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VERTICAL AND LATERAL DISTRIBUTION OF FINE-GRAINED PARTICULATES IN RIVERS: SAMPLING IMPLICATIONS FOR WATER QUALITY PROGRAMS

by

Edwin D. Ongley[1] and
Ted R. Yuzyk[2]

[1]Rivers Research Branch
National Water Research Institute
Environment Canada
Burlington, Ontario L7R 4A6

[2]Sediment Survey Section
Water Resources Branch
Inland Waters Directorate
Environment Canada
Ottawa, Ontario K1A 0E7

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Edwin D. Ongley
National Water Research Institute, Environment Canada
P.O. Box 5050, Burlington, Ontario, Canada L7R 4A6

Ted R. Yuzyk
Sediment Survey Section, Water Resources Branch
Inland Waters Directorate
Environment Canada, Ottawa, Ontario K1A 0E7

MANAGEMENT PERSPECTIVE

Sediment quality is increasingly being incorporated into water quality programs. There is no accepted protocol for sampling suspended sediment, especially the silt-clay fraction which carries the largest portion of the chemical load. Conventional sediment sampling programs focus on sand-sized materials; these require depth-integration techniques which are labour and time-intensive and are not well suited for water quality purposes. Fine grained materials are usually presumed to be evenly distributed in the vertical section. This paper examines Canadian data to establish the degree to which near-surface samples of suspended silts and clays are representative of the vertical profiles and of the cross sections. Conclusions are drawn which permit an informed judgement on sampling protocols for sediment-associated chemistry.

PERSPECTIVE DE GESTION

Les programmes de surveillance de la qualité de l'eau tiennent compte de plus en plus de la qualité des sédiments. Aucun protocole n'a encore été accepté pour l'échantillonnage des sédiments en suspension, notamment de la fraction limon-argile qui contient les plus fortes charges en substances chimiques. Les programmes d'échantillonnage classiques des sédiments portent sur les particules de la taille du sable; ces matériaux requièrent une intégration de la profondeur, méthode dont l'exécution nécessite du temps et une importante main-d'oeuvre et ne se prête pas aux contrôles de la qualité de l'eau. En général, on présume que les matériaux à grains fins sont répartis uniformément dans la section verticale. Ce document examine les données canadiennes afin de déterminer dans quelle mesure les échantillons de limon et d'argile en suspension prélevés près de la surface sont représentatifs des profils verticaux et des sections transversales. Les conclusions établies permettront aux intéressés de déterminer quels sont les protocoles d'échantillonnage qui, selon eux, se prêtent le mieux à l'analyse chimique des sédiments.

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EDWIN D. ONGLEY[1] AND TED R. YUZYK[2]

[1]National Water Research Institute, Environment Canada,
Burlington, Ontario, Canada L7R 4A6

[2]Sediment Survey Section, Water Resources Branch, Inland Waters
Directorate, Environment Canada, Ottawa, Ontario K1A 0E7

Abstract - The role of sediment in transporting nutrients and contaminants in rivers is increasingly being investigated in water quality programs. There is not yet an accepted sampling protocol for suspended sediment for water quality purposes. For water quality, the chemically active silt-clay fraction is usually presumed to be evenly distributed in the vertical column. Traditional sediment sampling techniques focus on sand-sized particles which are depth-dependent but are not considered to be significant for water quality issues. Using period of record data for three prairie rivers and three alpine river sites, as well as midstream data from the Mackenzie River, we examine the degree to which near-surface samples of silt and clay are representative of the vertical and cross section for high flow conditions. Generally, surface samples of silt + clay tend to underestimate the vertical mean concentration by less than 10%; also, 89% of the surface data at five of the six sampled sites are within ±15% of the vertical mean concentration. The individual vertical distributions of clay and silt display, however, inconsistent and variable patterns of concentration with depth and can include large excursions within individual profiles. Our data do not indicate that large, deep rivers behave differently from shallow ones. There is no evidence of increasing homogenization of silt + clay across the section as discharge increases. For sampling design purposes the data indicate typical errors that may be expected if surface samples are used to characterize the water column.

Key Words: suspended sediment, water quality, rivers, sampling, silts, clays, vertical distribution

DISTRIBUTION VERTICALE ET LATÉRALE DES MATIÈRES PARTICULAIRES À GRAINS FINS DANS LES COURS D'EAU : INCIDENCES SUR L'ÉCHANTILLONNAGE DANS LE CADRE DES PROGRAMMES DE SURVEILLANCE DE LA QUALITÉ DE L'EAU

EDWIN D. ONGLEY[1] ET TED. R. YUZYK[2]

[1] Institut national de recherche sur les eaux, Environnement Canada,
Burlington (Ontario), Canada L7R 4A6

[2] Étude des sédiments, Direction des ressources en eau, Direction générale des eaux intérieures,
Environnement Canada, Ottawa (Ontario) K1A 0E7

Résumé - Dans le cadre des programmes de surveillance de la qualité des eaux, on s'intéresse de plus en plus au rôle des sédiments dans le transport des matières nutritives et contaminantes dans les cours d'eau. Aucun protocole d'échantillonnage des sédiments en suspension n'a encore été accepté aux fins de la surveillance de la qualité des eaux. Pour les besoins de ces programmes, on présume généralement que la fraction d'argile-limon active est répartie de façon uniforme dans la colonne verticale. Les méthodes classiques d'échantillonnage des sédiments portent sur les particules de la taille du sable, qui varient en fonction de la profondeur; toutefois, on juge que ces particules ne renseignent pas sur la qualité de l'eau. À l'aide des données recueillies au cours de la période d'étude dans trois cours d'eau des Prairies et trois cours d'eau alpins ainsi que de données rassemblées au centre du fleuve Mackenzie, nous tentons de déterminer dans quelle mesure les échantillons de limon et d'argile prélevés près de la surface sont représentatifs des sections verticale et transversale dans des conditions de débit élevé. En général, les échantillons de limon et d'argile prélevés à la surface ont tendance à sous-estimer les concentrations moyennes verticales dans une proportion de moins de 10 %; en outre, dans 89 % des cas, l'écart observé entre les concentrations mesurées dans 5 des 6 stations d'échantillonnage et la concentration verticale moyenne est de ± 15 %. Toutefois, si l'on examine la distribution verticale d'argile et de limon dans chacune des stations, on constate que les concentrations présentent des tendances peu cohérentes et variables en fonction de la profondeur et que d'importants écarts peuvent être observés à l'intérieur d'un même profil. D'après les données que nous avons recueillies, les cours d'eau larges et profonds ne diffèrent pas des cours d'eau peu profonds. Rien ne nous permet de croire que l'homogénéité du limon et de l'argile augmentent dans la section parallèlement à l'accroissement du débit. Les données révèlent des erreurs types auxquelles on peut s'attendre si l'on emploie des échantillons prélevés en surface pour caractériser la colonne d'eau.

