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Magnitude and Sources of Sediment Input to the Mackenzie Delta, Northwest Territories, 1974–94

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ABSTRACT. Hydrometric and sediment data collected by Environment Canada in the Mackenzie Basin during the period 1974–94 have been analyzed to produce detailed estimates of sediment inputs to the Mackenzie Delta, based largely on sediment rating equations. The mean annual sediment supply to the delta is determined as 128 million tonnes (Mt), of which about 4 Mt is sandy bed material moved in by the Mackenzie River itself. Virtually all of this sediment (more than 99%) is supplied to the delta during the May–October period, the peak months being May (27%), June (36%), and July (19%). About 17% of the fine-sediment load is supplied by the Peel River; the rest is delivered by the Mackenzie. The largest single contributor to the Mackenzie River wash load (103 Mt) is the Liard River (41 Mt). The preliminary estimate of the contribution of the other west-bank tributaries, in combination, is about 36 Mt, though this figure is probably too low. The precision of these estimates using the sediment rating approach (compared to time-integration during months with reasonable sampling frequency) is about 10% for the mean monthly sediment loads and about 5% for the mean annual sediment load during the 1974–94 period. The absolute accuracy of sediment load estimates is more difficult to assess because published flow data for delta inflow stations are acknowledged to be much less reliable for the spring breakup period than for other times of the year.

Key words: Mackenzie Delta, sediment loads, rivers

RÉSUMÉ. On a procédé à l'analyse de données hydrométriques et sédimentaires recueillies par Environnement Canada dans le bassin du Mackenzie de 1974 à 1994 afin d'obtenir une estimation détaillée de l'apport solide au delta du Mackenzie, en se fondant en grande partie sur des équations de calibrage des sédiments. L'apport sédimentaire annuel moyen au delta est évalué à 128 millions de tonnes (Mt), dont 4 Mt environ consistent en matériaux sableux charriés par le fleuve lui-même. La majorité de l'apport de ces sédiments (plus de 99 p. cent) au delta a lieu durant la période allant de mai à octobre, les mois d'apport maximal étant mai (27 p. cent), juin (36 p. cent) et juillet (19 p. cent). Environ 17 p. cent de la charge solide à particules fines vient de la rivière Peel et le reste du Mackenzie. Le cours d'eau qui, à lui seul, apporte la plus grosse contribution à la charge de ruissellement du Mackenzie (103 Mt) est la rivière Liard (41 Mt). L'estimation préliminaire de l'apport combiné des autres affluents sur la rive ouest est d'environ 36 Mt, bien que ce chiffre soit probablement trop bas. En utilisant la méthode de calibrage des sédiments (comparée à l'intégration temporelle durant les mois où l'on peut procéder à un échantillonnage assez fréquent), la précision de ces estimations est d'environ 10 p. cent pour les moyennes mensuelles de charge solide et d'environ 5 p. cent pour la moyenne annuelle de charge solide pour la période d'étude allant de 1974 à 1994. Il est plus difficile d'établir le degré de précision absolue des estimations de charge solide quand on sait que les données sur le débit publiées pour les stations deltaïques de débit entrant ont la réputation d'être beaucoup moins fiables pour la débâcle de printemps que pour les autres périodes de l'année.

Mots clés: delta du Mackenzie, charges solides, cours d'eau

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INTRODUCTION

The Mackenzie River of northwestern Canada is the fourth largest contributor of freshwater flow to the Arctic Ocean after the Ob, Yenisey, and Lena Rivers of northern Asia (Todd, 1970). Early estimates of suspended sediment influx from these four rivers into Arctic waters (Strakhov, 1963, cited by Stoddart, 1969; Lisitzin, 1972) suggested that they were essentially the same, at about 15 Mt/yr each, though these estimates were made prior to any sediment monitoring program on the Mackenzie River.

Milliman and Meade (1983) accepted the figures of Lisitzin (1972) for the Asian rivers, but put the Mackenzie River annual suspended load substantially higher, at 100 Mt/yr.

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Other estimates of the Mackenzie load (Table 1), based on early monitoring by Environment Canada, agreed with this higher general order of magnitude.

In the ten years since the last of these reports (Lewis, 1988), additional monitoring has been undertaken by Environment Canada, all data sets have been thoroughly reviewed, and new estimates have been made. The basic data and analyses, including computation of sediment loads, are all available in Environment Canada reports, some of which are noted in the references. No summary report has been published, however, for wider circulation. This is the purpose of the present article. Data are presented for the period 1974 to 1994.

THE ENVIRONMENT CANADA MACKENZIE RIVER SEDIMENT SAMPLING PROGRAM

Monitoring of suspended sediment inputs to the Mackenzie Delta has been undertaken by Environment Canada since the mid-1970s. Attention has been concentrated on three stations: the Mackenzie River, immediately upstream of Arctic Red River; the Arctic Red River at its mouth (though the discharge gauge is upstream near Martin House); and the Peel River upstream of Fort McPherson (Fig. 1).

