SPATIAL AND TEMPORAL PATTERNS OF SUSPENDED SEDIMENT YIELD IN THE SASKATCHEWAN RIVER BASIN

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ABSTRACT

Long-term suspended sediment concentration and load records are available for twenty three Water Survey of Canada sediment monitoring stations in the Saskatchewan River basin with drainage areas ranging from 10 km^2 to over 300 000 km^2. Mean annual sediment yield is greatest in the western Alberta Plains along the Oldman and Red Deer Rivers (over 100 tonnes km^{-2} $years^{-1}$) and tends to increase downstream along the main rivers until major reservoirs in Saskatchewan intervene. Average sediment concentration shows a similar pattern of variation to that of yield. Temporal aspects of suspended sediment transport vary along the drainage network. The range and skewness of the yield and concentration duration curves are greater in the intermediate size basins close to the Rocky Mountains and in two small basins with Prairie sources than they are in the large Prairie streams with Mountain sources and the glacier-fed upper North Saskatchewan River. Similarly, infrequent flows transport a larger proportion of the annual load in the smaller Foothills and western Plains basins than in the large Prairie streams because of differences in drainage area and discharge regime.

INTRODUCTION

Suspended sediment loads and their pattern of spatial and temporal variability have been reported at a variety of scales from all over the world (Walling and Webb, 1983). Numerous studies of the influence of climate, topography, land use, lithology, basin area and other factors have sought to predict long-term fluvial denudation rates as well as assessing the impact of human activities on short and long-term erosion rates. However, other aspects of fluvial sediment transport have received comparatively little attention. This is true of some of the temporal aspects of suspended sediment transport including inter and intra-basin contrasts in the timing of sediment transport and the relative importance of events of different magnitudes and frequencies (Webb and Walling, 1984). In part this is due to the lack of sufficiently long data records.

In Canada, despite the fact that the Water Survey of Canada has maintained a national sediment monitoring program since the early 1960s there have been few regional summaries of sediment yield. Perhaps the best-known national summary of suspended sediment concentrations and yields is that prepared by Stichling (1973) using Water Survey of Canada data. Subsequently Dickinson and Wall (1977) described contrasts in yield timing and magnitude-frequency characteristics of selected basins from several regions across the country.

Attempts to correlate sediment yield with the physical properties of drainage basins include Robinson's (1972) study of basins with a wide range of drainage areas from across Canada and McPherson's (1975) study of relatively small basins in south-western Alberta. In addition, there are studies of the sediment yield of individual basins ranging from small mountain catchments (e.g. McPherson, 1971; Nanson, 1974) to large Plains rivers such as the Red Deer River (Campbell, 1977). However, there are no syntheses comparing spatial and temporal aspects of suspended sediment transport over a large area such as a major river basin. Suspended sediment transport through large river systems is not only of academic interest but has more immediate environmental relevance in, for instance, monitoring and understanding the routing of sediment-attached pollutants through the drainage basin. The basic data on sediment transport is essential background information for such problems.

The Water Survey of Canada has operated a network of sediment stations in the Saskatchewan River basin for over twenty years. The present data base includes more stations and a longer period of record than was available to Stichling (1973). This expanded data base is arguably the best available for a major Canadian river basin. The Saskatchewan River basin is also of interest because of the pronounced contrasts in the physical environment within the drainage basin between the Rocky Mountains and the Prairies and also because issues of water quality and water supply, as well as the physical aspects of erosion and sedimentation, are of great importance to the region. This paper summarizes the patterns of long-term suspended sediment load and yield, as well as differences in regime and the magnitude-frequency characteristics of suspended sediment transport between streams in the Saskatchewan River basin. Further details are contained in Ashmore (1986).

PHYSICAL GEOGRAPHY OF THE SASKATCHEWAN RIVER BASIN

The Saskatchewan River drains an area of approximately 363 000 km^2 extending from the continental divide to Lake Winnipeg (Figure 1a). The two branches of the river, the North and South

Saskatchewan Rivers, originate in the Rocky Mountains and flow eastward through the Foothills and across the Alberta and Saskatchewan Plains before joining in central Saskatchewan. In eastern Saskatchewan and western Manitoba the Saskatchewan River flows through the Cumberland Delta area upstream of Cedar Lake. This portion of the lower Saskatchewan River is a complex anastamosed channel network (Kuiper, 1960; Smith, 1983). Much of the sediment load is deposited in Cedar Lake which is linked to Lake Winnipeg by a short bedrock channel. There are few natural lakes along the main streams of the basin except in the Cumberland Delta and and the extreme north-eastern portion of the basin bordering the Canadian Shield. However, there are several reservoirs, most importantly Lake Diefenbaker and Tobin Lake, which influence the flow regime of the rivers and are important sediment traps.

A large proportion of the basin area is occupied by the Alberta and Saskatchewan Plains but the Rocky Mountains and Foothills along the western margin of the basin not only present a strong physiographic contrast to the Plains but are also the major source of runoff in the basin (Figure 1b and d). For example, mean annual flow of the North

Saskatchewan River, Red Deer River, Bow River and Oldman River in western Alberta is equivalent to About 70% of the mean annual flow of the Saskatchewan River at The Pas, Manitoba.

Mean annual precipitation is lowest in the central portion of the basin where it averages less than 300mm. This increases northward and eastward to over 400mm and increases rapidly to over 800mm towards the western margin of the basin. A similar spatial pattern is seen in the mean annual runoff which averages less than 5mm in parts of south-eastern Saskatchewan and exceeds 1000mm in the Rocky Mountains (Figure 1c).

The Rocky Mountains and Foothills are formed by eastward thrusting and folding of the bedrock to form a series of parallel ridges trending roughly NW - SE. The lower slopes and valley bottoms are often mantled with glacial, fluvio-glacial and lacustrine deposits into which the contemporary streams are eroded and which are important sources of sediment (Hudson, 1983). Locally sediment yields may be extremely high (McPherson, 1971) but along the main river valleys there are often depositional zones (for example, upstream of tributary alluvial fans) which may trap much of the sediment eroded from upstream (Shaw and Kellerhals, 1982).

The low relief of the Alberta and Saskatchewan Plains has resulted in large areas of poorly integrated drainage which do not contribute water or sediment to the main stream system. The main rivers are incised into the glacial deposits and erodible Cretaceous sandstone, clay and shale that underly the Prairie surface. The steep valley sides are often subject to gullying and mass movement and consequently may be the most important sediment sources in the basin (Campbell, 1977).

While the Rocky Mountains and Foothills as well as the north western portions of the Plains retain a forest cover up to an altitude of about 2000 m, much of the natural grassland and parkland of the Prairie portion of the basin has been replaced by arable and grazing land (Figure 1e).

DATA

Since 1961 the Water Survey of Canada has routinely collected suspended sediment samples at hydrometric stations in Canada. Samples are collected using standard U.S.G.S. depth integrated suspended sediment samplers at a single vertical in the rated cross section (Stichling, 1973). There are 112 stations in the Saskatchewan River basin at which sediment samples have been collected.

However, the period and frequency of sampling varies greatly between sites and only twenty or thirty stations may be active in a given year. Sixty four of these stations have only infrequent sampling programs in which only a few samples per year are collected and no calculations of load are made. These stations have not been used in the analysis.

The remaining stations have sampling programs which cover either the entire year or the open water season (March or April to October) with sample collection every few days under normal conditions and more frequently during high flow periods. A continuous plot of suspended sediment concentration is interpolated by hand between samples based on interpretation of the discharge record. The daily mean concentration and daily load are then calculated. This method differs from the suspended sediment rating curve used in many suspended sediment studies.

Several of these stations have sediment records which are too short (three years or less) to give reliable long-term load estimates, therefore this paper concentrates on twenty three stations with long-term records several, of which were established at the inception of the national program in the early 1960s. These stations are listed in Table 1 and their location is shown in Figure 2. Their drainage areas range from less than 10 km^2 to over 300 000 km^2.

Nine of the stations shown in Figure 2 are situated on the main rivers of the basin several hundred kilometres east of the Rocky Mountains. A second group of eleven stations consists of streams in the Rocky Mountains and Foothills and on the Alberta Plains close to their western margin. Most of these are on major tributaries of the stream system (Oldman River, Willow Creek, Elbow River, Bow River, Highwood River, Red Deer River and North Saskatchewan River) but Marmot Creek is a small experimental basin in the Front Ranges of the Rocky Mountains. The remaining two stations are situated on streams with their sources on the Prairies (Swift Current Creek and Carrot River).

SEASONAL SEDIMENT LOAD

It is not possible to calculate the mean annual sediment load for the period of record at all the stations because in some cases data have been collected only during the open water season. In the cases where year-round sampling has occurred the sediment load transported during winter (November to March) accounts, on average, for less than 5% and as little as 0.5% of the annual load. Assuming this applies to the remaining stations the seasonal (April to October) load is a close approximation to the annual load. In two cases (Bow River at Calgary and South Saskatchewan River at Saskatoon) flow regulation at upstream dams has increased the proportion of the annual load carried during winter. At these two stations the annual loads have been used. Table 2 displays the seasonal suspended sediment loads together with the standard error of the estimate of the mean and the skewness [$(m_3/m_2)^{3/2}$ where m_2 and m_3 are the second and third moments of the frequency distribution] of the distribution of annual loads. Variability in seasonal load, as shown by the standard error of the estimate of the mean, is considerable. Thus, the standard error ranges from 6.1% to 61.3% of the mean and tends to be greater for the smaller Mountain and Foothills streams than for the large Prairie streams. Differences in the length of record are responsible for some ofr these differences. The Mountain and Foothills streams, as well as the two Prairie source streams, also tend to have greater positive skewness of the annual load series than do the large Prairie streams.

Figure 3 shows the seasonal sediment load at the sediment stations in the Saskatchewan River basin. Prior to the construction of the Gardiner Dam (completed in 1963) on the South Saskatchewan River the mean annual suspended sediment load of the Saskatchewan River upstream of the Cumberland Delta was approximately 9 million tonnes. Northwest Hydraulic Consultants (1986) estimated that the mean annual at The Pas was 4 million tonnes, but there are few data on which to base this figure. Regardless, despite a considerable amount of deposition in the Cumberland Delta, a significant load reached Cedar Lake. Of the 9 million tonnes per year carried by the Saskatchewan River, approximately one third was derived from the North Saskatchewan River and two thirds from the South Saskatchewan River.

The construction of the Gardiner Dam has obviously had an impact on the sediment load of the rivers downstream. Much of the load of the South Saskatchewan River is derived from the Alberta portion of the basin and is now deposited in Lake Diefenbaker (Yuzyk, 1983). Thus the mean annual load at Saskatoon (downstream of the Gardiner Dam) is now less than 0.5 million tonnes (see also, Rasid,1979) compared with an estimated 6 million tonnes prior to the dam construction. At the same time the Squaw Rapids Dam (Tobin Lake), completed in 1962 on the Saskatchewan River traps the load of the North Saskatchewan River before it reaches the Cumberland Delta. Yet despite the presence of these two reservoirs, the Saskatchewan River at The Pas still transports a mean annual sediment load of 2 million tonnes, derived from the basin downstream of Tobin Lake. The contribution of the tributaries in this portion of the basin is not known but most of them drain Shield areas through a series of lakes and are unlikely to carry significant loads. The Carrot River accounts for a small proportion of the load but much of the remainder must be derived from the Saskatchewan River itself by bank and lake shoreline erosion in the Cumberland Delta region.

The absence of long-term sediment stations in the North Saskatchewan River basin between Whirlpool Point and Prince Albert makes it impossible to establish the pattern of sediment contribution within that portion of the basin. In the case of the South Saskatchewan River, of the mean annual load of 6 million tonnes deposited in Lake Diefenbaker, approximately 2.0 million tonnes is delivered from the Red Deer River basin and 1.5 million tonnes from the Oldman River basin. The contribution of the Bow River cannot be reliably estimated from the existing station network. The discrepancy between the combined loads of the South Saskatchewan River at Highway #41 (05AK001) and the Red Deer River near Bindloss (05CK004) with that of the South Saskatchewan River downstream of the Red Deer River confluence (near Lemsford, 05HB001) arises because of differences in the period of record between the three stations. When the loads for the common period 1967 to 1970 are compared the combined mean seasonal load of the Red Deer and South Saskatchewan River upstream of their confluence is 6.6 million tonnes compared with 7 million tonnes downstream of the confluence.