Mots clés : sédiments en suspension, qualité de l'eau, cours d'eau,
échantillonnage, limons, argiles, distribution verticale.

INTRODUCTION

The role of fine-grained particulates in fluvial transport of nutrients and contaminants is now well known. There is abundant literature which shows that the chemically active <63 µm (silt + clay) fraction is of primary interest for water quality purposes (Forstner and Whittman, 1981; Ongley _et al_., 1981; Witkowski _et al_., 1987). Inclusion of sediment-associated parameters into water quality programs has, however, been slow. This arises, in part, from the traditional differences between sediment quantity and water quality programs where the former focusses upon transport and physical sedimentation and the latter on whole and filtered water analyses, and in part because of difficulties in developing acceptable fine-grained sediment sampling protocols appropriate to water quality concerns.

Unlike >63 µm (sand-size material) suspended sediment which has increasing concentration with depth, concentration of the <63 µm fraction has been shown in numerous studies to be fairly evenly distributed with depth. For example, Culbertson _et al_. (1972) showed that the silt-clay fraction was not depth dependent in the Rio Grande conveyance channel. Using data from the Missouri River, the U.S. Soil Conservation Service (1983) drew the same general conclusion. Using Water Resources Branch sediment data for the South Saskatchewan River, Ongley _et al_. (1981) demonstrated that, in comparison with the coarser fractions, the <63 µm fractions were not depth dependent. Ongley (1982) came to a similar conclusion using data for two separate dates for the Fraser River. The lack of depth dependency reflects an equivalency of settling velocities with upward components of the turbulence field.

On the basis of this evidence, several studies of sediment-associated geochemical and contaminant flux in major Canadian rivers (e.g. Blachford and Ongley, 1984) have adopted near-surface sampling as a convention for fine-grained particles. Similar assumptions were made by Guy and Norman (1970). This convention has major advantages for sampling of sediment-associated chemistry; it presumes that an unbiased sample can be obtained at or near the surface without the logistical difficulties of depth-integration. It also facilitates large volume sampling in situations where bulk sediment samples are required for analysis of synthetic organic contaminants, particle-size and other analyses requiring gram-sized samples.

The 63 µm boundary is associated with other significant changes in suspended mineral sediment. The mineralogy of silt and clay is highly variable whereas the sand-size material is dominated by silica. In contrast with sand-size material, the geochemical activity of fine particles is associated not only with surface area effects of small particles but also with chemically active coatings of iron and manganese. Further, there is a significant shift in sediment provenance at the 63 µm boundary. The source of sand-size material is primarily in-channel deposits. The silt-clay fraction is often not well represented in channel deposits (Ongley, 1982). Geomorphologists refer to the <63 µm material as the wash load; it derives principally from extra-channel sources such as erosion of land surfaces, collapse of valley walls and erosion of glacio-lacustrine deposits.

Evidence from the Amazon River (Curtis et al., 1979) suggests that the assumption of uniform concentration of silt-clay with depth may not always be correct, especially in large rivers or under lower flow conditions. Moreover, the adequacy of a single mid-river sample to represent the cross section has not been systematically evaluated. Field programs such as that of Blachford and Ongley (1984) and Ongley et al. (in press) have utilized mid-river samples as representative of the cross section. Although the consistency of results under different flow regimes suggest that their sampling strategy was adequate for the purposes stated, the variability of the depth distribution of the <63 µm fraction either in time or across the river section was not investigated.

In this study we investigate the following questions:

1. How consistent is the assumption of vertical isometric distribution of <63 µm suspended sediment?
2. How variable is the <63 fraction across the river section?
3. Is cross-sectional variation influenced by flow regime?
4. Is a surface sample an adequate representation of <63 µm material in the sampled vertical and for the section as a whole?

DATA SET

To address these questions, we analyzed point-integrated sediment records of the Water Resources Branch of Environment Canada. Records exist for 26 stations in Canada; all are in western Canada. The earliest records are from 1954, however most of the stations have limited record lengh and infrequent sample coverage. Another limitation is that the data represent only high discharge conditions.

Point integration was carried out at a number of verticals across each section with US P-61 and US P-63 samplers (Vanoni, 1975). Samples were stabilized by addition of 1 ml of copper sulphate (Cu SO_4) in the field. Particle sizing was determined using bottom withdrawal tube procedures using native water without chemically dispersement (Environ. Canada, 1987).

Selection of sites for this study reflect geographical diversity, record length, and number of verticals per section. The six sites, (Table 1, Figure 1) include three major prairie rivers and three separate sites of the cordilleran Fraser River. Both the North and South Saskatchewan Rivers rise in the Rocky Mountains and flow eastwards across the three prairie provinces of Alberta, Saskatchewan and Manitoba. The two Saskatchewan rivers flow through large Pleistocene coulees. The Red River flows across extensive glacio-lacustrine deposits of glacial Lake Agassiz.

The dominance of high flow data are demonstrated in the discharge duration curves of Figure 2. In all the cases samples were collected from the upper 20% of the flow range. Relevant sampling information is noted in Table 2. The silt-clay fraction is a very large component of the suspended sediment on prairie rivers; this fraction also displays concentrations which are far larger than those of cordilleran sites.

Although total section width was not recorded, the end verticals are located well away from the banks - 30.5 m for the narrowest section (Red River) and 67 m for the widest (Fraser River at Hope, Table 2). The precise location of each vertical may vary several metres from one sampling date to another. The "surface" point-integrated sample is taken at a variable distance from the surface (Table 2) depending upon the river stage. The maximum depths (.30 m) of surface samples from prairie rivers is consistent with surface sampling protocols used in several major studies of prairie and northern rivers (Blachford and Ongley, 1984; Ongley _et al_., in press, Nagy _et al_., 1986).

The Mackenzie River data were obtained by personnel of the Water Resources Branch specifically for this study. Although the Fraser River sites are up to 22 m deep with sampled discharge up to 12,600 m^3s^{-1}, the Mackenzie data allow us to examine irregularities that might exist under spring high flow and late summer flow conditions for an extremely large river (sampled discharges to 23,000 m^3s^{-1}). Two sites, one near Wrigley and the second immediately upstream of the confluence with Arctic Red River (Figure 1) were sampled in June of 1986 and again in September. Point-integrated samples were taken for a vertical representing the deepest part of the Mackenzie channel. Suspended sediment concentrations were too small in September at the Wrigley site for particle-size determinations. Site data appear in Table 2.