Additional monitoring has also been undertaken, for different periods of time, on the major tributaries that supply sediment to the lower Mackenzie River: the upper Mackenzie River above Fort Simpson, the Liard River near its mouth at Fort Simpson, and the west-bank tributaries of the Root, Redstone, Carcajou, Mountain, and Ramparts Rivers (Fig. 1). Only the station on the Liard River has received the same long-term monitoring as the Mackenzie River itself.

The hydrometric and sediment monitoring programs began in response to plans for oil and gas exploration, production, and distribution in the Mackenzie valley and delta areas. Further work was undertaken in the early 1980s as part of investigations of possible power development on the Liard River by the British Columbia Hydro and Power Authority (BC Hydro). This work was stimulated by concerns over the impacts that development might have, through sediment trapping and flow regulation, on the delivery of sediment to the Mackenzie Delta. Additional work in 1983–87, and again in 1990–93, was undertaken as part of the Northern Oil and Gas Action Program (NOGAP).

Much of the BC Hydro work in the early 1980s was concerned with the magnitude of the sediment-bound nutrient load delivered to the delta ecosystem and the biological significance of these nutrients (Blachut et al., 1985). Inputs of sediment-associated nutrients and contaminants to the Beaufort Sea are similarly items of long-standing interest to the Canadian Department of Fisheries and Oceans, and are largely, but not entirely, controlled by sediment delivery at the delta head. Accurate estimates of sediment inputs to the Beaufort Sea are also needed by agencies such as the Geological Survey of Canada,which are concerned with net accumulation rates of sediment offshore (e.g., Jenner and Hill, 1991). And lastly, sediment delivery to delta channels is an important control on channel stability within the delta, a matter of some concern in the context of any future development.

TABLE 1. Estimates of Mackenzie Delta sediment input.

Author	Period	Load (Mt)
Lisitzin, 1972	?	15
Neill and Mollard, 1980	1973–76	150
Milliman and Meade, 1983	?	100
Brunskill, 1986	1973–81	118
Lewis, 1988	1974–83	126

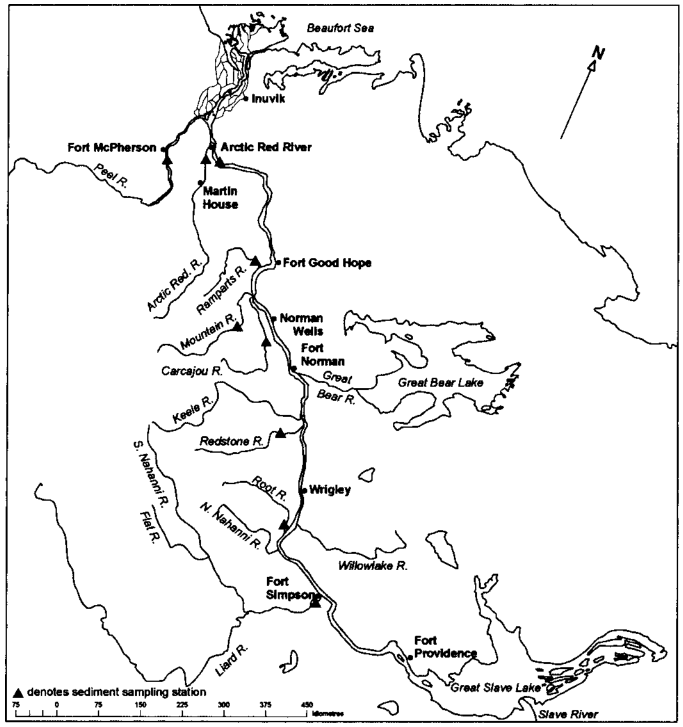

FIG. 1. Map of the Mackenzie River drainage system downstream of Great Slave Lake.

Aware of these concerns, much of the Environment Canada sediment monitoring program on the Mackenzie River at the delta head was undertaken for the specific purpose of determining long-term mean annual sediment supply to the delta. The investigations also included analysis of how sediment input changes on a monthly basis, determination of grain size composition, and identification of regional sediment sources. The results of these studies are presented here.

DETERMINATION OF MEAN ANNUAL SEDIMENT LOADS

All estimates by Environment Canada of sediment delivery to the delta are based on suspended sediment sampling. No measurements have been made of bed load. Annual suspended sediment loads have been determined from the summation of daily loads, the latter being derived from the product of the daily mean values for water discharge and sediment concentration.

Daily mean discharge (Q), in m^3/s, is determined from water level (stage) values at 15 minute intervals. Flow measurements to verify the stage-discharge rating curve are done several times a year, and accuracy is generally good at the delta-head sites under normal conditions, with a random error of less than 5% in daily mean discharge. Problems at times of high flow are noted in the next section.

Daily mean discharge data for the Arctic Red River are not available for periods of 2–6 weeks in 1974–76, 1980, and 1994. The Peel River discharge data contain significant gaps in 1974, and the 1987 discharge data are considered approximate and remain unpublished. These gaps and uncertainties stem from equipment malfunction.