In both the Oldman and Red Deer rivers much of the annual sediment load is contributed in the Alberta Plains region. In the case of the Red Deer River over 90% (1.8 million tonnes of the total of 2.0 million tonnes) of the mean annual load at Bindloss (05CK004) is derived from the portion of the basin downstream of Red Deer (see also Campbell, 1977). Similarly, approximately 82% of the mean annual load of the Oldman River at Lethbridge (05AD007) is derived from the basin downstream of Brocket. This contrasts with annual flow contributions of about 25-30% of the total in both cases. The badlands of the Red Deer River valley are known to contribute large amounts of sediment to the main stream and similar riparian sources also are likely to be important in the Oldman River basin (Kuiper, 1960).

Figure 4 plots the cumulative deviation from the mean seasonal load over the period of record at representative stations on the major rivers of the Saskatchewan River basin. The pattern of variation is similar in all cases. The period from the early 1960s to the mid 1970s is one of above average sediment loads while after 1975 a period of consistently below average loads occurred. The variation in annual sediment load necessarily follows that of annual flow. The fact that the pattern of variation is similar on all the major rivers of the drainage basin suggests that it is primarily the result of natural flow variation rather than flow regulation and abstraction. This trend in mean annual load over the 20 year period from 1963 to 1983 again raises the difficulty of comparing average load and yield between stations with differing periods of record.

ANNUAL SEDIMENT YIELD

It is well-known that sediment yield is highly spatially variable and that the use of sediment yield as a measure of average denudation in a large drainage basin gives a misleading impression of spatial uniformity. Nevertheless, the mean annual sediment yield of a drainage basin remains a useful means of standardising the sediment load of streams with differing drainage basin areas.

In the Saskatchewan River basin the definition of the drainage area is problematic because of the presence of large areas of internally drained land on the Prairies. The Prairie Farm Rehabilitation Administration (1983) calculated the area of internally drained land ("dead" drainage area) upstream of each Water Survey of Canada gauging station, from 1:50 000 topographic maps. When subtracted from the total drainage area within the drainage divide, the resulting "effective" area gives an estimate of the area contributing runoff, and therefore potentially contributing sediment, to the main stream system. The effective area was used to calculate the sediment yield although in some cases the drainage area upstream of lakes and reservoirs was also subtracted. The drainage area calculated as a result of these adjustments is referred to here as the potential sediment contributing area.

Figure 5 shows the pattern of sediment yield. There is a general tendency for the smaller headwater basins in the Rocky Mountains and Foothills to have relatively low yields and for yields to increase downstream into the western Plains region. The high yield from the glacierised upper North Saskatchewan River basin (at Whirlpool Point, 05DA009) is an exception. Further downstream yields decrease slightly. The consequence of this pattern is that, when plotted against drainage area, sediment yield shows a positive correlation with drainage area (Figure 6). Hudson (1983) describes a similar pattern for the Elbow River as it flows from the Rocky Mountains through the Foothills and out onto the Alberta Plains.

Existing data on the relationship between drainage area and sediment delivery ratio (see, for example, Walling and Webb,1983,Figure 4.8) imply that sediment yield declines with increasing drainage area. However, these results are derived from basins with drainage areas less than 1000 km^2 in presumably fairly uniform terrain. In much larger basins in which there may be large contrasts in geology, land use and relief it is to be expected that the relationship between sediment yield and drainage area would have a different form depending on the arrangement of major sediment source areas and sinks within the drainage basin . A more realistic model in such cases would be one of fluctuating load and yield downstream along the stream system in response to the juxtaposition of both point and non-point sources and sinks such as lakes and reservoirs. In this case the steep-sided valleys entrenched into glacial deposits and weak bedrock of the Plains are primarily responsible for the increase in sediment yield in the Alberta Plains area and hence for the increase in yield downstream along the main rivers.

In most cases it is possible to calculate the mean annual sediment yield separately for the portions of each drainage basin between adjacent sediment stations on the same river. The result of doing so (Figure 7) is that the relationship between yield and drainage area is less apparent and instead there is a distinction between a group of stations with yields less than 40 tonnes km^{-2} $years^{-1}$ and a second group with yields over 50 tonnes km^{-2} $years^{-1}$. The first group are mainly relatively small Mountain and Foothills catchments while the second group consists primarily of larger Plains rivers. This confirms the significance of the sediment sources in the western Plains to the variation in yield along the main streams of the drainage basin.

AVERAGE ANNUAL CONCENTRATION

An alternative to standardising the sediment loads of rivers with different drainage areas is to consider the load relative to the average annual flow. The ratio of mean annual load to mean annual flow volume is in effect a concentration and here is referred to as the average annual concentration. Figure 8 shows the pattern of variation of average annual concentration at the long term sediment stations in the basin.

The contrast between relatively low concentrations in the Mountain and Foothills streams and the high concentrations in the Alberta Plains portion of the basin parallels the pattern of variation of sediment yield. Concentration is also relatively high in the two streams with Prairie sources (Swift Current Creek and Carrot River). The effect of the reservoirs in reducing suspended sediment concentration in the Bow River at Calgary (05BH004), the South Saskatchewan River at Saskatoon (05HG001) and the Saskatchewan River downstream of Tobin Lake (05KD003) is also apparent.

Concentration is highest in the downstream portion of the Red Deer River presumably as a result of sediment eroded from the badlands along this portion of the valley. Although sediment yield appears to be greater on the Oldman River upstream of Lethbridge than on the Red Deer River, average concentration is lower in the Oldman River. Notice also that the average annual concentration is relatively low in the upper North Saskatchewan River at Whirlpool Point in contrast to the high yield recorded at this site.

ANNUAL SEDIMENT REGIME

The time distribution of suspended sediment load at a station is strongly dependent on the discharge regime but is also influenced by variation in concentration which, while positively correlated with discharge, is indirectly related to it. The annual discharge regimes, and therefore the suspended sediment regimes, of the streams of the Saskatchewan River basin are influenced by whether the stream has a Prairie or Mountain source and, if the latter, by the distance of the station from the Mountains. Figure 9 shows examples of flow and sediment regimes based on average monthly flow and load over the period of record which illustrate this point.

Marmot Creek is a small (9 km^2) experimental basin in the Rocky Mountain Front Ranges at an elevation of over 1600m. Both runoff and sediment regime show a single peak in June. In the case of sediment load June is by far the dominant month. The drainage basin of the Highwood River includes areas of the Rocky Mountains, Foothills and the western Plains. Here again discharge and load are highest in June but runoff from lower altitudes contributes to significant flow and sediment load in May and to a lesser extent in April.

This pattern of a single peak in early summer prevails further downstream along the larger rivers with Mountain sources. In some instances where the station is several hundred kilometres from the Mountains the peak is delayed until early July. The North Saskatchewan River at Prince Albert shows this effect and also has a second smaller peak in April resulting from the contribution of flow and load from Prairie rivers such as the Battle River. Since 1975 flow regulation for power generation upstream has resulted in the April peak becoming the dominant sediment transporting event at this station (Ashmore, 1987).

The regime of the Prairie source streams is illustrated by Swift Surrent Creek which has a single peak in April due to Prairie snowmelt and negligible load throughout the remainder of the year.

The North Saskatchewan River at Whirlpool Point has a regime that is influenced by glacier melt. The result is that in contrast to Marmot Creek it has a prolonged summer flow and load peak from May to September with maximum average load in July.

When mean monthly load is plotted against mean monthly discharge the resulting graph shows hysteresis in the relationship such that, in most cases, load is greater at a given discharge on the rising limb of the annual hydrograph than at the same discharge on the falling limb (Figure 10). Such seasonal variation in concentration is normally attributed to flushing of the sediment sources close to the stream system by the early season high discharges and to differences in the relative contribution of high concentration quickflow and low concentration base flow on the rising and falling limbs of the annual hydrograph (Gregory and Walling, 1973). The Highwood River near the mouth and the South Saskatchewan River at Highway 41 both show a simple clockwise loop.

However, in other cases the pattern is more complex. For example the North Saskatchewan River at Prince Albert has a loop with two peaks at high discharge reflecting the April and July peaks in the annual regime. In addition the North Saskatchewan River has a counter-clockwise loop at low discharges which may be due to the release of water for power generation from upstream reservoirs resulting in slightly higher discharges with very low sediment concentration during December, January and February. The complex hysteresis pattern of the South Saskatchewan River at Saskatoon illustrates the impact that upstream flow regulation has on the sediment regime of some portions of the stream system.

DURATION CURVES OF DAILY CONCENTRATION AND YIELD

Table 3 shows the values of graphical dispersion and graphical skewness {[1/99] and $\log[(1 \times 99)/50^2]$ respectively, where the numbers are percentiles of the distribution} of the daily concentration and daily yield duration curve. Selected examples of these curves, showing the range of variation in their form, are displayed in Figures 11 and 12. Considerable variability is apparent in the dispersion and skewness of the distributions as well as the actual values of concentration and yield.

The daily yield duration curves show the difference in yield between the upstream Mountain basins and the downstream Plains streams that was discussed in the section on annual sediment yield. Apart from these differences, the duration curves from different parts of the basin can also be distinguished on the basis of their shape, as defined by graphical measures of skewness and dispersion. For example, the intermediate size basins in western Alberta such as the Oldman River, Willow Creek, the Elbow River and The Highwood River have duration curves with large dispersion and high positive skewness. This can be seen in Figure 11 in the curves for the Oldman River near Brocket and near Lethbridge. The same is true of Swift Current Creek, a relatively small stream fed entirely by Prairie runoff.

By comparison with the smaller Foothills and western Plains basins the large Prairie streams such as the North Saskatchewan River at Prince Albert, as well as some of the Mountain streams (for example the Crowsnest River), have smaller values of graphical dispersion and skewness. In two cases the duration curves are negatively skewed.

The first of these is the North Saskatchewan River at Whirlpool Point whose glacial regime has already been shown to be distinct in other respects and the second is the Saskatchewan River at The Pas in which flow is strongly regulated by natural lakes and by reservoirs. The general pattern downstream along the main streams is for skewness and dispersion to be relatively low in the small Mountain streams, to increase at the western margin of the Plains and then to decrease downstream.

A similar spatial pattern can be seen in the daily concentration duration curves (Figure 12). Notice again that the daily duration curves show the same general pattern of variation of average concentration as the mean annual concentration. Thus, the concentration tends to increase downstream along the main rivers and the Red Deer River at Bindloss has consistently higher concentrations across the whole duration curve than any other station. There are also differences in the shapes of the duration curves. Mountain streams (for example Crowsnest River) are characterised by low dispersion and skewness which are both greater downstream at the stations on streams in the western Plains such as those on the Oldman River, Willow Creek, the Elbow River, the Highwood River and the upstream stations on the Red Deer River. The duration curves for the Prairie source streams such as Swift Current Creek are similar to those from the western Plains stations.

Further downstream along the main rivers the skewness and dispersion of the duration curves tend to decrease again (for example, see the curve for the North Saskatchewan River at Prince Albert). In some cases this effect is enhanced by the presence upstream of lakes and reservoirs (for example, the Saskatchewan River at The Pas). Thus, while concentrations at the 95th percentile are greater in the large Plains rivers than in the smaller rivers closer to the mountains, the concentrations at the 5th percentile of the duration curves are greater in the smaller western Plains streams than they are further downstream.