For clarity, the following terms are used:

Vertical mean: mean of data for one vertical on any one sampling date.

Mean vertical: average of several verticals. This may apply to
average vertical concentration for any sampling
date, or the average of all verticals for period
of record, depending upon the context.

These terms are analogous to daily mean and mean daily that are conventionally used in hydrology.

ANALYSIS AND DISCUSSION

Surface Sample as Representative of the Vertical

The degree to which a surface sample is representative of a vertical, irrespective of the number of verticals or of the location of each vertical in the section, is indicated in Table 3. The analysis is for silt, clay and silt + clay.

The data are generated for each vertical; the surface concentration of each size fraction is expressed as a percent of the vertical mean concentration. The data of Table 3 are averaged values for period of record. The sign indicates whether the surface sample is, on average, greater or less than the vertical means. Table 3 records the extreme values for the record period; these reflect the maximum positive and negative variation recorded for individual verticals within the entire data set. Silt + clay is not necessarily the average of each of the silt and clay components because small absolute differences at low concentrations in one or the other can result in high percentage differences from the vertical means.

On average, each of silt and clay fractions and the silt + clay fraction vary less than 10% from vertical means. The extreme differences of Table 3 indicate, however, that on any particular sampling date and for any particular vertical, the variation between the surface sample and the vertical mean can be quite large. For sampling design purposes, the distribution of surface data about the vertical mean is important. The probability of positive and negative deviations is illustrated in Figure 3. Table 4 summarizes these distributions for clay, silt and silt + clay for increments of five percent deviation about each vertical mean.

Figure 3 demonstrates that over- or under-representation of clay by the surface samples tends to be equally probable. Although this results in small average differences from the vertical mean (Table 3), tabulation of absolute differences (Table 4) clearly shows that the distribution of positive and negative variation is sufficiently large that the probability of any one sample being representative of the section (e.g. ±10% of vertical mean) is quite variable (35% to 88.9%). With the exception of the most downsteam cordilleran site (Fraser River at Mission), 89% of the silt + clay data are within 15% of the vertical means (Table 4). Prairie sites, with their higher proportion of <63 µm material in the suspended load, have a large proportion of data falling within 10% of the vertical means.

Figure 3 demonstrates consistent under-representation (negative deviation) of the surface silt and silt + clay sample relative to the vertical mean concentration. Presumably, this reflects the larger settling velocities of the silt-size particle leading to under-representation at the surface. With the exception of the Red River, silt concentrations exceed those for clay (Table 2); it is consistent, therefore, that silt + clay tracks the silt fraction.

There are a number of reasons for the observed variability of the surface sample relative to the vertical. Figure 4 illustrates some of the abberations observed in each station record.

1) Although individual verticals may have a relatively equal concentration down the vertical, one data point may exhibit a large excursion (V61.0 Figure 4E) from the trend. Because of the small number of data points per vertical, this greatly influences the vertical mean and, consequently, the ability of the surface sample to predict the vertical mean. With so few data points in each vertical, it is not useful to employ a more statistically sophisticated measure of estimation for the surface sample.

2. Commonly, we see a substantial excursion, both positive and negative, in the sample closest to the bed (most data, Figure 4). We decided not to arbitrarily eliminate these data. However, we expect that the interaction of current with bed topography is likely to cause zones of settling or of turbulent resuspension from the bottom, depending upon the dynamic conditions at the time of sampling. Figure 4E, which depicts a river with a mobile sand bed, sharp increases and decreases in clay concentration are found in the same cross section.

3. Although silt and clay concentration tend to display a fairly regular relationship with depth, individual verticals can display wholely anomolous behaviour. In Figure 4A&B clay concentration increases regularly with depth (except at the bottom), whereas silt (the heavier fraction) decreases consistently with depth. The pattern is not repeated on other sampling dates.
4. Where suspended sediment concentrations are low, small absolute changes in concentration can produce large percentage errors.
5. We have no knowledge of sampling or analytical error which might explain large excursions. While the overall sediment program is subject to quality assurance, individual samples are not.

The above observations suggest that the fluid dynamics of silt and clay transport is complex and not easily reduced to consistent generalities.

Cross-Sectional Variation

An important sampling question is the degree to which one vertical may be representative of the cross section. The verticals of Figures 4D-F indicate the kind of variability which may be observed. For clay (4E) surface concentrations change by a factor of 4 across the section; however, this and other patterns are not necessarily consistent between sampling dates nor between stations. Table 5 demonstrates the cross-sectional variability for the surface sample and for the vertical means for silt + clay. Variability (%) is expressed as 100x (maximum value - minimum value)/(maximum value).

The calculations are made for each sampled date; the mean $\bar{x}$ is the average for the period of record and the range expresses the minimum and maximum variability of the period of record. Because each vertical mean encompasses several data points, sectional variation for the verticals is less than for surface data alone. In either case, average variation is perhaps, unexpectedly small; however, the range in variation for any one site can be very large indeed. For prairie sites, suspended sediment is dominated by the silt + clay fraction (Table 2). For cordilleran sites with a smaller proportion of silt + clay material, the cross-sectional variation is larger. The largest cross-sectional differences for surface data can be up to 50% in cordilleran or prairie sites.

Comparing data of Tables 3 and 5, the surface sample from a vertical appears to better represent that vertical (up to 10.3% difference) than surface concentrations across the section (up to 23.4% difference). Nevertheless, the total data set exhibits such variability that one could not safely conclude that this generality applies to a specific sample without recourse to a complete section survey.

We investigated the extent to which increasing discharge and associated turbulence might homogenize surface concentrations of silt + clay across the section. In Figure 5 the cross-sectional variability for the surface silt + clay sample for each sample date is plotted against discharge. Discharge is only one of several variables that can affect wash load concentration (e.g. differential source inputs, boundary effects, secondary current patterns, bottom resuspension, etc.). There is no consistent pattern displayed in Figure 5. Variability appears to increase with discharge in the North Saskatchewan River and is unrelated to discharge in the Red River, the South Saskatchewan River and the Fraser River at Marguerite. Only at the Hope station on the Fraser is there some evidence of homogenization (decreasing variability) across the channel with increasing flow. Even here, however, the trend is too imprecise for sampling design purposes.

The Mackenzie River

As we note above, the Mackenzie data represent single samples at two different points in the hydrograph. The sampled spring flow above Artic Red River has been equalled or exceeded by only 5% of the daily mean flow over the period of record. The sampled September flow has been equalled or exceeded by 26% of the daily mean data.

The degree to which the surface sample represents the vertical mean concentration of silt + clay (Table 3) is consistent with data from the other six sites, both in magnitude (less than -6.9%) and in sign (i.e. under-representation). Data for clay are highly variable reflecting, in part, large variances associated with low clay concentrations (27/09/86 sample, Table 2).