Daily mean suspended sediment concentration (c), in mg/L, was derived, where samplings were frequent (two or more samples per week), through construction of "sedigraph" time charts, analogous to hydrographs for water discharge (Environment Canada, 1990a). At all stations, however, sampling was insufficient for this purpose in some years, especially in winter and spring, and estimates of c were then derived through regressions of log(c) on log(Q), the familiar sediment-rating approach (Walling, 1977). At some stations, all c values were estimated in this way.

A problem exists with logarithmic sediment ratings, however, in that, on detransformation, the nonlogarithmic predictions tend to underestimate actual values. Various "correction factors" have been suggested to adjust for this detransformation bias (summarized in Helsel and Hirsch, 1992:256–257) but these adjustments tend to overcompensate (Koch and Smillie, 1986). There is still no universally accepted solution to this issue. The procedure taken here is to compute the Duan (1983) bias correction factor, and then take the mean of the unadjusted and the "corrected" values as the prediction. The discrepancy in mean annual sediment load in using the above approach, rather than using either unadjusted or "corrected" values, amounts to 3 Mt for both the Mackenzie and Peel Rivers as they enter the delta, and is less than 1 Mt on smaller rivers.

Where sample size was large enough (at the Mackenzie, Peel and Liard sites), a further refinement was undertaken: using an additional correction factor for each month to reduce scatter. This adjustment is the mean value of the ratio of actual/predicted c for the different months. Thus months which tend to have actual concentrations higher (or lower) than predicted by the sediment rating are increased (or decreased).

All c values for the Arctic Red and Peel Rivers were based on the sediment rating approach. Samplings on the latter river adequately covered the open-water, sediment-moving period from May to September, but the Arctic Red River data, dating back to the early 1970s, lack samplings from the month of May.

Sediment rating diagrams and associated equations for the three delta-head stations are given in Figures 2, 3 and 4. Sample statistics for the logarithmic regression on which the rating is based are also given in the figure captions: N is sample size, PP is percentage prediction of log(c), and SEE is the standard error of estimate in log units.

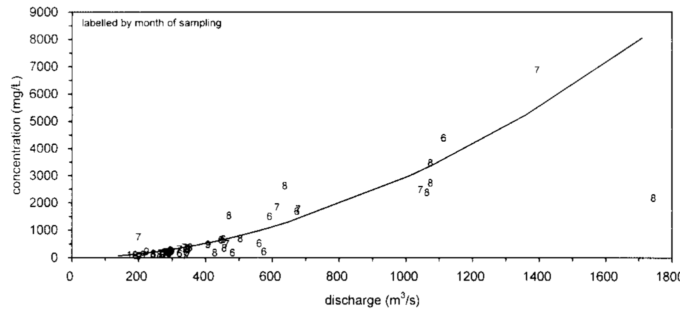

FIG. 2. Sediment rating curve for the Arctic Red River near the mouth ($c = 6.04 \times 10^{-3} \times Q^{1.88}$; N = 56 (1972–75); PP = 76%; SEE = 0.27)

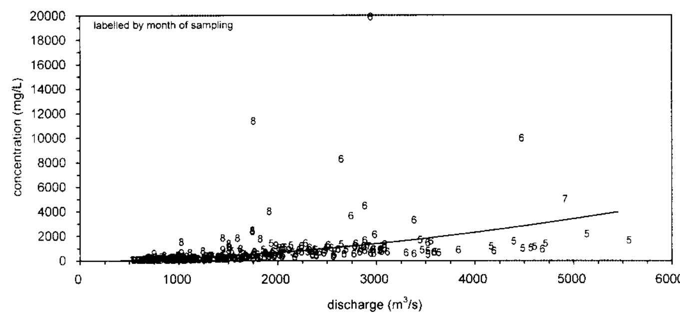

FIG. 3. Sediment rating curve for the Peel River near Fort McPherson ($c = 8.97 \times 10^{-4} \times Q^{1.76}$; N = 221 (1988–93); PP = 69%; SEE = 0.30. For August: $c = 1.87 \times 10^{-3} \times Q^{1.72}$; PP = 61%; SEE = 0.34).

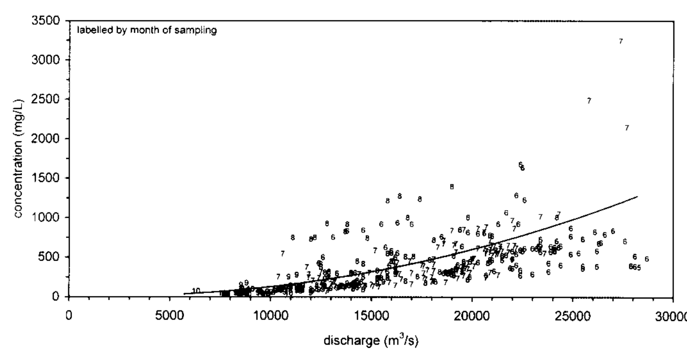

FIG. 4. Sediment rating curve for the Mackenzie River at Arctic Red River ($c = 7.49 \times 10^{-8} \times Q^{2.29}$; N = 502 (1972–88); PP = 76%; SEE = 0.22).