MAGNITUDE AND FREQUENCY CHARACTERISTICS

Table 4 lists average maximum 4 consecutive day and 36 consecutive day loads as a percentage of the seasonal load. Because only a small fraction of the total load is transported during winter these values are approximately equivalent to proportions of the annual load and therefore represent 1% and 10% of the time respectively. The highest four consecutive day load ranges from 4 to 40% of the seasonal total load is and averages about 20% for the stations analysed. For individual years the range is greater than this with a maximum of 72% (Willow Creek) and a minimum of 2.9% (Saskatchewan River below Tobin Lake). The highest 36 consecutive days account for between 25% and 90% of the seasonal total load and in some years approaches 100% in Swift Current Creek and the Carrot River.

Generally speaking the highest proportional 4 and 36 day loads occur in the streams draining the Rocky Mountains and Foothills (the Oldman River, Willow Creek, the Elbow River, the Highwood River and the upper Red Deer River) and also in the two Prairie source streams (Swift Current Creek and the Carrot River). The larger mainstem Prairie rivers, as well as those strongly influenced by upstream flow regulation (Bow River at Calgary, South Saskatchewan River at Saskatoon and Saskatchewan River below Tobin Lake), have much lower proportions of the total load transported during short time periods. The glacier-fed North Saskatchewan River at Whirlpool Point also has relatively small sediment loads transported by peak annual events.

Figure 13 shows some examples of cumulative load duration curves from the long-term stations. Index values from these and the other long-term stations are given in Table 5. The pattern of variation between stations is similar to that for the 4 and 36 day loads. Greater proportions of the total load are transported by short duration events in the eastern slopes streams (particularly the Oldman River and Willow Creek) and in the Prairie-source streams (Swift Current Creek), than in the large Prairie rivers (South Saskatchewan River at Highway 41 and near Lemsford and the Red Deer River near Bindloss). The consequence is that the proportion of the total load transported in a given percentage of the time decreases downstream along the main rivers. For example, along the Oldman River the percentage of the total load transported in 0.1% of the time decreases downstream from 20% at Brocket, to 18% at Lethbridge, 8% at Highway 41, 4% near Lemsford, and 2% at Outlook. A similar pattern can be seen on the Red Deer River. The curve for the glacier-fed upper North Saskatchewan River resembles those of the main-stem Prairie streams. It should be pointed out that these percentage loads in percent time are calculated for seasonal data only (i.e. for the period April to October) so that the stations with only seasonal data could be included in the analysis. On average 95% of the annual load is transported during the open-water season and therefore, if the calculations were made for the whole year the percentage of the annual load transported in a given percentage of the time would be greater than reported here.

This pattern of changing magnitude-frequency characteristics across the drainage basin is similar to that shown by Dickinson and Wall (1977) in their analysis of regional differences in Canada (see their Figure 6) except that their Prairie-source streams plot to the right of the large Prairie streams with Mountain sources rather than on the extreme left as in Figure 13. The explanation for this difference may lie in Dickinson and Wall's (1977) choice of Prairie-source streams. It is possible that the large streams such as the Red River or Assiniboine River in Manitoba have cumulative duration curves of the form shown by Dickinson and Wall (1977) for Prairie-source streams.

The differences in the relative significance of short duration events in the total sediment load of these streams may be related to differences in drainage area as well as the hydrological regimes (Wolman and Miller, 1960). Thus, the eastern slopes have annual regimes in which a large proportion of the annual load is transported in only one or two months (usually May and June). Similarly the annual regimes of the Prairie-source streams are dominated by a single spring runoff event. In contrast, the large Prairie streams have spring and summer peak load periods of longer duration than either of the previous two groups. In addition, it is likely that the smaller basins are more strongly affected by intense storms that cover a limited area than are the large Prairie basins.

The possible influence of differences in the discharge regime on the magnitude-frequency characteristics of sediment transport can be seen in Figure 14. Here the percentage of the seasonal total load transported by the highest 1% of daily loads is plotted against the graphical dispersion and skewness of the daily flow duration curve. There is a clear positive correlation between the proportion of the seasonal load transported in 1% of the time and both the dispersion and skewness of the flow duration curve. Presumably these differences in flow regime and discharge duration may in turn be related to drainage area, and other physical properties of the drainage basins as well as to differences in the precipitation and snowmelt inputs to the streams. Explanation of the differences in temporal patterns of sediment transport in these terms has not been attempted but is an important future step.

SUMMARY AND CONCLUSIONS

The suspended sediment transport characteristics of streams in the Saskatchewan River basin show considerable variation across the basin because of differences in geology, physiography, hydrological regime and drainage area.

Estimates of mean annual sediment load are not directly comparable between stations because of differences in the length and period of record. However, the estimates indicate that prior to the construction of the Gardiner Dam on the South Saskatchewan River and the Squaw Rapids Dam on the Saskatchewan River, the combined mean annual load of the North and South Saskatchewan Rivers was about 9 million tonnes of which about two thirds was derived from the South Saskatchewan River. The Red Deer River badlands and Oldman River basin upstream of Lethbridge account for a large proportion of the load of the South Saskatchewan River. Since the construction of the two dams, the load of the South Saskatchewan River has been deposited in Lake Diefenbaker and that of the North Saskatchewan River in Tobin Lake. Nevertheless, the Saskatchewan River at The Pas still transports an average of slightly over 2 million tonnes per year most of which apparently is derived from bank and lake shoreline erosion in the Cumberland Delta.

Mean annual sediment yield increases downstream along the major rivers between the Rocky Mountains and the Saskatchewan Plains. The highest yields are recorded along the lower Red Deer River and Oldman Rivers. The high yield from the upper North Saskatchewan River which receives a large flow contribution from glacial melt is an exception to this pattern. The pattern of sediment yield along the Saskatchewan portions of the main rivers is disturbed by the presence of the large reservoirs.

There is a tendency among the stations analysed for mean annual yield to increase with increasing drainage area because of the large amount of sediment contributed from the Plains portions of the Red Deer and Oldman River basins compared to that supplied from the Mountain and Foothills portions of these basins. This is contrary to the decrease in yield with area normally found in fairly small agricultural basins. In the case of these much larger basins the changes in yield across geological and physiographic boundaries and the occurrence of sediment traps such as reservoirs leads to a more variable pattern of downstream changes in sediment yield.

The annual sediment regime of a stream closely follows the discharge regime stream except that sediment transport peaks tend to be more pronounced and of shorter duration than the annual peaks in discharge. In the Saskatchewan River basin the annual sediment regime changes downstream along the main streams. Generally, close to the Rocky Mountains, there is a single peak in May or June which is responsible for a large proportion of the annual load. Further downstream on the large Prairie streams this peak occurs in June and July and is often preceeded by a smaller peak in April due to spring runoff from Prairie tributaries. These tributaries have almost their entire annual load concentrated in this one event. These differences in regime have consequences for the magnitude and frequency characteristics of sediment transport in these streams.

The form of the daily concentration and yield duration curves varies acoss the basin. In general both the measures of graphical dispersion and skewness for these curves are greatest in the intermediate size basins close to the Rocky Mountains and in the two small Prairie-source streams. Downstream along the main rivers, as drainage area increases, the dispersion and the skewness decline. Once again the glacier-fed upper North Saskatchewan River is an exception to this pattern and has duration curves very similar to those of the large Prairie streams. It is not known why these differences occur but they are presumably related to the hydrological characteristics of the basin as well as to the sediment source dynamics.

The intermediate size basins close to the Rocky Mountains as well as the small Prairie-source streams also tend to have the most skewed cumulative load duration curves. This means that a greater proportion of the total sediment load is transported by short duration events than is the case for the larger Prairie streams. For example, for the seasonal period April to October the highest 1% of the load duration curve is responsible for between 40 and 74% of the total load in the smaller basins and between 12 and 35% of the load in the large Prairie streams and the upper North Saskatchewan River. Thus there is a considerable change in the magnitude-frequency characteristics of sediment transport downstream along the stream system. This is expected given the changes in drainage area, topography and discharge regime that occur along these streams, and agrees with previous analyses.

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FIGURE CAPTIONS

Figure 1 Physical Geography of the Saskatchewan River Basin.

(a) Drainage system and physiographic regions

(b) Relief

(c) Mean annual precipitation

(d) Mean annual runoff

(e) Natural vegetation

2 Long-Term Water Survey of Canada Sediment Monitoring Stations

3 Mean seasonal suspended sediment load at WSC sediment stations

4 Cumulative deviation from the mean annual sediment load from 1963 to 1983 at selected stations.

5 Mean seasonal suspended sediment yield at WSC sediment stations.

6 Mean seasonal suspended sediment yield versus potential sediment contributing area. Stations are identified by abbreviated WSC station numbers.

7 Mean seasonal suspended sediment yield versus potential sediment contributing area for sub-basins. Stations are identified by abbreviated WSC station numbers.

8 Annual load/flow ratio at WSC sediment stations.

9 Annual flow and load regimes for selected stations.

10 Patterns of seasonal hysteresis in the relationship between monthly flow and monthly load.

11 Daily suspended sediment yield duration curves for selected stations.

12 Daily suspended sediment sediment concentration duration curves for selected stations.

13 Cumulative load duration curves for selected stations.

14 Relationship between the cumulative proprtion of the total load transported in 1% of the time and the dispersion and skewness of the daily discharge duration curve.

TABLE 1: Long-Term Continuous and Seasonal Sediment Stations in the Saskatchewan River Basin

Station Name	Station Number	Drainage Area (km^2)	Period of Sediment Record Continuous	Seasonal
Crowsnest River at Frank	05AA008	402	1978	1976-77, 1979-80
Oldman River near Waldron's Corner	05AA023	1 440	1977-78	1976, 1979-83
Oldman River near Brocket	05AA024	4 400	1967-78	1966, 1979-83
Willow Creek near Claresholm	05AB021	1 100	1965-74	1964
Willow Creek above Chain Lakes	05AB028	162	1967-77	1965-66
Oldman River near Lethbridge	05AD007	17 000	1973-78	1972, 1979-83
South Saskatchewan River at Highway #41	05AK001	66 000	1967-78	1966, 1979-83
Marmot Creek Main Stem near Seebe	05BF016	9	1964-78	1963, 1979-83
Bow River at Calgary	05BH004	7 860	1973-78	1972, 1981
Elbow River at Bragg Creek	05BJ004	792	-	1968-69, 1971-75
Highwood River near the mouth	05BL024	3 990	1972-78	1970-71, 1979-80
Red Deer River at Red Deer	05CC002	11 600	1972-73, 1978	1971, 1974-77, 1979-83
Red Deer River at Drumheller	05CE001	24 800	1977-78	1975-76, 1979-83
Red Deer River near Bindloss	05CK004	44 700	1967-78	1966, 1979-83
South Saskatchewan River near Lemsford	05HB001	119 000	1962-70	1966
Swift Current Creek near the mouth	05HD037	3 910	-	1965-72
South Saskatchewan River near Outlook	05HF001	136 000	-	1948-52, 1955-61
South Saskatchewan River at Saskatoon	05HG001	141 000	1962-71	1961
North Saskatchewan River at Whirlpool Point	05DA009	1 920	1973-75, 1977-78	1972, 1976, 1979-81
North Saskatchewan River at Prince Albert	05GG001	131 000	1963-75, 1977-78	1958, 1962, 1979-83
Carrot River near Smoky Burn	05KC001	9 250	-	1972, 1974-79
Saskatchewan River below Tobin Lake	05KD003	289 000	1966, 1969-70	1965, 1967-68
Saskatchewan River at The Pas	05KJ001	347 000	1963-1983	1954-61, 1962