The profiles of silt, clay, and silt+clay for the two sites (Figure 6) illustrate the same kinds of abberations and inconsistencies noted for the other sites. Silt has a tendency to increase with depth, however, the increase is highly irregular. The clay data exhibit three totally different depth characteristics as do the silt + clay data. Apart from irregular changes with depth, several plots demonstrate pronounced excursions within the vertical. The river was overflown during the June sampling program. Throughout its length the Mackenzie demonstrated large, densely packed, turbulence structures emerging from depth and bursting at or near the surface. It is not known to what extent these structures may influence the concentrations and particle size of suspended matter within or between them.

CONCLUSIONS

Using period of record point-integrated data from six sites - a total of 436 verticals, we evaluated the assumption that the concentration of silt + clay is relatively evenly distributed in the vertical section. We find that, on average, a surface sample (taken from the top 0.3 metre) under-represents the vertical mean concentration by less than 10% and that 89% of the surface data at five of the six sites are within ±15% of the vertical mean. The individual silt and clay fractions exhibit variable and inconsistent patterns of concentration with depth and may include large positive and negative excursions both within and at the bottom of the vertical.

The possibility that very large rivers may behave differently was examined using limited data collected for this purpose from two sites on the Mackenzie River. These data are very similar to the other sites insofar as the surface silt + clay concentration under-represents the vertical mean by <7%. As with the other sites, there is no consistent depth relationship of concentrations of silt or clay at or between sites.

Cross-sectional variability of silt + clay for the six long-term sites is <17% for vertical mean concentration and <24% for surface silt + clay samples. There is no evidence of increasing homogenization across the section with rising stage.

For sampling design purposes the data indicate typical errors that may be expected if the surface sample is assumed to be representative of the vertical section. Nevertheless, for many water quality purposes, the probability that 90% of the surface data are ±15% of the vertical mean is sufficient justification for utilizing surface sampling protocols. The alternative is depth integration which, for large volume sampling, is logistically difficult. Cross-sectional data suggest that, providing one avoids proximity with the banks, the exact location across the section is not important. The criteria used by Blachford and Ongley (1984) where the mid-channel site is denoted by maximum depth and maximum current, appears to be a reasonable field procedure.

Our study is based upon high discharge information. While high flow conditions are especially valuable for determining chemical loads, compliance to water quality criterion, especially for industrial and municipal discharges, tends to be a low flow problem. The degree to which our conclusions apply to low flow conditions requires further study.

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LIST OF FIGURES

Table 1. Study Sites

Station Name	Record Period	No. of Station Records	Total No. of Verticals	Drainage Area (km^2)
Red River (near Ste. Agathe)	1962-1976	11	53	117 000
S. Saskatchewan River (at Highway 41)	1966-1971	9	45	66 000
N. Saskatchewan River (at Prince Albert)	1963-1984	17	85	131 000
Fraser River at				
Marguerite	1971-1984	12	60	114 000
Hope	1967-1978	16	93	217 000
Mission	1965-1984	20	100	228 000
Mackenzie River at				
Wrigley	-	-	-	unknown
Arctic Red River	-	-	-	1 660 000

Table 2. Sampling Data

Station Name	Usual No. of Verticals	Depth of Deepest Vertical (m)		No. of Points in Deepest Vertical		Depth of Surface Sample in Deepest Vertical (m)	
		Min.	Max.	Min.	Max.	Min.	Max.
Red River near Ste. Agathe	5	3.75	12.89	5	8	.09	.18
South Saskatchewan River at Highway 41	5	3.96	6.83	6	8	.09	.30
North Saskatchewan River at Prince Albert	5	2.53	5.64	5	6	.09	.30
Fraser River near Marguerite	5	4.88	11.28	6	7	.10	1.83
Fraser River at Hope	6	13.96	22.19	7	9	.15	3.51
Fraser River at Mission	5	10.94	18.56	6	8	.15	2.83
Mackenzie River at Wrigley (17/06/86)	1	13.5		7		2.0	
Mackenzie River at Arctic Red River 12/06/86	1	19.8		9		2.0	
27/09/86	1	16.0		8		0.4	

Table 2. Continued

Station Name	Maximum Section Width Between End Verticals (m)	Suspended Sediment Concentration (mgL^{-1}) - All Data - Clay Min.	Clay Max.	Silt Min.	Silt Max.	Silt + Clay Min.	Silt + Clay Max.	Silt + Clay as % Total Suspended Sediment (Mean of all Verticals) Min.	Max.	Bed Material
Red River near Ste. Agathe	91.4	125	796	19	421	294	1158	97	99	sand
South Saskatchewan River at Highway 41	140.2	134	1125	82	2003	233	2981	72	94	sand
North Saskatchewan River at Prince Albert	189.9	12	626	139	1317	267	1640	53	83	sand
Fraser River near Marguerite	155.4	13	183	89	581	120	750	47	70	gravel
Fraser River at Hope	473.9	8	211	48	588	79	723	46	67	gravel
Fraser River at Mission	365.8	12	201	41	596	59	768	29	70	sand
Mackenzie River at Wrigley (17/06/86)	-	27	37	58	78	97	114	65		sand
Mackenzie River at Arctic Red River	-									sand
12/06/86		132	211	379	467	554	632	77		
27/09/86		9	17	49	68	61	77	83		

Table 3. Representativeness[1] of Surface Samples Relative to Vertical Mean Concentration

Location	Average % Difference for All Verticals*			Extreme % Difference for All Verticals *					
	Clay	Silt	Silt + Clay	Clay		Silt		Silt + Clay	
Red River	+0.5	-1.4	+0.5	-28	+23	-26	+45	-11	+13
S. Saskatchewan River	-2.8	-6.4	-5.1	-18	+18	-24	+6	-22	0
N. Saskatchewan River	+0.3	-6.6	-4.9	-44	+54	-48	+4	-42	+8
Fraser River (Marguerite)	+0.3	-2.1	-1.7	-68	+126	-27	+33	-26	+61
Fraser River (Hope)	+0.3	-3.3	-2.1	-75	+112	-37	+62	-21	+71
Fraser River (Mission)	-5.5	-11.6	-10.3	-60	+111	-47	+10	-34	+6
Mackenzie River at Wrigley (17/06/86)	-20.6	+1.4	-4.9	-		-		-	
Mackenzie River at Arctic Red River 12/06/86	+8.8	-12.9	-6.9	-		-		-	
27/09/86	+41.7	-14.0	-2.9	-		-		-	

[1] Data averaged for all verticals for period of record.