On the Peel River, monthly correction factors ranged from 0.62 (October) to 1.13 (June). Summer storms produced unusually high concentrations (relative to discharge) on the Peel in August, and a separate regression was used for this month.

In the case of the Mackenzie River, almost all c values during the sediment-moving flows in 1982–88 were taken directly from sedigraphs. In other years, and in winter months in all years, sediment concentration was predicted by the sediment rating (Fig. 4). For reasons given below, the Mackenzie River sediment rating refers to wash load (finer than 0.125 mm) and not to total suspended sediment.

ACCURACY OF LOAD DATA

Overview

The accuracy of load estimates depends on both discharge and concentration error. In both cases, it is difficult to provide exact estimates.

In terms of discharge, uncertainties exist during extreme flows and, especially, immediately after spring breakup, because complicated backwater conditions are produced by downstream ice jams in river and delta channel reaches. These problems are difficult to solve because staff safety considerations often prevent flow measurements in spring. Earlier published discharge values during breakup (up to 1986) were revised downwards, sometimes substantially, by Water Survey of Canada after a major review of the data based on a special program of springtime backwater gaugings in 1986–88 (Carson, 1992a). Variations in the magnitude of annual sediment loads estimated in different Environment Canada reports over the last ten years reflect revisions that have been made to the discharge data.

The error in suspended load values arising from errors in concentration is controlled largely by three factors (Carson, 1992a): the paucity of sediment concentration data during the month of May; the degree of imprecision in using the sediment rating approach rather than the sedigraph approach to estimate c; and the cross-sectional representativeness of the sampled concentrations, given that sampling at a site was almost always based on a single, depth-integrated vertical in the cross-section. These factors are discussed in turn below as they relate to the four benchmark stations on the Liard, Mackenzie, Arctic Red, and Peel Rivers.

Uncertainty in May Loads

The real unknown in the estimation of annual loads is the reliability of May estimates. For obvious logistical reasons, sampling at the delta head on the Mackenzie River during May has been undertaken on only seven occasions. However, the mean value of the actual-to-predicted ratio on these seven occasions is 1.02, which, at least, does not indicate any significant bias in the sample.

On the Liard River, however, the comparable ratio for May is 1.71. Some of this May increase is due to ice scour and ice jam surges during short periods of mechanical breakup (Prowse, 1993; Milburn and Prowse, 1996). A large part of it, however, appears to result from conditions specific to the Liard catchment, namely the early breakup of two tributaries, the Muskwa and the Fort Nelson Rivers. These tributaries are known to have unusually high sediment yields because of local geology (Grey and Sherstone, 1980).

No samplings at all were done in May on the Arctic Red River, but almost 20% of the recent sampling program on the Peel River was done in May. The monthly correction factor for May at the Peel site, 0.86, makes that site more comparable to the Mackenzie River than to the Liard River.

Imprecision in Sediment Rating Approach

The imprecision (taken as 68% probability) in the sediment rating approach relative to the loads based on sedigraph c values was computed by comparing loads using the two methods in those months with frequent sampling (Carson, 1992a, Section 4.3). This imprecision was determined at 20% for loads of individual years at the three delta-head stations. Comparison of predicted and actual (Water Survey of Canada) loads for the Mackenzie River for 1982–88 is shown in Figure 5.

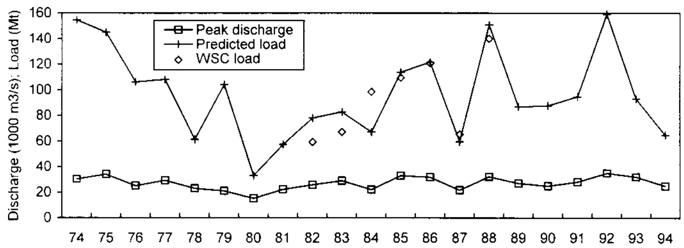

FIG. 5. Annual fluctuations in peak discharge and wash load of the Mackenzie River at Arctic Red River, 1974–94. (Actual WSC sediment loads are only available for the period 1982–88.)

Over longer periods, imprecision is reduced by partial compensation of positive and negative errors: mean monthly sediment loads for the 1974–94 period have an imprecision estimated at 10%; and imprecision for the mean annual load 1974–94 is estimated at 5%. These figures are comparable to those determined for other large rivers in northwestern Canada (Carson, 1992b). The imprecision in the Peel and Arctic Red sediment rating curves may, in fact, be greater than indicated above because of the absence of sampling at extremely high flows.

Representativeness of the Sampling Site

The cross-sectional representativeness of the sampling verticals has generally been good. The mid-stream sampling vertical on the Liard and Arctic Red Rivers is representative of the full section, and no adjustment has been needed for sampled concentrations.

The most troublesome of the three delta-head sites was that on the Peel River, and regular adjustments to increase the sampled c values by up to 35% have been necessary in some years, depending upon the stage and the actual location of the sampling vertical. No data on the cross-sectional representativeness of other tributaries are available.

