. *Travel time from Mackenzie at Arctic Red River (10LC014) to (a) outer delta stations (10MC012, 10LC016, 10MC013) versus flow at 10LC014, (b) mid-delta stations (10MC003, 10LC002, 10MC008) versus flow at 10LC014, (c) Peel River at Fort McPherson (10MC002) versus flow at 10MC002.*

trend, with the exception of station 10MC003 on August 31, 1993, and 10MC002 on August 17, 1991. The reason for these anomalies is unknown. The plots of estimated travel time versus flow (Figs. 7a–c) can be used to interpolate for measured flows not presented in this paper.

The logarithmic relationship exists for the Peel River (Fig. 7c), since the travel time is influenced primarily by its own discharge. The travel time difference between the Mackenzie River station and the Peel River is obviously influenced by the Peel River discharge. However, the flow in the Mackenzie creates a condition in the Delta that creates either a backwater effect on the Peel (high flow on the Mackenzie) or a flood wave (high flow on the Peel and low flow on the Mackenzie). This backwater effect is not fully understood, but at least one channel in the upper delta has been seen to flow in both directions at different times.

An intensive field campaign in the Slave Delta occurred in 1980, with three sets of flow and sediment measurements at the mid-delta stations (presented in Environment Canada, 1997). The travel time plots for two lower than average annual flows and one slightly higher are illustrated in Figs. 8a, b, and c, for May 14, August 20, and October 7, respectively. The travel times from the entrance of the delta to the 7 hydrometric stations in the delta are summarised in Table 3. The difference in the travel times is moderate since the range of flows modelled was small. Although flow and water level data for a high flow event are still required to model a high flow regime, the travel times presented in Table 3 can serve as a guide to sediment sampling. Over the narrow range of measurement, the isochrones are a function of flow, thus for a storm event, an extrapolation would scale the travel times based on inflow.

To evaluate the flow derived suspended sediment travel times for the Mackenzie Delta, the most complete set of suspended sediment and concentration measurements was considered. For the late July 1974 period, there were several sediment concentration measurements at the delta inflow and across the mid-delta transect stations (Table 4). A large suspended sediment slug started to appear at the Mackenzie entrance to the delta (at station 10LC014) on July 25th, 1974 (Fig. 9a). From the 22nd July until the 4th August, 34.3 Mt of suspended sediment were entered the delta passed station 10LC014, with a peak daily load of 7.39 Mt observed on the 28th. This sediment slug was attenuated as it travelled through the delta. Figure 9b illustrates the daily suspended sediment concentrations for the inflow station (10LC014) and four stations primarily influenced by the Mackenzie, on the right side of the delta (see Fig. 4a). The Mackenzie inflow was 26 900 $m^3 s^{-1}$ on the 28th, while the corresponding Peel River inflow was approximately 1350 $m^3 s^{-1}$ (Table 5). (Unfortunately, no streamflow or sediment data were collected after the 28th on the Peel River, so the Peel River is not included in the evaluation). Since these observed flows are similar to those seen on July 24th, 1988 (see Table 2), the late July 1988 simulated sediment travel times were compared to the observed late July 1974, based on lagging of the pycnograph peaks. Table 5 illustrates that most of the simulated results are similar to observed results, with the exception of Kalinek Channel (10LC006) and East Channel (10LC002). Carson (1994) noted that a sediment deposition at the mouth of the East Channel is likely decreasing the flow and sediment transport to station 10LC002. Similarly, the flow and sediment transport regime to the station 10LC006 is likely being altered, since the Kalinek Channel branches off the East Channel, downstream of the observed sedimentation. Station 10MC003 (Peel Channel) is influenced primarily by the Peel River, and station 10MC004 (West Channel) is influenced to a lesser extent (the Mackenzie has a significant contribution via Aklavik Channel). Since the suspended sediment regime on the Peel River was not monitored in late July 1974, the travel times directly from the Peel River station to these two downstream stations could not be estimated. However, the travel times with reference to the Mackenzie inflow station (10LC014) are reasonable (Table 5).

The continuous suspended sediment load estimates are daily values based on periodic suspended sediment concentration measurements combined with daily streamflow. For the late July and early August 1974 period, several sediment concentration measurements were taken at all stations (Table 4) and thus the continuous daily sediment record is considered representative of daily sediment loads. However, the sub-daily variations in sediment concentrations are unknown, and should be measured for a particle sediment slug event. This is especially crucial for the Slave River Delta where net travel time through the delta can be as little as 4 to 6 hours.