*Denotes - underestimate
+ overestimate

Table 4. Cumulative Probability (Σp) of Surface Sample Being within ±X% of Vertical Mean

Location	± Difference (%) from Vertical Mean						
X =	5	10	15	20	25	30	>30
Red River							
Σp:Silt	35.8	71.7	83.0	86.8	94.3	96.2	100
Σp:Clay	43.4	67.9	84.9	94.3	96.2	100	
Σp:Silt + Clay	73.6	94.3	100				
S. Saskatchewan River							
Σp:Silt	51.1	80.0	93.3	97.8	100		
Σp:Clay	62.2	88.9	93.3	100.0			
Σp:Silt + Clay	66.7	86.7	93.3	97.8	100		
N. Saskatchewan River							
Σp:Silt	55.3	78.8	91.8	95.3	97.6	97.6	100
Σp:Clay	42.4	63.5	71.8	76.5	80.0	84.7	100
Σp:Silt + Clay	64.7	88.2	94.1	96.5	97.7	97.7	100
Fraser River (Marguerite)							
Σp:Silt	50.0	76.7	85.1	91.7	95.1	98.4	100
Σp:Clay	18.3	35.0	43.3	51.7	63.3	73.3	100
Σp:Silt + Clay	58.3	78.3	90.0	95.0	95.0	96.7	100
Fraser River (Hope)							