The Mackenzie River sampling site adequately represented the cross-sectional mean for wash load sediment (taken as 0.125 mm and finer) at least until 1988 (the last sampling used in the sediment rating); but coarser sediment was found to be overrepresented by varying amounts throughout the sampling period. All Mackenzie loads upstream of Arctic Red River were therefore initially restricted to wash load. Separate estimates were made of the discharge of the sandy bed material coarser than this size, as discussed in a

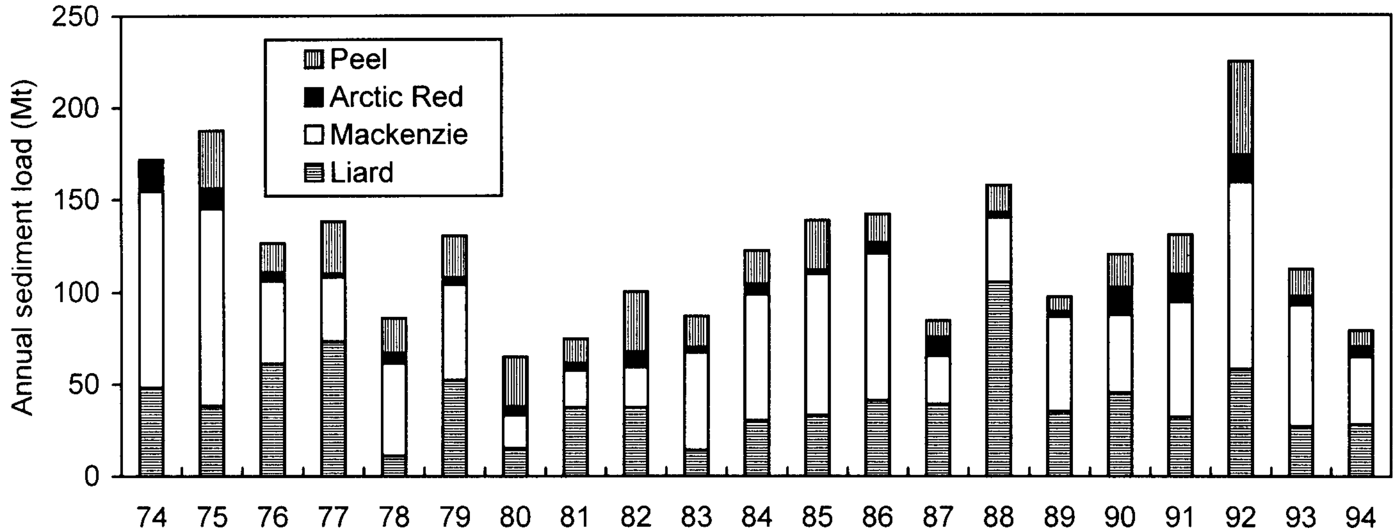

FIG. 6. Annual fluctuations in fine-sediment load inputs to the Mackenzie Delta, 1974–94. (The "Mackenzie" component refers to the Mackenzie load at Arctic Red River minus the Liard load.)

later section. Using this information, the mean annual load on the Mackenzie River for the period 1974–94 was then increased to include bed material discharge.

Discussion of fine-grained sediment inputs to the delta is thus, unfortunately, complicated by analyses done using different criteria. In the discussion below, the term *fine-sediment load* is used to refer to the wash load (finer than 0.125 mm) on the Mackenzie River; to the total suspended load on the Peel and Arctic Red Rivers; and to the fraction of the suspended load finer than 0.125 mm on all tributaries to the Mackenzie River.

INPUTS OF FINE SEDIMENT TO THE MACKENZIE DELTA, 1974–94

Mean Monthly Sediment Inputs

The mean monthly fine-sediment loads from 1974 to 1994 for the three delta-head stations are given in Table 2. Load is minute in the period from November through April: on the Mackenzie, the predicted load is 0.3 Mt in November, and 0.1 Mt in each of the other winter months. On the Arctic Red River, gaps in the discharge data prevented the determination of sediment load for May in 1980 and 1994, for June in 1974 and 1994, for July in 1974, and for August in 1975 and 1980. This was also the case on the Peel River for May through August in 1974.

The suspended sediment load for both the Arctic Red and Peel Rivers peaks in May-June. The load estimates are largely controlled by the pattern of peak discharges. On the Mackenzie River, the peak sediment load occurs in June, coinciding with peak flows from the Liard River. The major difference between the monthly regimes of the Mackenzie and Peel Rivers is the much greater percentage of the Mackenzie load (37%) entering the delta in July–August, compared to only 10% on the Peel River. This difference reflects the difference in runoff regimes between the two rivers.

Annual Sediment Inputs

The annual fine-sediment loads for the delta-head stations are summarized in Figure 6. In those years with missing discharge data, the days involved have been allocated a daily load equal to the 1974–94 daily mean for that month. The combined mean annual fine-sediment load entering the Mackenzie Delta is estimated at 124 Mt, of which 103 Mt is from the Mackenzie River itself and 21 Mt from the Peel.