TABLE 2: Mean Seasonal Sediment Load and Discharge

Station Name	Station Number	Mean Seasonal Total Discharge (dam^3)	Seasonal Sediment Load		
			Mean (tonnes)	Std. error (%)	Skewness
Crowsnest River at Frank	05AA008	107 800	2 500	23.2	-0.41
Oldman River near Waldron's Corner	05AA023	307 000	17 000	46.1	1.33
Oldman River near Brocket	05AA024	1 129 000	260 000	28.5	1.66
Willow Creek near Claresholm	05AB021	96 600	53 000	37.0	1.70
Willow Creek above Chain Lakes	05AB028	31 800	6 000	45.2	1.86
Oldman River near Lethbridge	05AD007	2 015 000	1 451 000	32.5	1.63
South Saskatchewan River at Highway #41	05AK001	4 492 000	2 786 000	18.3	0.94
Marmot Creek Main Stem near Seebe	05BF016	3 740	25	24.5	2.64
Bow River at Calgary	05BH004	2 107 000	28 200	27.6	0.64
Elbow River at Bragg Creek	05BJ004	226 000	23 300	36.7	0.90
Highwood River near the mouth	05BL024	561 000	124 000	28.2	0.67
Red Deer River at Red Deer	05CC002	1 129 000	213 000	27.4	1.39
Red Deer River at Drumheller	05CE001	1 174 000	572 000	20.8	0.35
Red Deer River near Bindloss	05CK004	1 634 000	2 000 000	18.5	1.05
South Saskatchewan River near Lemsford	05HB001	7 022 000	6 020 000	18.3	0.21
Swift Current Creek near the mouth	05HD037	80 000	67 000	52.2	1.41
South Saskatchewan River near Outlook	05HF001	7 831 000	5 270 000	31.6	1.24
South Saskatchewan River at Saskatoon	05HG001(1962-66	6 924 000	2 700 000	19.3	0.18
	(1967-71	4 290 000	568 000	61.3	1.42
North Saskatchewan River at Whirlpool Point	05DA009	1 480 000	235 000	6.1	-1.50
North Saskatchewan River at Prince Albert	05GG001	6 455 000	3 070 000	20.6	1.33
Carrot River near Smoky Burn	05KC001	294 000	156 000	33.7	1.99
Saskatchewan River below Tobin Lake	05KD003	10 820 000	92 000	30.5	1.04
Saskatchewan River at The Pas	05KJ001	19 060 000	2 110 000	15.7	-0.10

TABLE 3: Graphical Dispersion and Skewness of Daily Sediment Yield and Concentration Duration Curves

Station Name	Station Number	Daily Suspended Sediment Yield (t km^{-2})		Daily Suspended Sediment Concentration (mg l^{-1})	
		Dispersion	Skewness	Dispersion	Skewness
Crowsnest River at Frank	05AA008	23.1	0.95	9.3	0.25
Oldman River near Waldron's Corner	05AA023	81.3	1.06	14.8	0.99
Oldman River near Brocket	05AA024	156.6	1.41	29.3	0.85
Willow Creek near Claresholm	05AB021	204.7	1.42	42.2	0.60
Willow Creek above Chain Lakes	05AB028	188.1	1.75	24.4	1.00
Oldman River near Lethbridge	05AD007	139.7	1.79	20.7	1.11
South Saskatchewan River at Highway #41	05AK001	125.6	0.83	29.0	0.38
Marmot Creek Main Stem near Seebe	05BF016	13.5	1.36	6.2	1.18
Bow River at Calgary	05BH004	18.5	0.95	8.6	0.56
Elbow River at Bragg Creek	05BJ004	75.8	1.95	21.1	1.63
Highwood River near the mouth	05BL024	127.8	1.73	31.8	1.04
Red Deer River at Red Deer	05CC002	123.9	0.90	29.3	0.73
Red Deer River at Drumheller	05CE001	79.9	0.77	38.1	0.60
Red Deer River near Bindloss	05CK004	57.1	0.65	13.5	0.45
South Saskatchewan River near Lemsford	05HB001	48.2	0.41	12.1	0.03
Swift Current Creek near the mouth	05HD037	292.6	2.42	37.6	1.12
South Saskatchewan River at Saskatoon	05HG001(1962-63	44.0	0.57	13.2	0.28
	(1967-71	97.4	0.41	17.1	0.31
North Saskatchewan River at Whirlpool Point	05DA009	40.9	-0.85	11.0	-0.34
North Saskatchewan River at Prince Albert	05GG001	46.6	1.02	8.8	0.41
Carrot River near Smoky Burn	05KC001	145.1	2.77	14.3	0.64
Saskatchewan River at The Pas	05KJ001	18.1	-0.17	6.9	-0.34

TABLE 4: Percentage of the Seasonal Load Transported During the Highest Four and Thirty-six Consecutive Days

Station Name	Station Number	Mean Percentage of Seasonal Load Transported During Highest Four Consecutive Days	Mean Percentage of Seasonal Load Transported During Highest Thirty-six Consecutive Days
Crowsnest River at Frank	05AA008	13.7	26.7
Oldman River near Waldron's Corner	05AA023	22.5	65.3
Oldman River near Brocket	05AA024	28.3	65.8
Willow Creek near Claresholm	05AB021	33.4	67.9
Willow Creek above Chain Lakes	05AB028	39.8	70.2
Oldman River near Lethbridge	05AD007	22.7	66.2
South Saskatchewan River at Highway #41	05AK001	19.6	63.7
Marmot Creek Main Stem near Seebe	05BF016	22.0	64.5
Bow River at Calgary	05BH004	10.2	44.1
Elbow River at Bragg Creek	05BJ004	34.8	87.1
Highwood River near the mouth	05BL024	32.4	70.8
Red Deer River at Red Deer	05CC002	24.3	56.6
Red Deer River at Drumheller	05CE001	19.6	45.2
Red Deer River near Bindloss	05CK004	15.6	48.9
South Saskatchewan River near Lemsford	05HB001	15.7	48.5
Swift Current Creek near the mouth	05HD037	36.7	90.2
South Saskatchewan River near Outlook	05HF001	10.2	41.2
South Saskatchewan River at Saskatoon	05HG001 (1967-71)	10.0	47.9
North Saskatchewan River at Whirlpool Point	05DA009	10.6	33.1
North Saskatchewan River at Prince Albert	05GG001	11.7	45.7
Carrot River near Smoky Burn	05KC001	24.5	84.8
Saskatchewan River below Tobin Lake	05KD003	3.9	24.4
Saskatchewan River at The Pas	05KJ001	7.2	35.2

TABLE 5: Percentage of the Seasonal Load Transported in 0.1, 1 and 5% of the Time

Station Name	Station Number	Percentage of Seasonal Load Transported in Percentage of Time 0.1%	1%	5%
Crowsnest River at Frank	05AA008	5	30	60
Oldman River near Waldron's Corner	05AA023	18	62	82
Oldman River near Brocket	05AA024	20	55	81
Willow Creek near Claresholm	05AB021	15	55	82
Willow Creek above Chain lakes	05AB028	20	74	91
Oldman River near Lethbridge	05AD007	18	48	78
South Saskatchewan River at Highway #41	05AK001	8	35	62
Marmot Creek Main Stem near Seebe	05BF016	15	45	65
Bow River at Calgary	05BH004	5	30	55
Elbow River at Bragg Creek	05BJ004	8	48	82
Highwood River near the mouth	05BL024	11	42	78
Red Deer River at Red Deer	05CC002	12	42	73
Red Deer River at Drumheller	05CE001	5	28	61
Red Deer River near Bindloss	05CK004	6	32	63
South Saskatchewan River near Lemsford	05HB001	4	23	52
Swift Current Creek near the mouth	05HD037	15	70	95
South Saskatchewan River near Outlook	05HF001	2	15	40
South Saskatchewan River at Saskatoon	05HG001 (1962-63	3	30	60
	(1967-71	10	50	73
North Saskatchewan River at Whirlpool Point	05DA009	2	12	30
North Saskatchewan River at Prince Albert	05GG001	5	25	52
Carrot River near Smoky Burn	05KC001	5	50	85
Saskatchewan River below Tobin Lake	05KD003	1	10	30
Saskatchewan River at The Pas	05KJ001	2	12	32

Fig. 1(a)

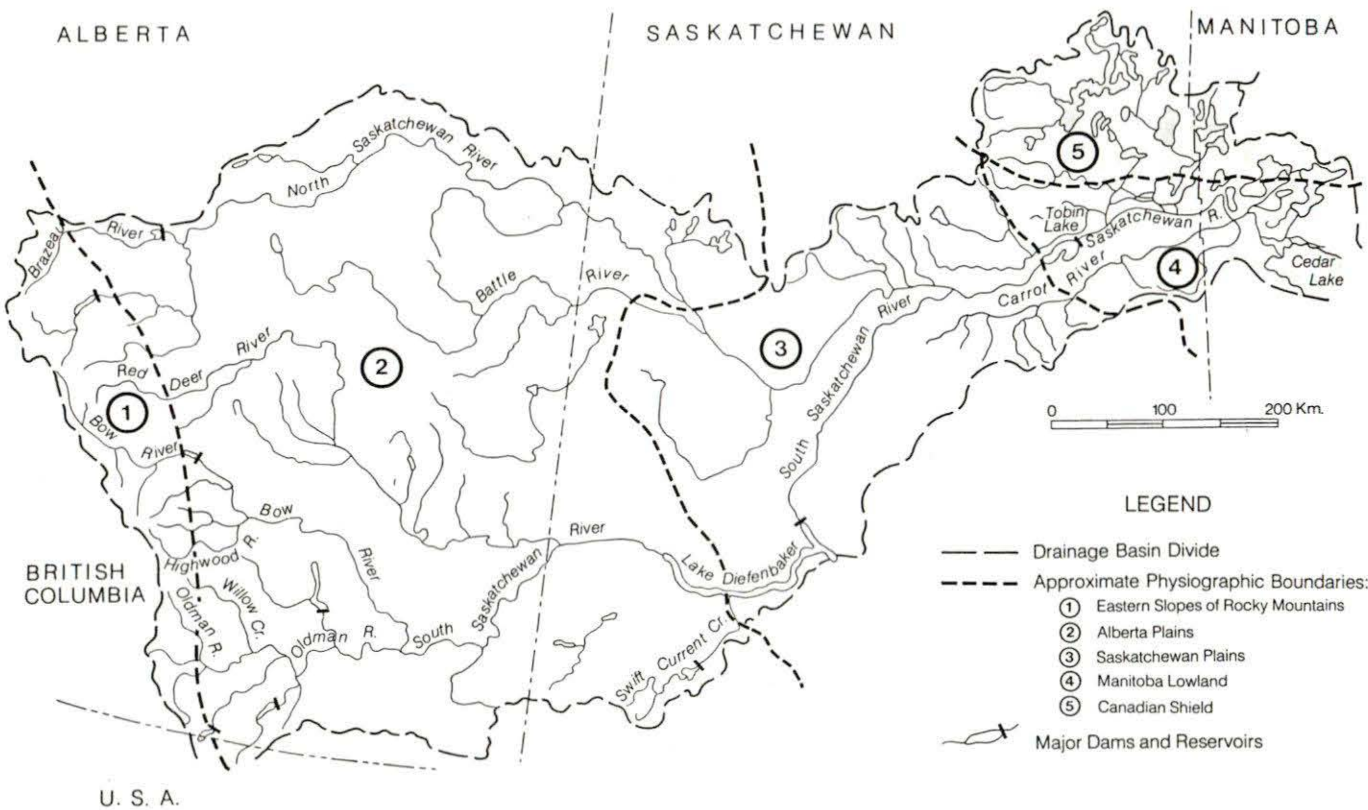
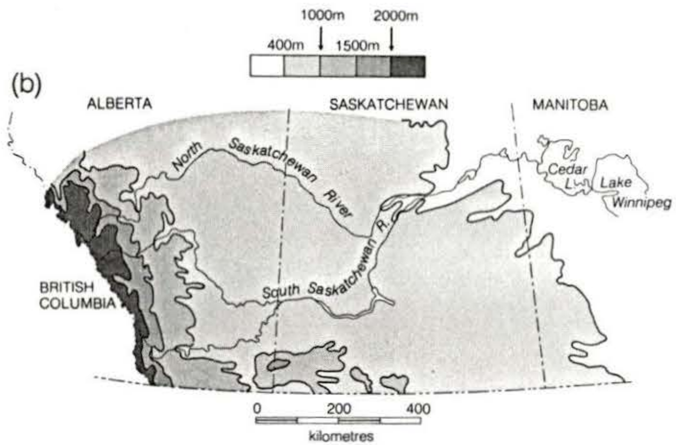
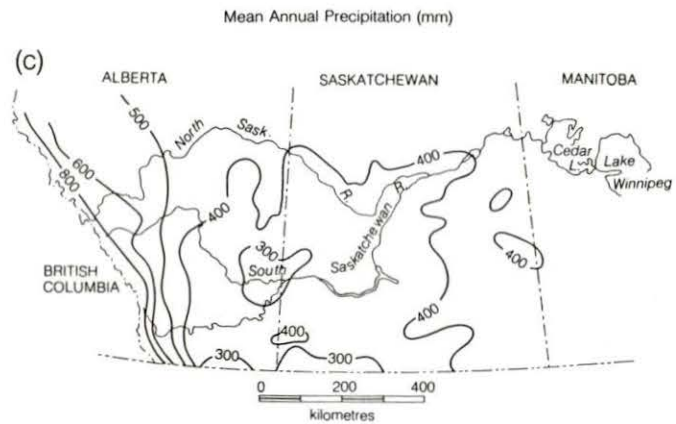
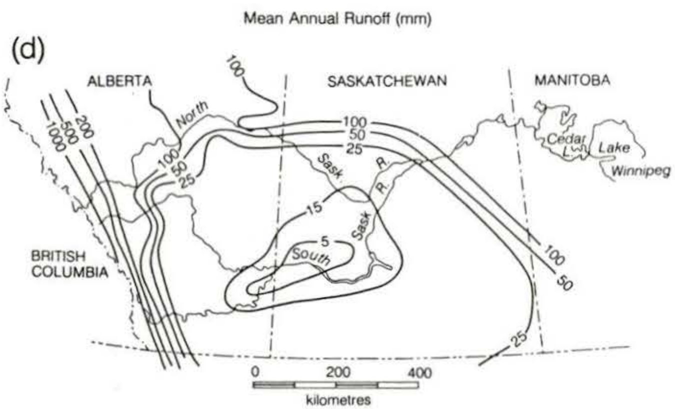