Σp:Silt	52.7	76.4	89.3	96.8	97.9	97.9	100
Σp:Clay	19.4	35.5	54.9	65.6	69.9	75.3	100
Σp:Silt + Clay	62.4	78.5	89.3	95.7	98.9	98.9	100
Fraser River (Mission)							
Σp:Silt	22.0	50.0	72.0	85.0	94.0	96.0	100
Σp:Clay	15.0	36.0	53.0	67.0	78.0	81.0	100
Σp:Silt + Clay	23.0	56.0	79.0	93.0	96.0	99.0	100

Table 5. Mean (X) and Range of Cross-Sectional Variability of Silt + Clay.*

Location	Surface		Vertical Mean	
	$\bar{X}$ %	Range %	$\bar{X}$ %	Range %
Red River	13.3	5-24	10.2	4-20
S. Saskatchewan River	11.6	5-23	7.2	2-15
N. Saskatchewan River	17.8	6-42	16.3	4-38
Fraser River -				
Marguerite	23.4	10-52	13.5	6-21
Hope	21.4	7-48	12.0	3-25
Mission	17.3	11-32	15.0	6-28

*Expressed as % of maximum observed concentration on each sampled date.

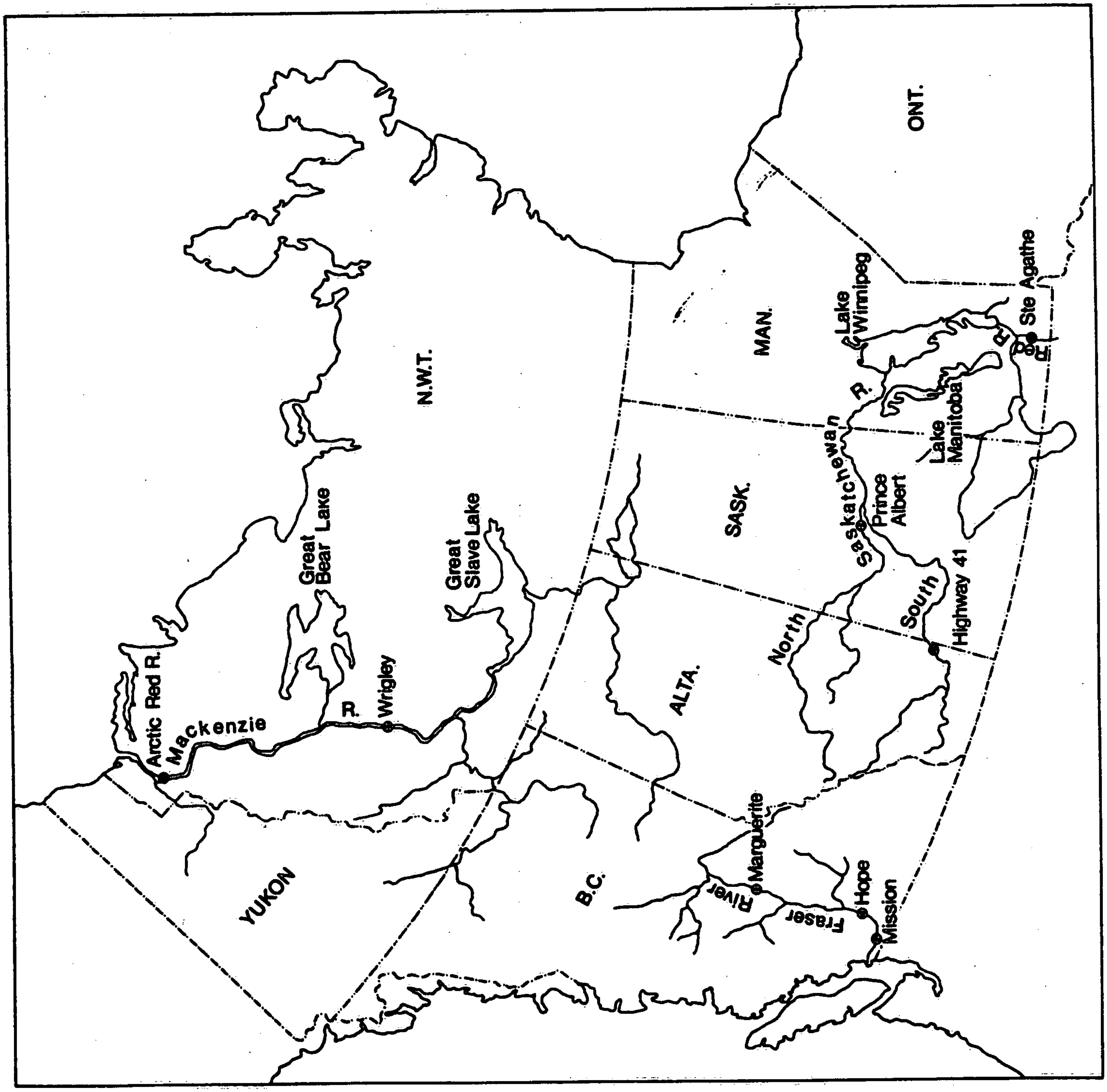
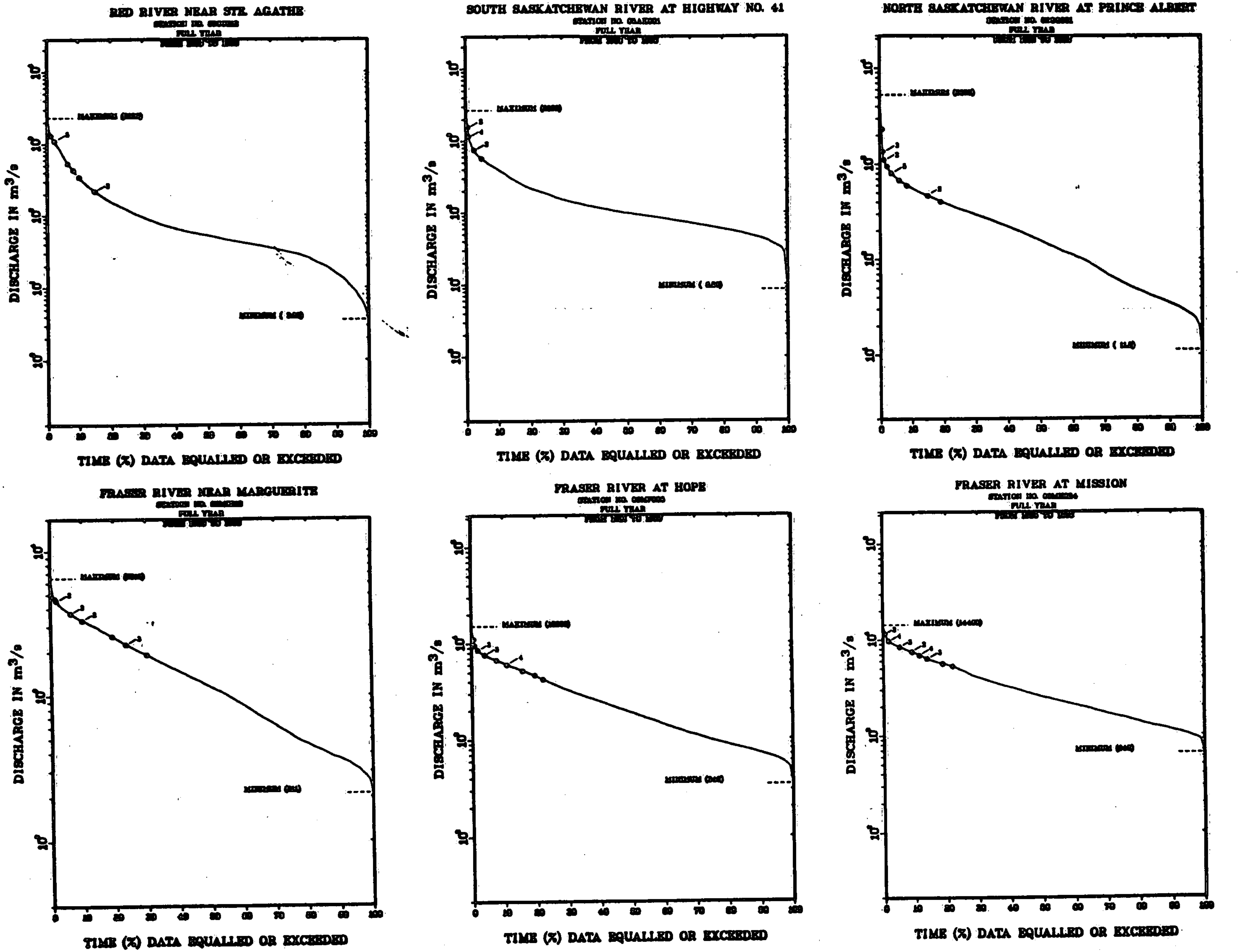