The standard error of the overall sample mean is 10 Mt. This may be taken as 68% confidence limits for the long-term mean, assuming that the annual series is stationary. There are, however, some indications that present-day discharges (and therefore sediment loads) may be higher in the 1974–94 period than in the previous 30 years. This interpretation is based on discharge records for the Mackenzie River at Norman Wells, as recognized by Church et al. (1987).

Grain Size Composition of Suspended Sediment

Interpretation of grain size data is complicated by many factors, including location of sampling site, mode and timing of samplings, and method of analysis. The data below refer to samplings undertaken at the single-vertical sampling site at each station, using depth-integrating sampling through the full depth of flow (Environment Canada, 1990b). All samples that were analyzed for grain size were done with bottom-withdrawal tubes using native river water (Environment Canada, 1990c). To minimize error, which increases at low sediment concentrations, all analyses were restricted to samples with concentrations greater than 300 mg/L.

The mean percentage breakdown of grain size at the three delta-head stations is given in Table 3. The grain size compositions of the suspended sediment in the Mackenzie and

TABLE 2. Mean monthly fine-sediment loads for delta-head rivers, 1974–94[1]. All values are in megatonnes (Mt).

Month	Mackenzie	Arctic Red	Peel	TOTAL
May	21	3.1	10.1	34
June	34	2.4	8.2	45
July	21	0.6	1.5	23
August	14	1.0	0.7	16
September	4	0.1	0.3	4
October	2	0.1	0.0	2
Total	96	7.3	20.8	124

[1] Mackenzie River: wash load (< 0.125 mm); Arctic Red and Peel Rivers: suspended load

TABLE 3. Mean grain size composition of suspended sediment. N = sample size and number in parentheses is the standard error of the mean. The clay/silt boundary is 0.004 mm.

River	Months	Percentage Clay	Percentage Silt	Percentage Sand	N
Mackenzie	June–October	34 (1)	57 (1)	9 (1)	62
Arctic Red	June–October	35 (4)	58 (3)	7 (2)	15
Peel	May–June	26 (1)	69 (2)	5 (2)	26
Peel	July–September	34 (3)	59 (4)	7 (2)	13

Arctic Red Rivers are very similar. In neither case is there significant change from month to month, although the sand percentage decreases at very high sediment concentrations (> 1000 mg/L).

The Peel River data are more difficult to summarize because of changes in sampling locations and time of sampling during the course of the sediment program. Suspended sediment size is similar to that in the other two rivers in summer, but apparently more silty during May and June.

In all cases, it is likely that some of the silt-size sediment is actually made up of clay-size grains that have been flocculated into larger aggregates. This phenomenon has certainly been reported in the case of other Canadian rivers (Droppo and Ongley, 1990).

SOURCES OF SEDIMENT SUPPLIED TO THE MACKENZIE RIVER

Estimates of suspended sediment inputs to the Mackenzie River between Fort Simpson and Arctic Red River are available for the following rivers: the upper Mackenzie River and the Liard River where they meet at Fort Simpson, and most of the main west-bank tributaries, namely the Root, Redstone, Carcajou, and Mountain Rivers. In terms of partitioning the sediment load of the Mackenzie River into its constituent sources, however, it should be recalled that the Mackenzie load is being determined from the sum of its wash load (< 0.125 mm) and bed material load. Thus estimates are needed of that portion of tributary loads that is finer than 0.125 mm.

The Upper Mackenzie Upstream of Fort Simpson

On the basis of spot samplings during the 1972–75 open water seasons, the suspended load for the upper Mackenzie is estimated at 2.5 Mt per year. Concentrations were low (13 to 52 mg/L), reflecting the sediment-trapping of Great Slave Lake, 350 km upstream, and the absence of large tributaries in the intervening reach. Peak monthly outflow from Great Slave Lake occurs in July, and the 1972–75 July mean is virtually identical to the long-term July mean (1962–78 at Fort Providence): thus the 1972–75 load estimate is taken as representative of the long-term load.

The small amount of data available suggest that most of this sediment is associated with outflow from Great Slave Lake, and it is therefore assumed that all of this sediment is less than 0.125 mm in size. No actual grain size data are available because of the low concentrations.

There is little change in monthly mean concentration during the open water period (about 19 mg/L) and these levels may, therefore, decline only slowly through the winter. In that case, the Great Slave Lake outflow may be relatively important in terms of winter sediment supply to the Mackenzie Delta, even though on an annual basis its contribution is minimal. Inspection of discharge data for Fort Providence indicates that the Great Slave Lake outflow accounts for about 60% of the discharge of the Mackenzie above Arctic Red River during winter.

The Liard River at Fort Simpson

The suspended load of the Liard River near its mouth is determined from a strong adjusted sediment rating (Fig. 7). Monthly correction factors ranged from 0.64 in October to 1.71 in May. The resultant estimate of the mean annual load for 1974–94 is 46 Mt. Of this amount, approximately 11% is sand coarser than 0.125 mm. Thus, about 5 Mt should be subtracted from the above load in order to provide an estimate of the Liard's contribution to the wash load of the Mackenzie. The latter amount is therefore estimated at 41 Mt.