ALBERTA
SASKATCHEWAN
MANITOBA
BRITISH COLUMBIA
U. S. A.
North Saskatchewan River
Brazeau River
Battle River
Red Deer River
Bow River
Highwood R.
Willow Cr.
Oldman R.
South Saskatchewan River
Lake Diefenbaker
Swift Current Cr.
Saskatchewan R.
Tobin Lake
Carrot River
Cedar Lake
0 100 200 Km.
LEGEND
Drainage Basin Divide
Approximate Physiographic Boundaries:
1 Eastern Slopes of Rocky Mountains
2 Alberta Plains
3 Saskatchewan Plains
4 Manitoba Lowland
5 Canadian Shield
Major Dams and Reservoirs

Fig. 1 contd.

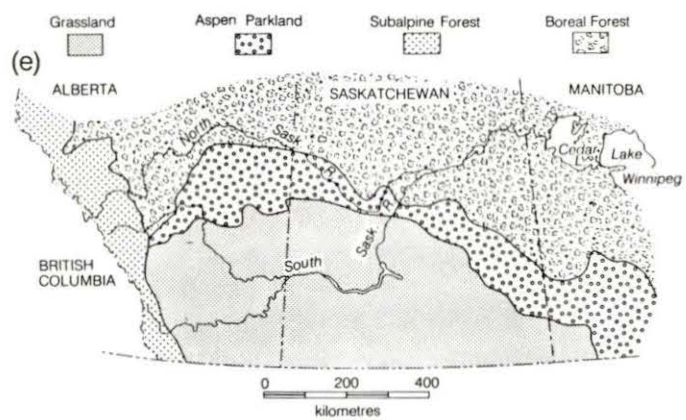




Source: Hydrological Atlas of Canada, 1978



Source: Hydrological Atlas of Canada, 1978



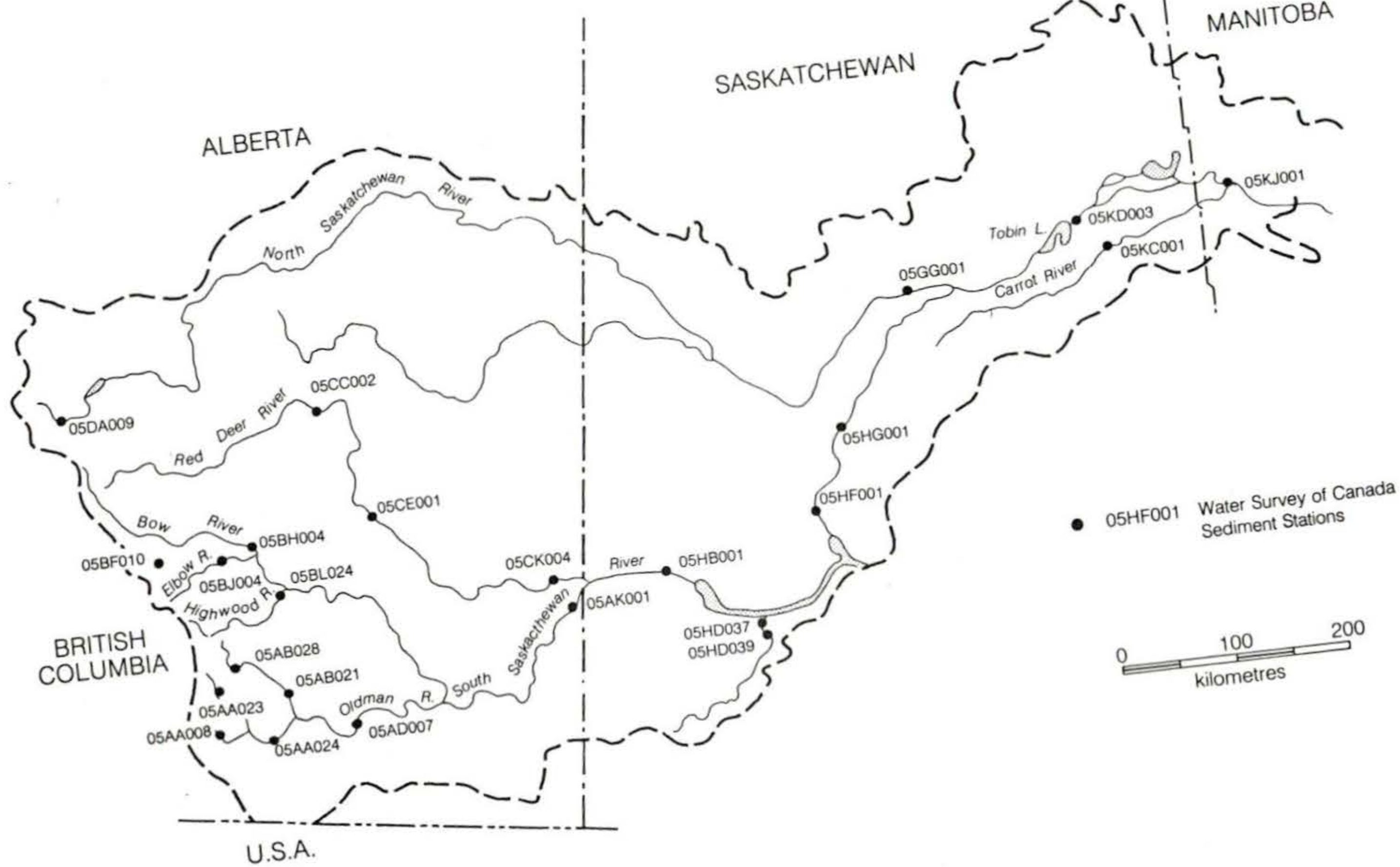
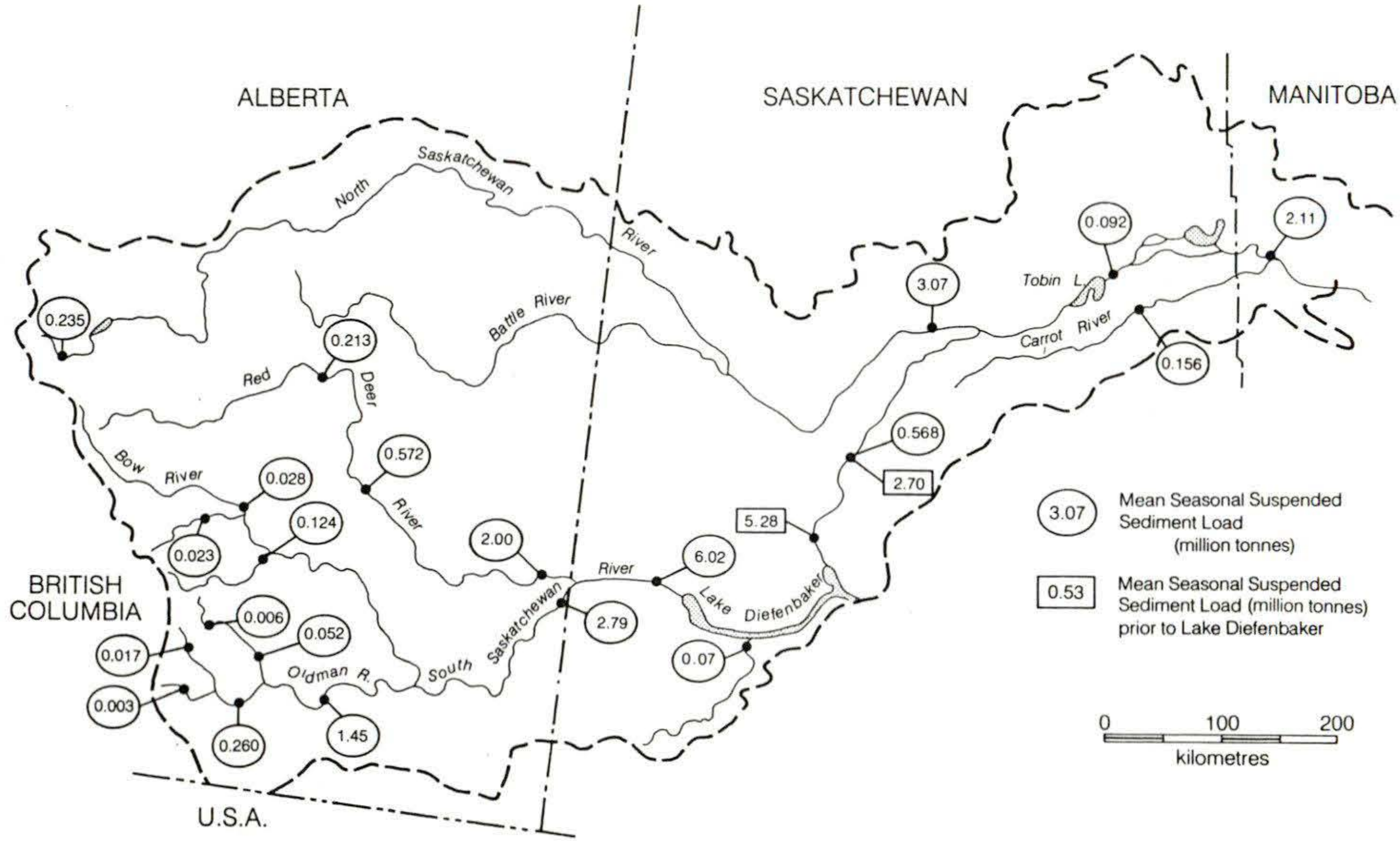
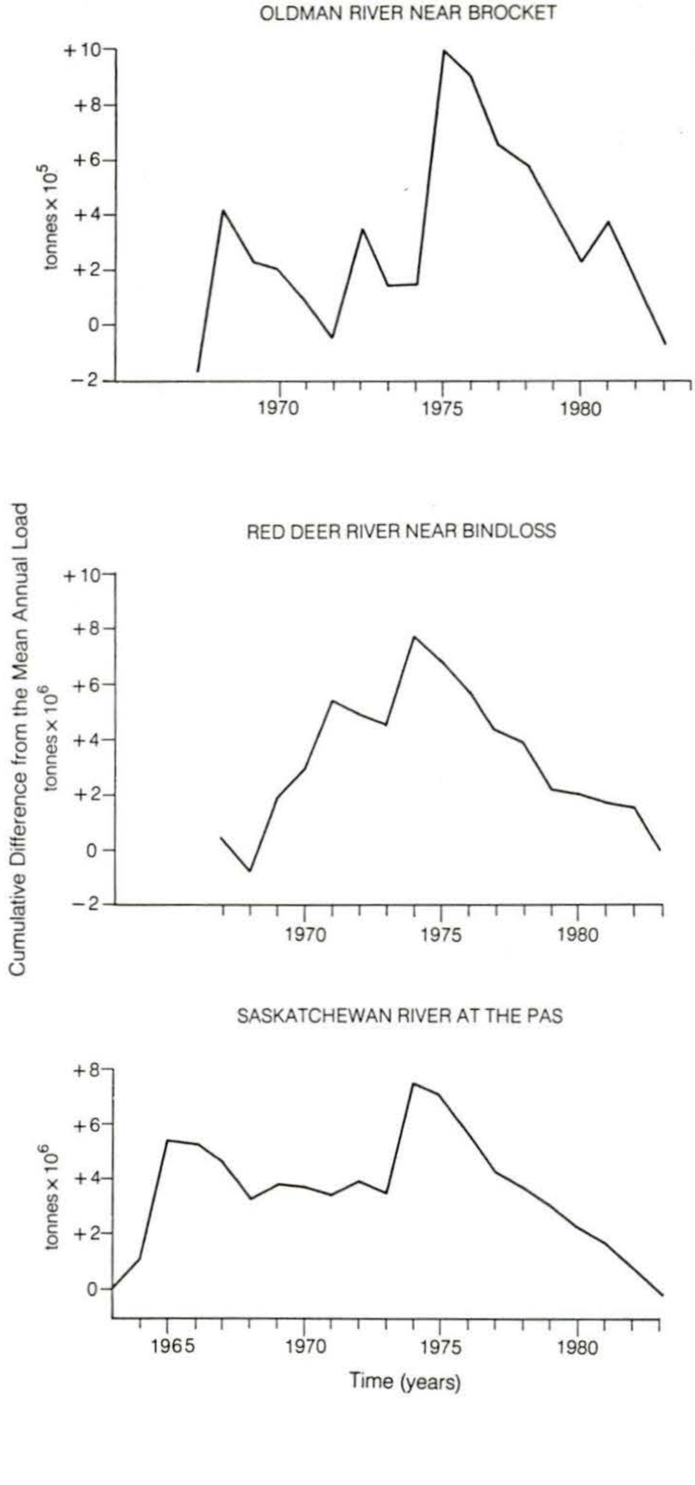