Different flow regimes have been modelled for the Mackenzie Delta and significantly different suspended sediment travel time estimates have been derived. However, for the Slave River Delta, a thorough dataset for high flows conditions did not exist and only the average conditions were simulated. The Mackenzie Delta estimates can be used to assist in developing a sampling strategy for a particular flow regime. The Slave Delta estimates should be used to test the assumption that suspended sediment is transported at the average flow velocity, since there is only one river flowing into the Slave Delta and the system itself is much smaller than the Mackenzie Delta. Continuous measurement of suspended sediment concentrations and discharge at several locations during flow and suspended sediment transport events of different size will enable the examination of the movement and downstream attenuation of large sediment slugs. As per Figs. 1a–d, the rapid change in the sediment loads at the different locations will be evident. However, the flow travel times within the Slave River Delta are in hours (Figs. 8a–c), thus hourly concentrations are required. This can be an onerous task, especially during higher flow events, so tracer studies should be performed in conjunction with continuous sampling. The locations should include the inflow into the delta, several mid-delta

Fig. 8. *(a) Four hour discharge isochrones through the Slave Delta in May 14, 1980 for an inflow of 2800 $m^3 s^{-1}$, (b) Four hour discharge isochrones through the Slave Delta in August 20, 1980 for an inflow of 3010 $m^3 s^{-1}$, (c) Four hour discharge isochrones through the Slave Delta in October 7, 1980 for an inflow of 3680 $m^3 s^{-1}$.*

sites, and sites at the mouth of the delta, downstream of the mid-delta sites.

More data are required both temporally and spatially to assess the transport of suspended sediment through a multi-channel system, such as a delta. There are numerous lakes in the upstream areas of the Mackenzie Delta. These lakes act as reservoirs to store flood waters during the spring snowmelt peak streamflows and to release water later in

Table 3. Approximate sediment travel times in hours from the mouth of the delta to Slave Delta hydrometric stations for three 1980 flow events, and average daily discharge at upstream boundary.

Station	May 14, 1980	August 20, 1980	October 7, 1980
07NC002	0.1	0.1	0.1
07NC003	7.5	9.0	6.0
07NC004	10.7	11.9	8.4
07NC005	3.6	3.5	3.1
07NC006	7.3	7.3	5.9
07NC007	7.9	8.3	7.1
07NC008	8.1	7.8	6.5
07NC009	1.9	1.9	1.6
Flow ($m^3 s^{-1}$)	2800	3010	3680

the summer. As such they trap large quantities of sediment. However, the large sediment transport events within the Mackenzie Delta, that usually occur in July or August as a result of precipitation events in the upstream mountains, are accompanied by lower water levels (Marsh and Hey, 1989). This results in less lake flooding, and less attenuation of peak flows and sediment loads than during the spring peaks.

If suspended sediment is transported at a rate different than water, it is moved at a slower rate. Flocculation of fine grained particles, deposition and resuspension in channel and at the bank, and activity at confluences and bifurcations also act to hinder the transport of suspended sediment particles with respect to the water that is the transport media.

Conclusions

The measurement of flow, sediment concentrations and

Table 4. Summary of daily suspended sediment concentration measurements in the Mackenzie Delta during the late July 1974 sediment slug (from Environment Canada, 1997).

WSC station	Dates of measurement
10LC014	July 19, 25, 28, 29, August 5, 12
10MC002	July 17
10LC002	July 26 –31
10LC006	July 17, 31, August 8
10LC008	July 19, 31, August 8
10MC005	July 18, August 2, 8
10MC003	July 18, August 1, 8
10MC004	August 1, 8