Figure 1. Sample sites used in this study.

FIGURE 2 : DISCHARGE DURATION CURVES FOR SAMPLED SITES



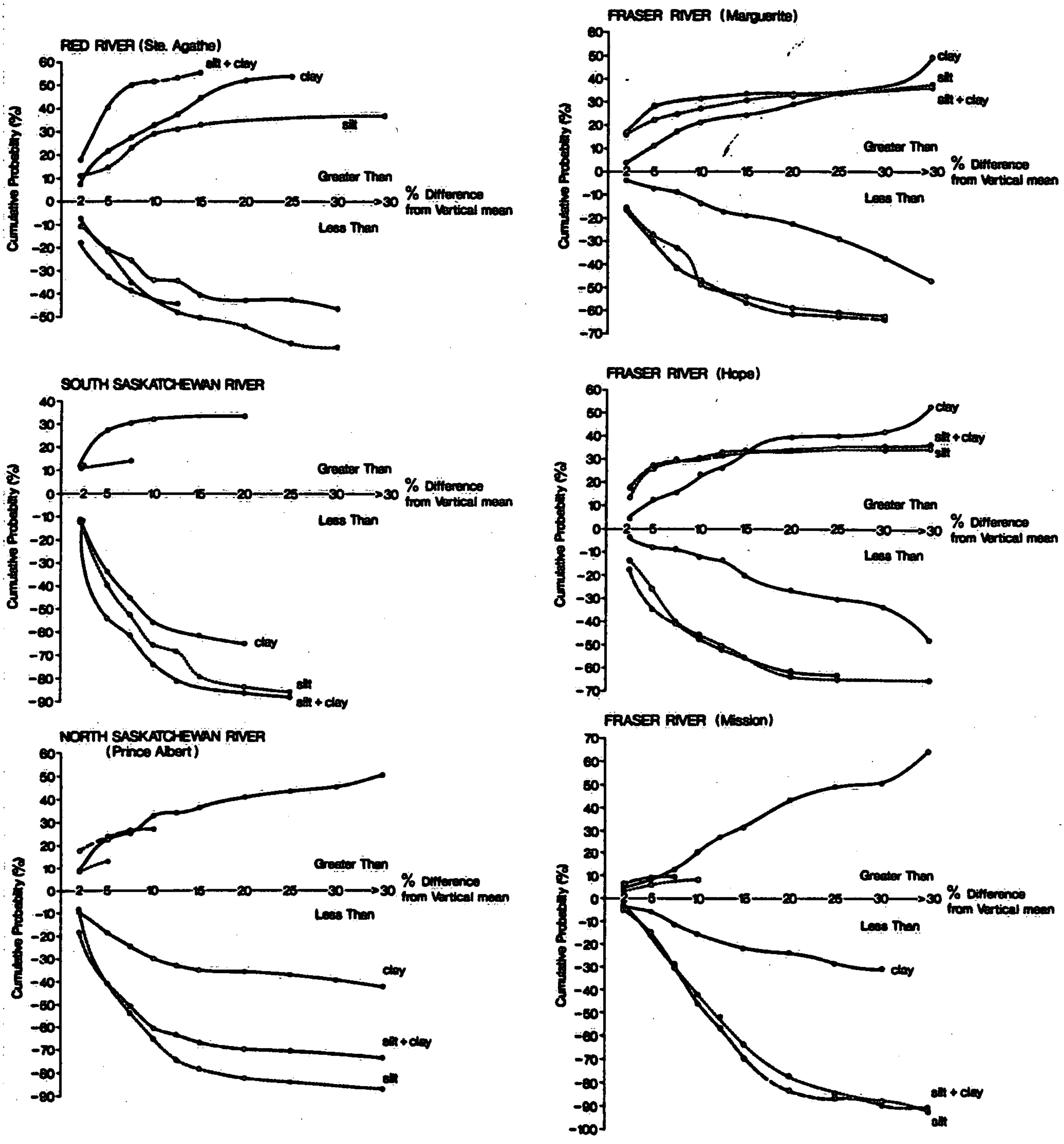
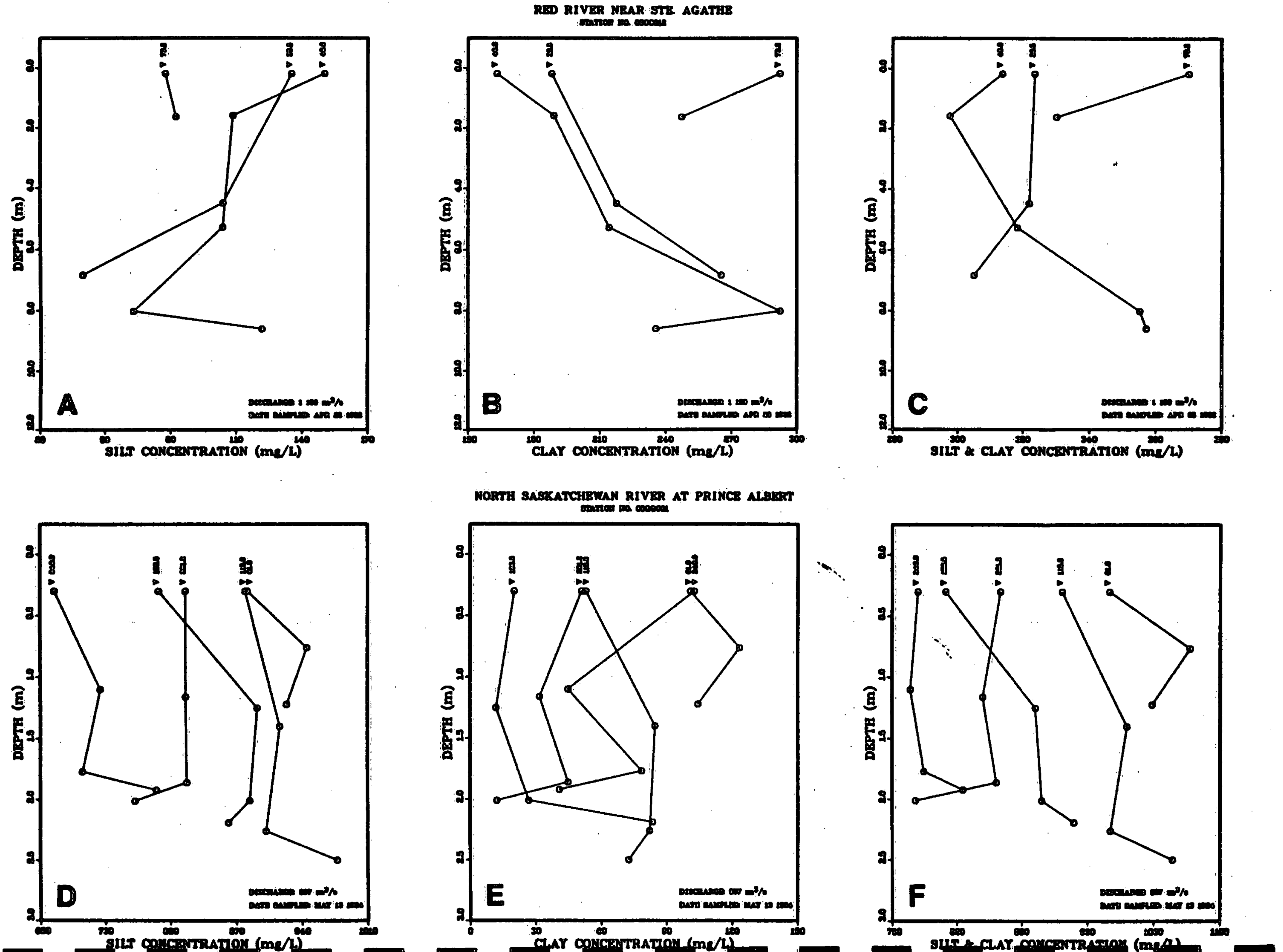


Figure 3. Cumulative probability distribution of greater/less than values of the surface sample relative to the vertical mean concentration of each size category.

FIGURE 4 : CONCENTRATIONS OF SILT, CLAY AND SILT & CLAY WITH DEPTH. "V" DENOTES VERTICAL WITH POSITION IN SECTION.