ALBERTA
SASKATCHEWAN
MANITOBA
BRITISH COLUMBIA
U.S.A.
North Saskatchewan River
Red Deer River
Bow River
Elbow R.
Highwood R.
Oldman R.
South Saskatchewan River
Tobin L.
Carrot River
05DA009
05CC002
05CE001
05BH004
05BF010
05BJ004
05BL024
05AB028
05AB021
05AA023
05AA008
05AA024
05AD007
05CK004
05AK001
05HB001
05HD037
05HD039
05HF001
05HG001
05GG001
05KD003
05KC001
05KJ001
05HF001 Water Survey of Canada Sediment Stations
0
100
200
kilometres

Fig. 3



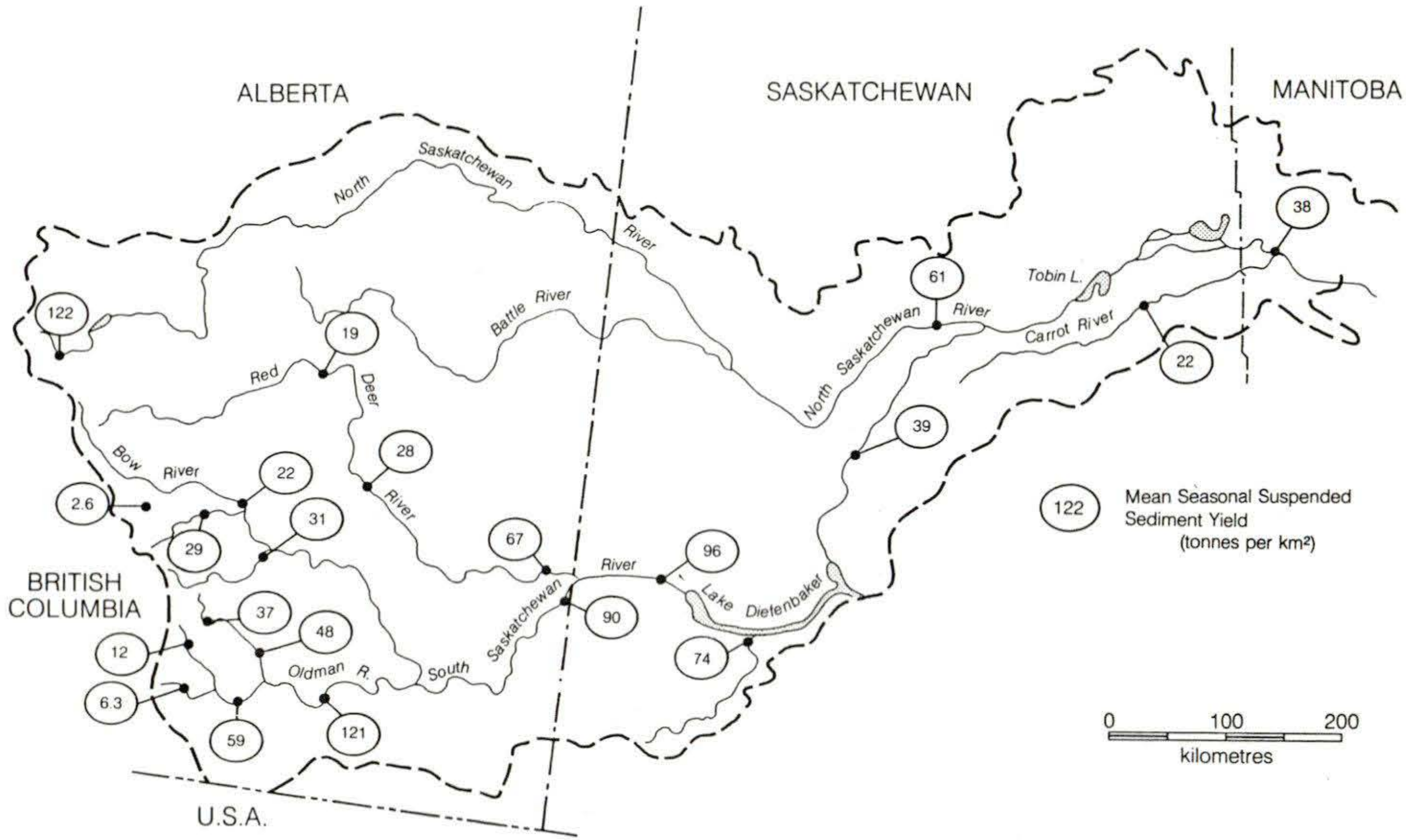
ALBERTA
SASKATCHEWAN
MANITOBA
BRITISH COLUMBIA
U.S.A.
North Saskatchewan River
Battle River
Red Deer River
Bow River
Oldman R.
South Saskatchewan River
Lake Diefenbaker
Tobin L.
Carrot River
0.235
0.213
0.572
0.028
0.124
0.023
2.00
2.79
6.02
0.006
0.052
0.017
0.003
0.260
1.45
0.07
5.28
0.568
2.70
3.07
0.092
2.11
0.156
3.07 Mean Seasonal Suspended Sediment Load (million tonnes)
0.53 Mean Seasonal Suspended Sediment Load (million tonnes) prior to Lake Diefenbaker
0 100 200
kilometres

Fig. 4



OLDMAN RIVER NEAR BROCKET
tonnes x 10^5
+10
+8
+6
+4
+2
0
−2
1970
1975
1980
RED DEER RIVER NEAR BINDLOSS
Cumulative Difference from the Mean Annual Load
tonnes x 10^6
+10
+8
+6
+4
+2
0
−2
1970
1975
1980
SASKATCHEWAN RIVER AT THE PAS
tonnes x 10^6
+8
+6
+4
+2
0
1965
1970
1975
1980
Time (years)

Fig. 5


ALBERTA
SASKATCHEWAN
MANITOBA
BRITISH COLUMBIA
U.S.A.
North Saskatchewan River
Battle River
Red Deer River
Bow River
Oldman R.
South Saskatchewan River
Lake Diefenbaker
Tobin L.
Carrot River
122
19
28
22
2.6
29
31
67
37
48
12
6.3
59
121
90
96
74
61
39
38
22
Mean Seasonal Suspended Sediment Yield (tonnes per km²)
0 100 200
kilometres

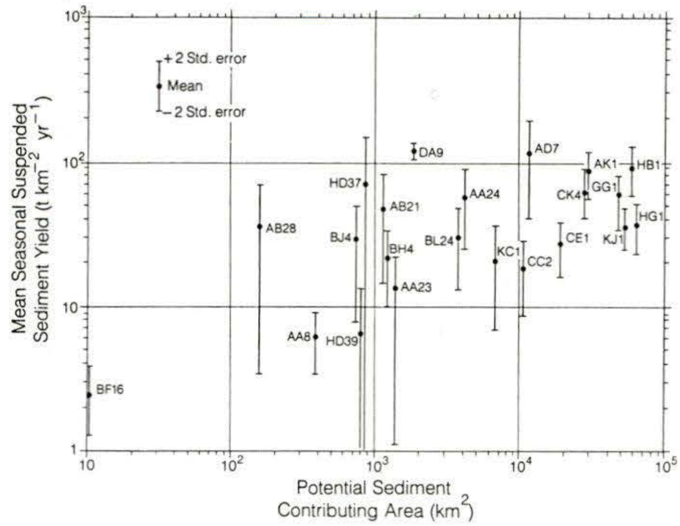

+2 Std. error
Mean
−2 Std. error
Mean Seasonal Suspended Sediment Yield (t km^{-2} yr^{-1})
Potential Sediment Contributing Area (km^2)
BF16
AB28
AA8
HD39
BJ4
HD37
AB21
BH4
AA23
DA9
BL24
AA24
KC1
CC2
AD7
CE1
CK4
AK1
GG1
KJ1
HB1
HG1

Fig. 6.