Other West-Bank Tributaries

The sediment ratings for the other five west-bank tributaries must be considered as preliminary, as they are based on small samples of 15 to 42 points. Interim discussion of the ratings is provided by Carson (1993). Intermittent sediment sampling by Environment Canada continues at these sites at times of large flows in order to increase confidence in the ratings.

No data are available for the grain size of the samplings on these rivers. The portion finer than 0.125 mm on the Arctic Red River is 95% (compared to 89% on the Liard), and a mean value of 92% was used for the intervening west-bank tributaries.

The specific annual fine-sediment yields of the west-bank tributaries range from 108 t/km^2/yr (Ramparts River) to

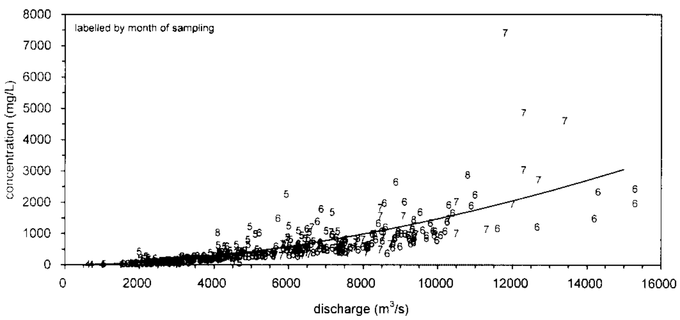

FIG. 7. Sediment rating curve for the Liard River near the mouth ($c = 8.83 \times 10^{-5} \times Q^{1.80}$; N = 396 (1972–88); PP = 84%; SEE = 0.21).

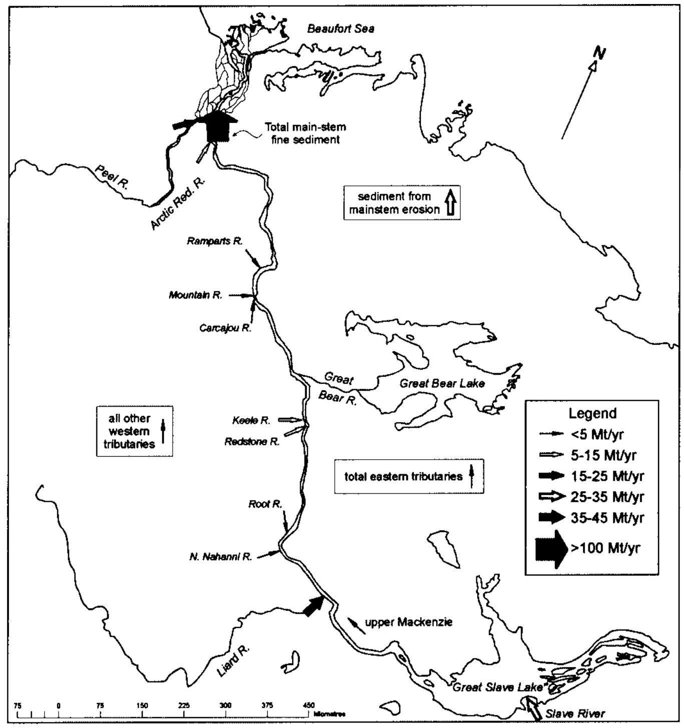

FIG. 8. Schematic representation of fine-sediment sources for the Mackenzie Delta.

346 t/km²/yr (Root River). The mean is 238 t/km²/yr, intermediate between the yields of the Liard River (144 t/km²/yr) and the Arctic Red River (398 t/km²/yr). Most of the unsampled area on the west bank belongs to the Keele and North Nahanni basin, where the specific yield is expected to approximate that of the Root basin. Making this assumption, we calculate that the total fine-sediment load of all west-bank tributaries between the Liard and Arctic Red Rivers is 29 Mt. The approximate breakdown of this load among the rivers is given in Figure 8.

The 29 Mt sediment load from these west-bank tributaries is substantially less than the 52 Mt of fine-sediment load picked up by the Mackenzie River between the Liard and the Arctic Red Rivers. The difference (23 Mt) reflects sediment from the banks and side slopes of the main stem Mackenzie downstream of Fort Simpson, contributions from east-bank tributaries, and error in the sediment balance. In particular, the 29 Mt west-bank load almost certainly underestimates the true load of west-bank tributaries because some of the sampling stations are located well upriver from the Mackenzie confluence. These lower areas adjacent to the Mackenzie River are believed to be important sediment sources (Mackay and Mathews, 1973), with above-average specific sediment yields. A recent inventory of landslides in the Mackenzie basin (Aylsworth and Egginton, 1994) adds support to the idea that lower areas are important sediment sources.

Other Sources

In general, all east-bank tributaries are thought to be relatively insignificant in their sediment delivery to the Mackenzie because of their lower gradients, the presence of lakes, and the much less extensive deposits of fine-grained glacial sediment than are found on the western slopes. In a few places, e.g., the small Hanna River, downstream of Norman Wells, thermokarst erosion can produce high sediment concentrations, but east-bank tributaries are usually clear or humic-coloured (Brunskill, 1986).