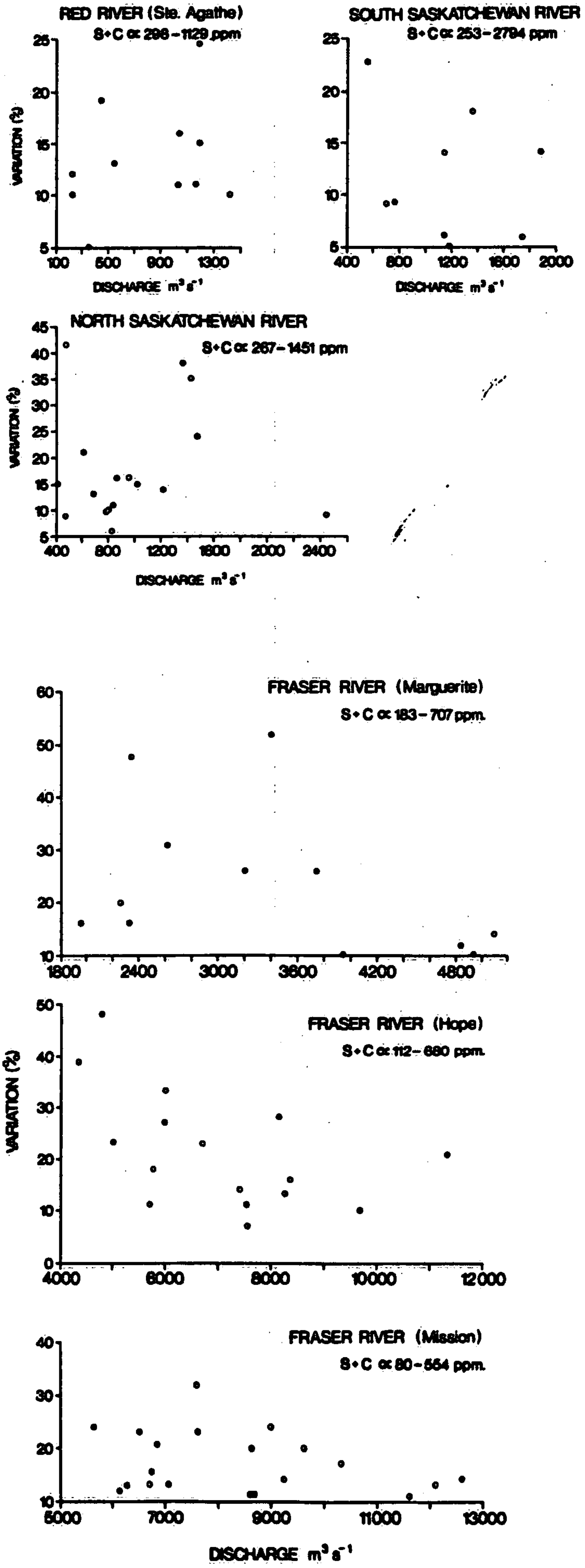
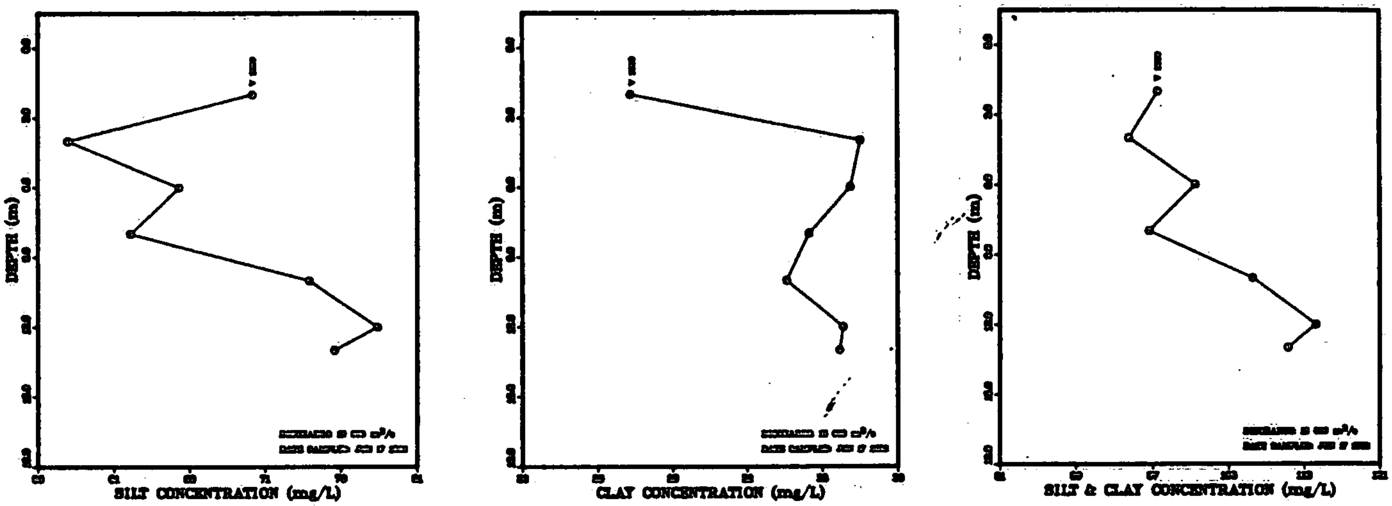


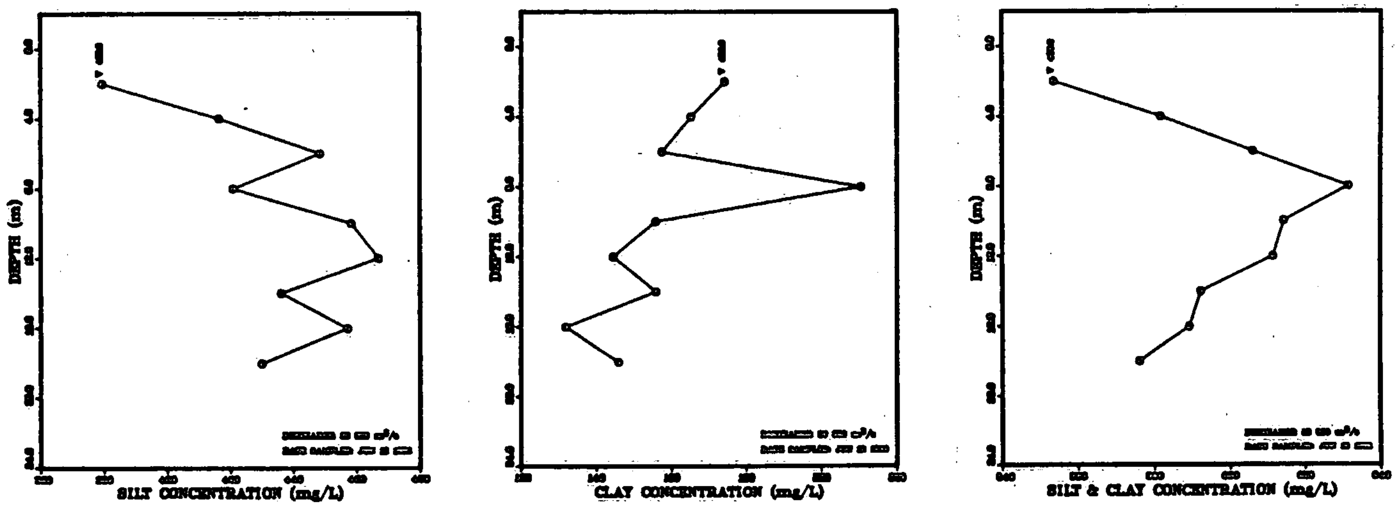
Figure 5. Plots of cross-sectional variation of surface samples of silt + clay against discharge do not reveal a tendency of homogenization of silt + clay concentrations across the section with increasing discharge.

FIGURE 6 : DISTRIBUTION OF SILT, CLAY, AND SILT & CLAY IN MID-STREAM OF MACKENZIE RIVER

MACKENZIE RIVER NEAR WRIGLEY



MACKENZIE RIVER AT ARCTIC RED RIVER



MACKENZIE RIVER AT ARCTIC RED RIVER