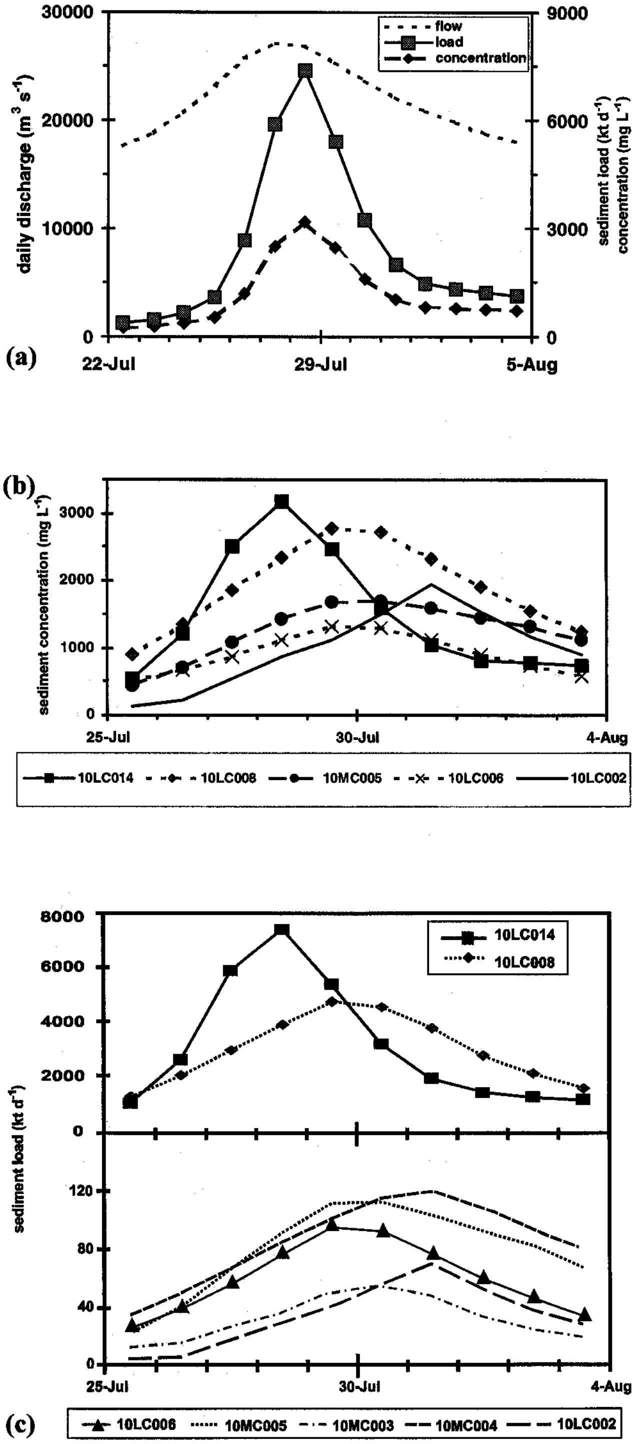

Fig. 9. *(a) The large sediment load (in kt d^{-1}) observed at the end of July in 1974 on the Mackenzie River at Arctic Red River, with the corresponding suspended sediment concentration (in mg L^{-1}) and discharge (in $m^3 s^{-1}$) (data from Environment Canada, 1997), (b) Suspended sediment concentrations at the inflow and four stations within the Mackenzie Delta for the late July, 1974 large sediment slug (data from Environment Canada, 1997) (c) Suspended sediment loads at the inflow and six stations within the Mackenzie Delta for the late July, 1974 large sediment slug (data from Environment Canada, 1997).*

Table 5. Comparison of "observed" suspended sediment travel times based on the suspended sediment slug peaks (Figs. 9a–c) versus modelled suspended sediment travel times (as per Table 2) for similar inflow conditions. The observations are from Environment Canada (1997).

Date station	Observed (July 28, 1974)	Modelled (July 24, 1988)	Difference (observed–modelled)	Percent difference
10LC014 flow ($m^3 s^{-1}$)	26 900	26 800	−100	−0.37%
10MC002 flow ($m^3 s^{-1}$)	1350[1]	1240	−110	−8.1%
10MC002	–	−1.4	–	–
10LC002	3.0	1.8	−1.2	−40%
10LC006	1.0 to 1.5	2.2	0.95	−76%
10MC008	1.0 to 1.5	1.1	−0.15	−12%
10MC005	2.0	2.0	0	0%
10MC003	2.0	2.8	0.8	40%
10MC004	3.0	3.2	0.2	6.7%

[1] This flow is based on the modelled −1.4 days travel time from 10LC014 to 10MC002, using the observed daily flow of 1180 $m^3 s^{-1}$ on the 26th of July, 1974 and 1460 $m^3 s^{-1}$ on the 27th.

particle size, and related parameters are difficult in the Mackenzie and Slave River Deltas, owing to the remoteness of the systems and, for the Mackenzie, the size. Therefore, the estimates of travel times presented herein should be used as a guide to sampling in the two deltas. Similarly, modelling should be used prior to hydrometric sampling to establish travel times for any multi-channel system, such that the same water and suspended sediment are sampled throughout the channel network. This is especially important during periods of high flow that are very dynamic and often individually different.

For the Mackenzie Delta, travel times are dependent on flows in both the Mackenzie and Peel River systems; however, the Mackenzie is obviously more important, as times can vary by more than a factor of two. The data available for the Slave Delta have limited the estimation of travel times, yet these times can be scaled to provide useful approximations.

The mechanics of suspended sediment transport within the various reaches, in particular the deposition, resuspension and erosion, must be investigated for several flow events to refine the understanding of time of travel of sediment particles in suspension, and sediment slugs. As well, the movement of sediment in and around bifurcations and confluences must be examined.

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