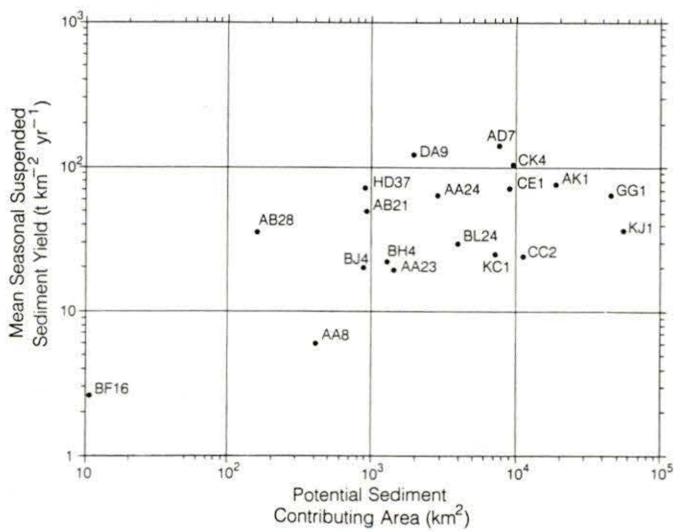

Mean Seasonal Suspended Sediment Yield (t km^{-2} yr^{-1})
Potential Sediment Contributing Area (km^2)
BF16
AA8
AB28
BJ4
BH4
AA23
HD37
AB21
DA9
AA24
BL24
KC1
CC2
AD7
CK4
CE1
AK1
GG1
KJ1

Fig. 7

Fig. 8

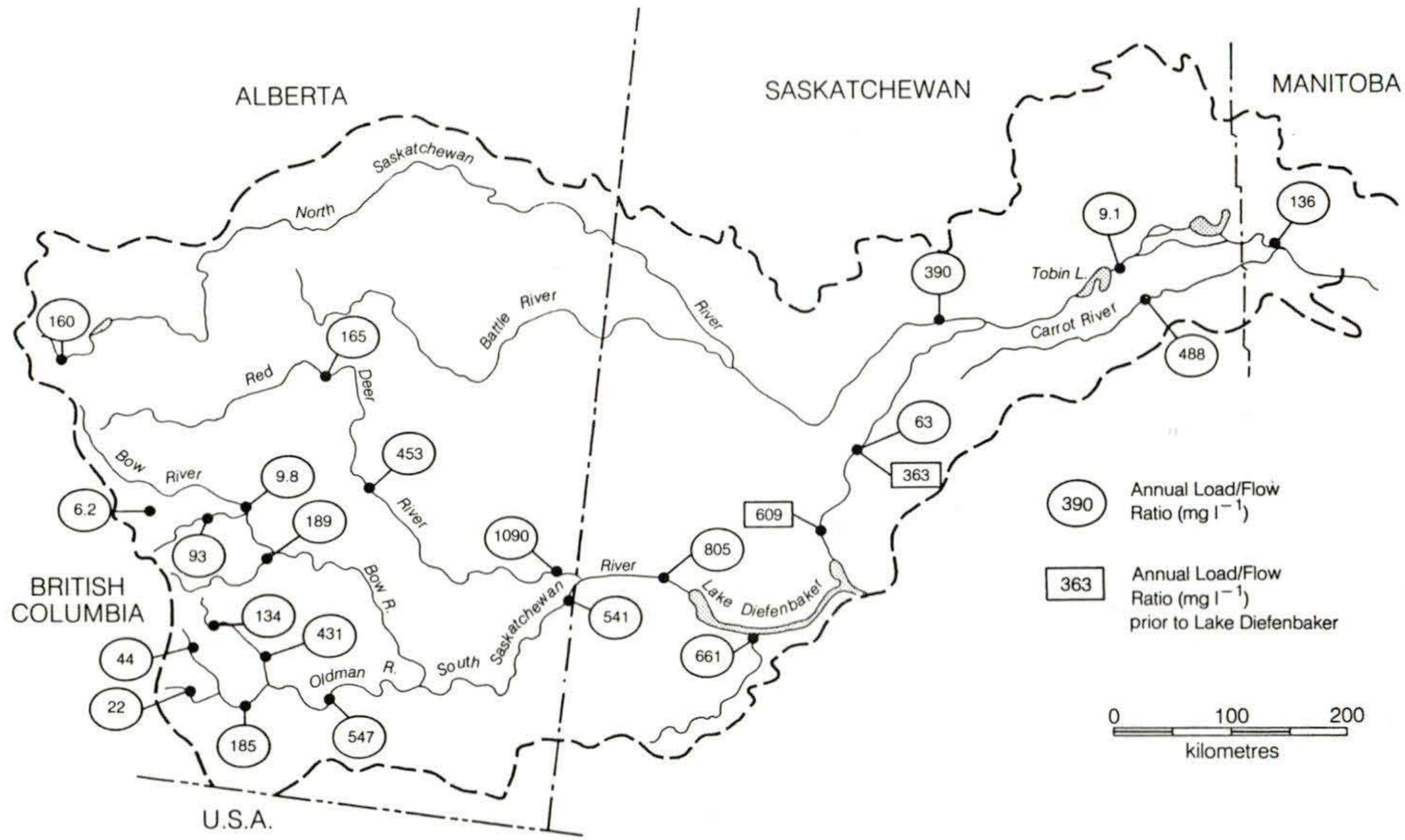
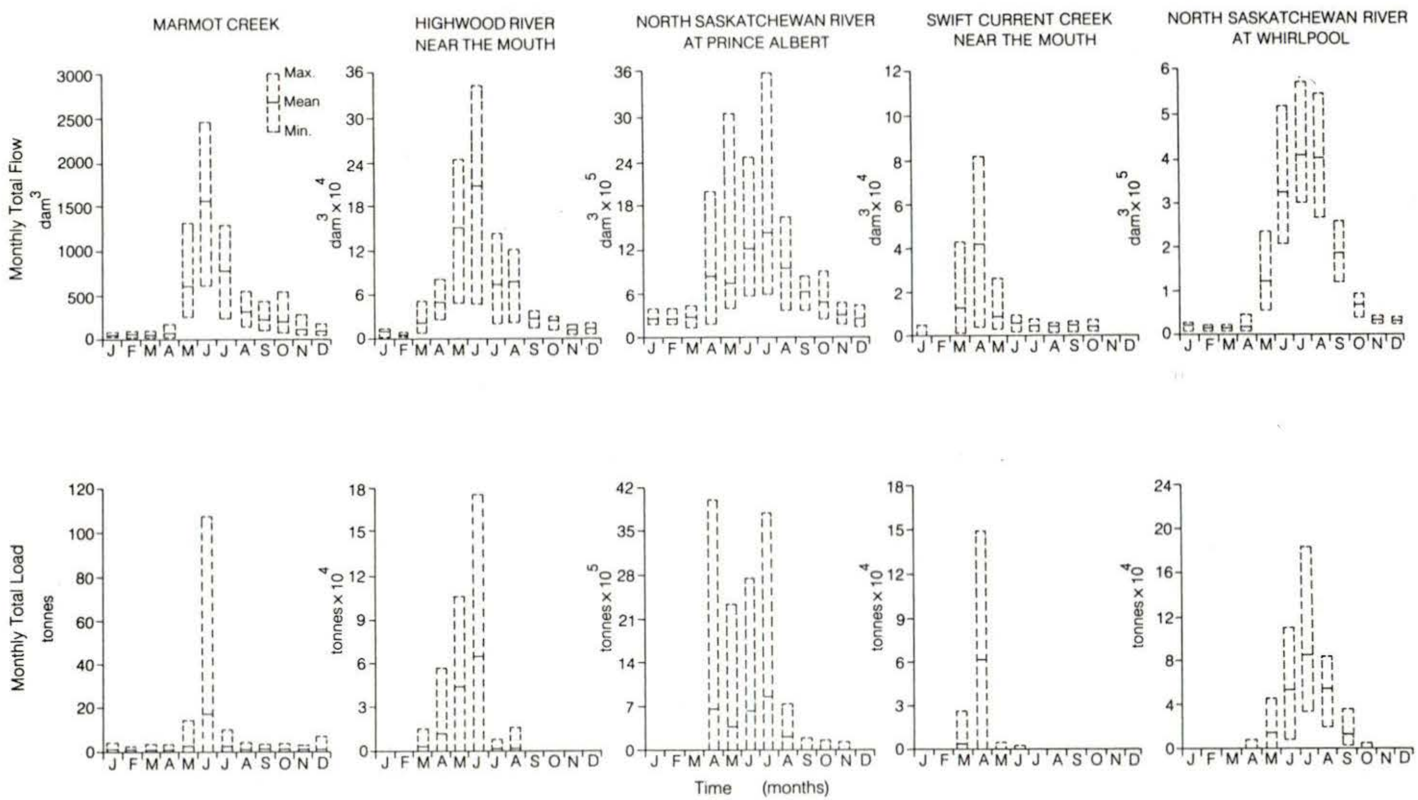
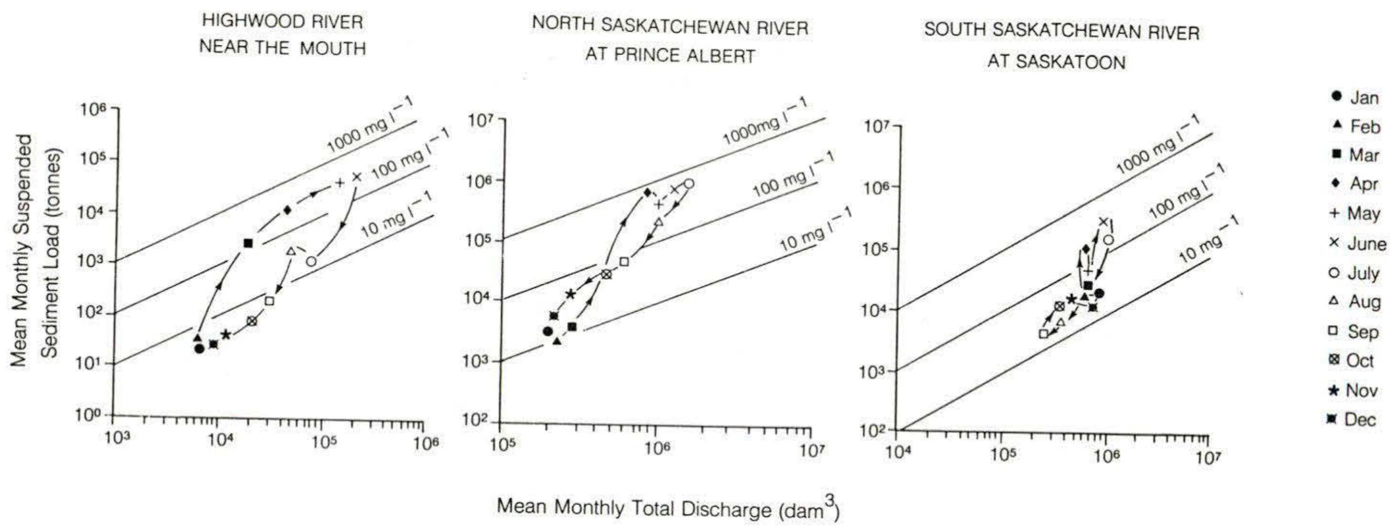

ALBERTA
SASKATCHEWAN
MANITOBA
BRITISH COLUMBIA
U.S.A.
North Saskatchewan River
Battle River
Red Deer River
Bow River
Bow R.
Oldman R.
South Saskatchewan River
Lake Diefenbaker
Carrot River
Tobin L.
160
165
453
1090
9.8
189
6.2
93
134
431
44
22
185
547
541
805
661
609
63
363
390
9.1
136
488
390 Annual Load/Flow Ratio (mg l⁻¹)
363 Annual Load/Flow Ratio (mg l⁻¹) prior to Lake Diefenbaker
0 100 200
kilometres