It is speculated therefore that most of the "residual" 23 Mt not accounted for by the west-bank tributaries is derived from the banks of the main stem Mackenzie River itself, with less than 5 Mt from the eastern tributaries. Ongoing sampling of tributaries over the next 5–10 years will provide firmer estimates of the west-bank loads, and thus a better estimate of the "residual" sediment supply.

BED MATERIAL LOAD OF THE MACKENZIE RIVER

The bed material of the lower Mackenzie River, downstream of Fort Norman at the mouth of the Great Bear River, is essentially sand. Church et al. (1987) estimated the mean annual load of this sandy bed material near Norman Wells by comparing aerial photographs for the period 1950–71. The resultant figure was 550 000 m³ per year, equivalent to 1 Mt/yr, assuming a bulk density of 1.8 tonnes per cubic metre.

A second estimate was made by Carson (1991) for the sandy reach upstream of the Lower Ramparts (20–35 km upstream from Arctic Red River), which amounted to 4.5 million m³ per year, for the period encompassing the open water seasons of 1974–77. This is equivalent to 8 Mt per year assuming the same bulk density. This estimate was based on the amount of scour on the upstream side of alternate bars, 5 km in length, migrating downriver, as determined from depths beneath low-water datum on charts of the Canadian Hydrographic Service.

Part of the difference between the two estimates must result from the different locations of the two reaches. The mean annual flood on the Mackenzie at Arctic Red River is about 26% bigger than at Norman Wells, and additional bed material is supplied between the two reaches by the Carcajou, Mountain, and Ramparts Rivers. Thus the Norman Wells reach will underestimate bed material movement at the delta head. Some of the difference must also be due to different flow conditions in the two study periods. Peak flow data are available for only 13 years in the 22-year period of the

Norman Wells study. The mean annual flood in those years for which data are available is 18% less than that for the same station in the years of the Lower Ramparts study.

An estimate of the *suspended* bed material load can be obtained from the grain size breakdown of suspended sediment samples at the Mackenzie River sampling site (Carson, 1988). These analyses typically showed the material coarser than 0.125 mm to constitute 2–6% of the suspended sediment. Thus, based on a wash load of 96 Mt, the mean annual suspended bed material load is about 4 Mt. This compares with the *total* bed material load of 8 Mt per year estimated above by morphometric means. The latter figure is too high, however, as an estimate of long-term conditions because of above-average peak flows in the short study period. The long-term annual *total* bed material input to the delta is taken here as 4 Mt, implying that the unsuspended (bed) load is negligible.

The last statement is consistent with observations on bed form migration in the 1974–77 morphometric study (Carson, 1991:71–72). Sediment that was scoured from the upstream side of alternate bars was deposited in the pool area downstream for distances of up to four kilometres. This suggests settling from suspended sediment plumes rather than movement as bed load over the migrating front of the bar.

The bed load inputs of the Peel and Arctic Red Rivers are not known. However, if the bed material load on these rivers amounts to the same percentage of the total load as on the Mackenzie (about 4%), the combined bed material load of the two rivers would be about 1 Mt. The bed load portion of the sandy bed material is expected to be much smaller, for the reasons given above.

CONCLUSIONS

Since the mid-1970s, Environment Canada has undertaken a comprehensive program of suspended sediment sampling and discharge monitoring to compute sediment inputs to the Mackenzie Delta. The data from this investigation indicate that the mean annual sediment input to the delta is about 128 Mt for the period 1974–94. The Mackenzie River itself, downstream of Arctic Red River, supplied about 103 Mt of this as wash load, and about 4 Mt as sandy bed material load (believed to be mostly in suspension). The balance (21 Mt) was suspended sediment from the Peel River. The total fine-sediment load input to the Mackenzie Delta in this period is virtually identical to that computed by Lewis (1988) for the shorter 1974–83 period.

The longer data set (in which discharge data were revised downwards for the Peel in some spring periods) indicates that the contribution of the Peel is not as great as the 31 Mt indicated by Lewis (1988) for the 1974–83 period, whereas the mean annual load of the Mackenzie downstream of Arctic Red River is higher than the 95 Mt determined by Lewis.

The major source of Mackenzie River wash load is the Liard River, amounting to 40% (41 Mt) of the 103 Mt. Other west-bank tributaries, including the Arctic Red River, are estimated collectively to supply at least 35% (36 Mt) of the Mackenzie wash load, with most of the balance derived from erosion along the course of the main stem itself, downstream of Fort Simpson. Eastern tributaries are believed to contribute less than 5% of the delta sediment input.

These results confirm the much higher sediment load on the Mackenzie, compared to the Ob, Yenisey, and Lena Rivers of northern Asia. As noted by Milliman and Meade (1983), the discrepancy presumably reflects the contrast in topography and surficial sediments. The terrain of the Asian river basins is largely low-lying and much of the overlying surficial material has been stripped by Pleistocene glacial activity.

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