Fig. 9



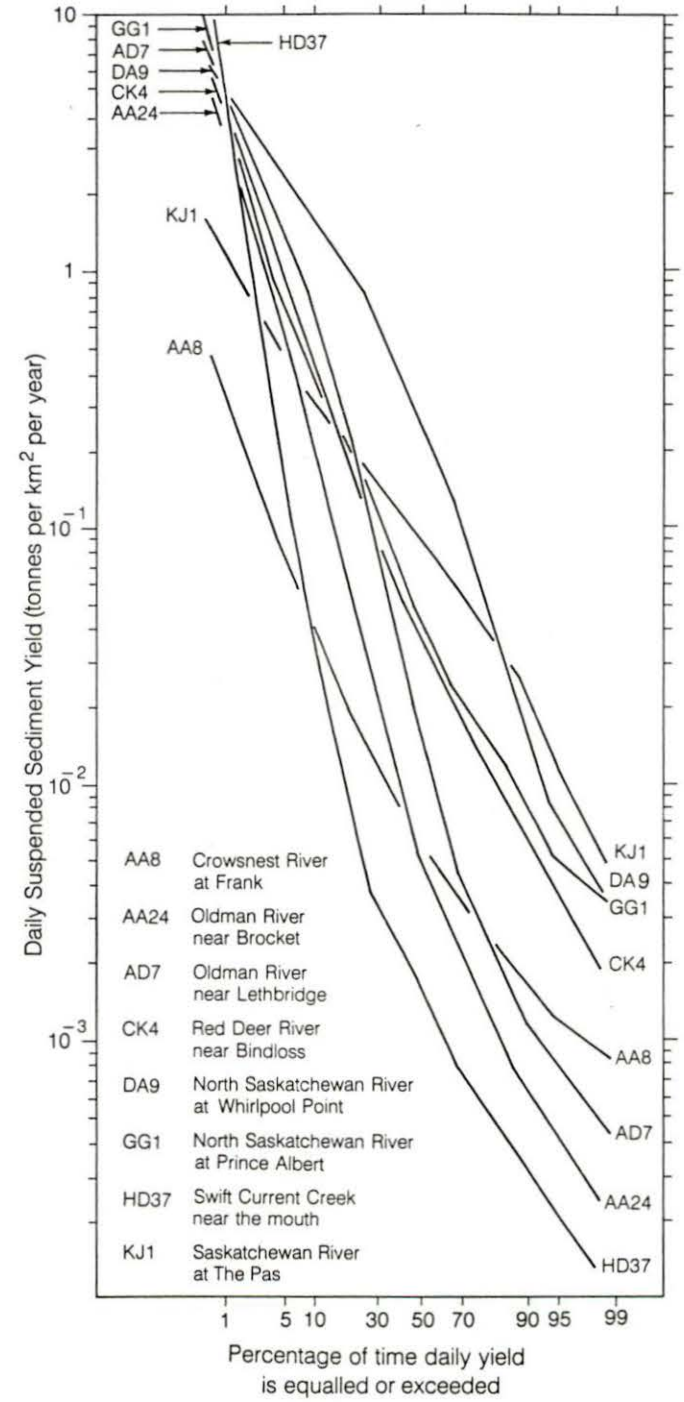
MARMOT CREEK
HIGHWOOD RIVER NEAR THE MOUTH
NORTH SASKATCHEWAN RIVER AT PRINCE ALBERT
SWIFT CURRENT CREEK NEAR THE MOUTH
NORTH SASKATCHEWAN RIVER AT WHIRLPOOL
Max.
Mean
Min.
Monthly Total Flow
dam3
dam3 × 10^4
dam3 × 10^5
Monthly Total Load
tonnes
tonnes × 10^4
tonnes × 10^5
J F M A M J J A S O N D
Time (months)

Fig. 10



HIGHWOOD RIVER
NEAR THE MOUTH
NORTH SASKATCHEWAN RIVER
AT PRINCE ALBERT
SOUTH SASKATCHEWAN RIVER
AT SASKATOON
Mean Monthly Suspended Sediment Load (tonnes)
Mean Monthly Total Discharge (dam3)
1000 mg l−1
100 mg l−1
10 mg l−1
Jan
Feb
Mar
Apr
May
June
July
Aug
Sep
Oct
Nov
Dec

Fig. 11



10
1
10^-1
10^-2
10^-3
Daily Suspended Sediment Yield (tonnes per km² per year)
GG1
AD7
DA9
CK4
AA24
HD37
KJ1
AA8
KJ1
DA9
GG1
CK4
AA8
AD7
AA24
HD37
AA8 Crowsnest River at Frank
AA24 Oldman River near Brocket
AD7 Oldman River near Lethbridge
CK4 Red Deer River near Bindloss
DA9 North Saskatchewan River at Whirlpool Point
GG1 North Saskatchewan River at Prince Albert
HD37 Swift Current Creek near the mouth
KJ1 Saskatchewan River at The Pas
1
5
10
30
50
70
90
95
99
Percentage of time daily yield is equalled or exceeded

Fig. 12

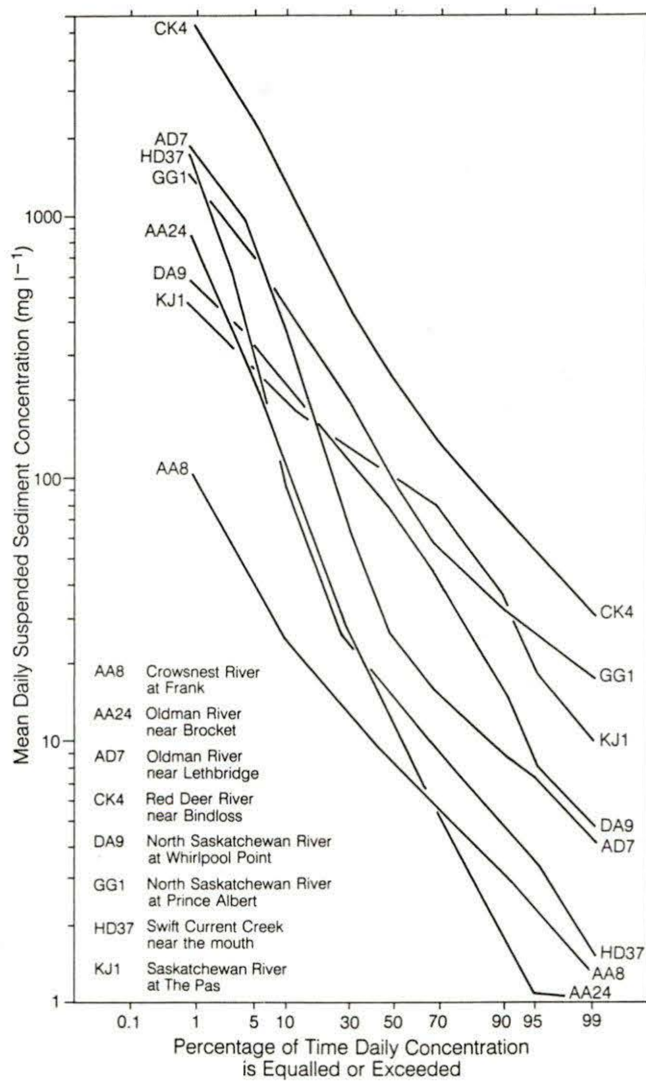
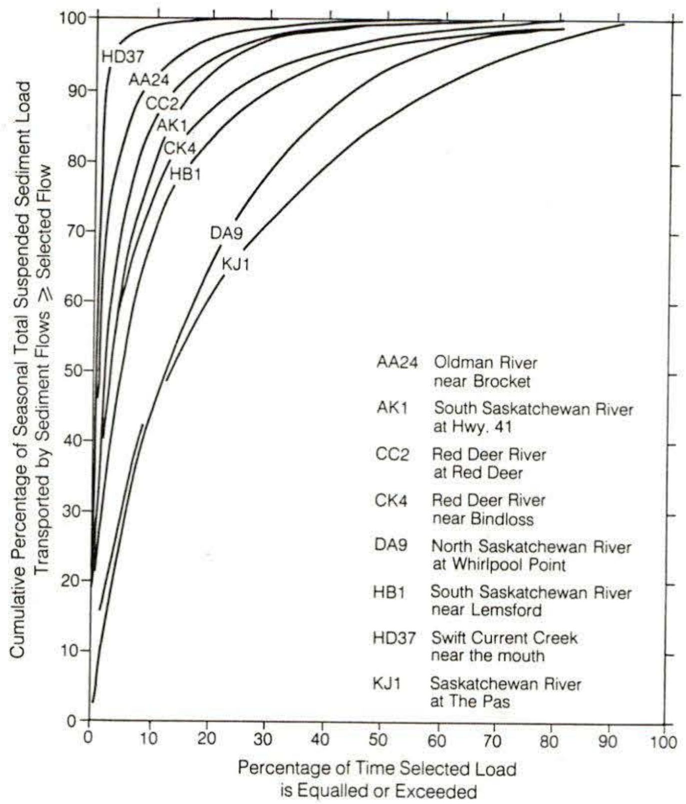
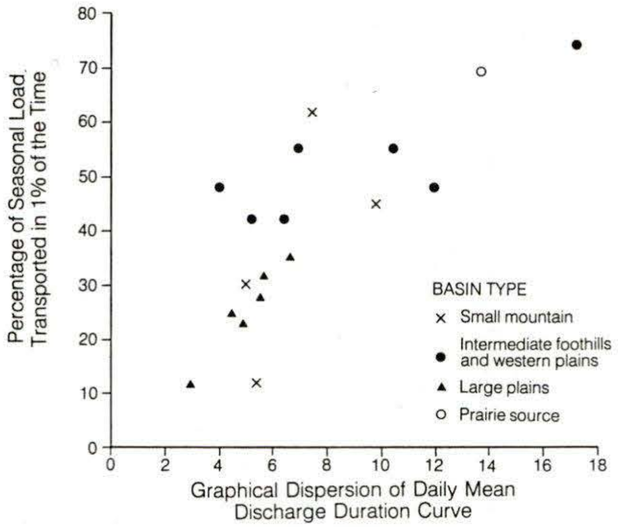

CK4
AD7
HD37
GG1
AA24
DA9
KJ1
AA8
CK4
GG1
KJ1
DA9
AD7
HD37
AA8
AA24
1000
100
10
1
0.1
1
5
10
30
50
70
90
95
99
Mean Daily Suspended Sediment Concentration (mg l⁻¹)
Percentage of Time Daily Concentration is Equalled or Exceeded
AA8 Crowsnest River at Frank
AA24 Oldman River near Brocket
AD7 Oldman River near Lethbridge
CK4 Red Deer River near Bindloss
DA9 North Saskatchewan River at Whirlpool Point
GG1 North Saskatchewan River at Prince Albert
HD37 Swift Current Creek near the mouth
KJ1 Saskatchewan River at The Pas

Fig. 13

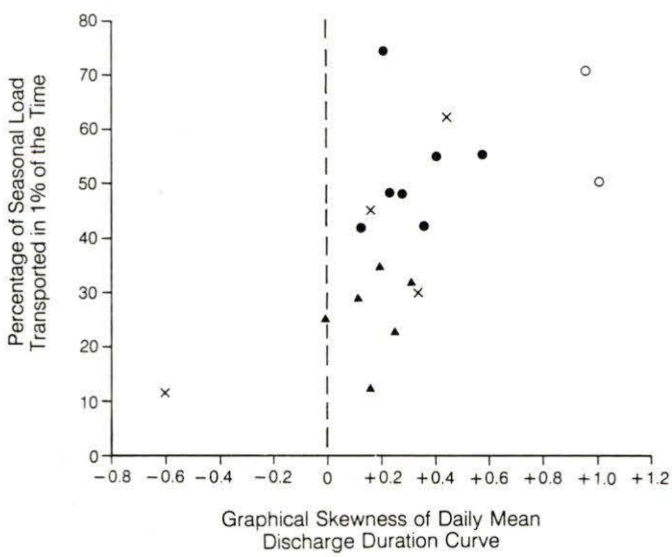


Cumulative Percentage of Seasonal Total Suspended Sediment Load Transported by Sediment Flows ≥ Selected Flow
Percentage of Time Selected Load is Equalled or Exceeded
0
10
20
30
40
50
60
70
80
90
100
HD37
AA24
CC2
AK1
CK4
HB1
DA9
KJ1
AA24 Oldman River near Brocket
AK1 South Saskatchewan River at Hwy. 41
CC2 Red Deer River at Red Deer
CK4 Red Deer River near Bindloss
DA9 North Saskatchewan River at Whirlpool Point
HB1 South Saskatchewan River near Lemsford
HD37 Swift Current Creek near the mouth
KJ1 Saskatchewan River at The Pas

Fig. 14



Percentage of Seasonal Load Transported in 1% of the Time
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
Graphical Dispersion of Daily Mean Discharge Duration Curve
BASIN TYPE
× Small mountain
● Intermediate foothills and western plains
▲ Large plains
○ Prairie source



Percentage of Seasonal Load Transported in 1% of the Time
80
70
60
50
40
30
20
10
0
−0.8
−0.6
−0.4
−0.2
0
+0.2
+0.4
+0.6
+0.8
+1.0
+1.2
Graphical Skewness of Daily Mean Discharge Duration Curve