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Spatial and Temporal Patterns of Suspended-Sediment Yield in the Saskatchewan River Basin

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Spatial and temporal patterns of suspended-sediment yield in the Saskatchewan River basin

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Long-term suspended-sediment concentration and load records are available for 23 Water Survey of Canada sediment-monitoring stations in the Saskatchewan River basin, where the drainage areas range from 10 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 t km^{-2} year^{-1}) and tends to increase downstream along the North and South Saskatchewan rivers until major reservoirs in Saskatchewan intervene. Average sediment concentration shows a pattern of variation similar to that of yield. Temporal aspects of suspended-sediment transport vary along the drainage network. The range and skewness of the yield–duration 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.

Des enregistrements de longues durées portant sur la concentration et la charge des sédiments en suspension sont disponibles pour 23 stations de surveillance de la Commission des eaux du Canada implantées dans le bassin de la rivière Saskatchewan où les aires de drainage varient de 10 à plus de 300 000 km^2. La production annuelle moyenne de sédiments atteint sâ apogée dans la partie occidentale des Plaines de l'Alberta, le long des rivières Oldman et Red Deer (plus de 100 t km^{-2} année^{-1}), et elle tend à s'accroître en aval le long des rivières Saskatchewan Sud et Nord jusqu'au lieu de déversement dans les grands réservoirs. La concentration moyenne et la production des sédiments suivent un même mode de variation. Les données temporelles pour le transport des sédiments en suspension diffèrent le long du réseau de drainage. La variation et l'indice de symétrie dans les courbes de temps de la concentration et de la production des sédiments sont plus grands dans les bassins de dimension intermédiaire situés près des Rocheuses et aussi dans deux petits bassins alimentés par les cours d'eau des Prairies qu'ils le sont dans le haut de la rivière Saskatchewan Nord prenant sa source dans le glacier il en est ainsi pour les cours d'eau peu fréquents qui transportent une grande proportion de la charge annuelle vers les plus petits bassins des Foothills et des Plaines occidentales plutôt que dans les grandes rivières des Prairies à cause de versants et de régimes de débit différents.

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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 and to assess the impact of human activities on short- and long-term erosion rates. However, temporal aspects of suspended-sediment transport including inter- and intrabasin contrasts in the timing of sediment transport and the relative importance of events of different magnitudes and frequencies have received comparatively little attention (Webb and Walling 1984).

The regional patterns of sediment yield in Canada were first summarized by Stichling (1973). Subsequently, Dickinson and Wall (1977) described contrasts in the timing and magnitude–frequency characteristics of sediment load in selected basins from several regions across the country. More recently, summaries of the suspended sediment data collected at individual Water Survey of Canada stations have been published, including stations in the Saskatchewan River basin (e.g., Day and Spitzer 1985; Northwest Hydraulic Consultants Limited 1986; Ashmore 1987; Hudson and Askin 1987; Hydrocon Engineering Limited 1987).

A number of previous studies reported on sediment loads of the major rivers in the Saskatchewan River basin (Kuiper 1962; Slaymaker 1972; Slaymaker and McPherson 1973; Stichling 1973). In addition, there are several studies of the sediment yield of streams in various parts of the basin and with a wide range of drainage areas.

In some small mountain basins annual yields exceed 1000 t km^{-2} (e.g., McPherson 1971; Nanson 1974), although much of this sediment is deposited along the larger river valleys (Shaw and Kellerhals 1982). Along with the generally coarse colluvium and dense forest cover this results in relatively low sediment yields (less than 10 t km^{-2} year^{-1}) from many of the mountain drainage basins (Hudson 1983; Ashmore 1986). The larger Foothills and Plains rivers have annual sediment yields of 10–100 t km^{-2} (Stichling 1973; Luk 1975; McPherson 1975; Campbell 1977; Neill and Mollard 1982; Hudson 1983). There is a general tendency for yields to be higher in the Plains region than in the Foothills because of the large sediment supply from valley-side gullies, badlands, and slumps in the

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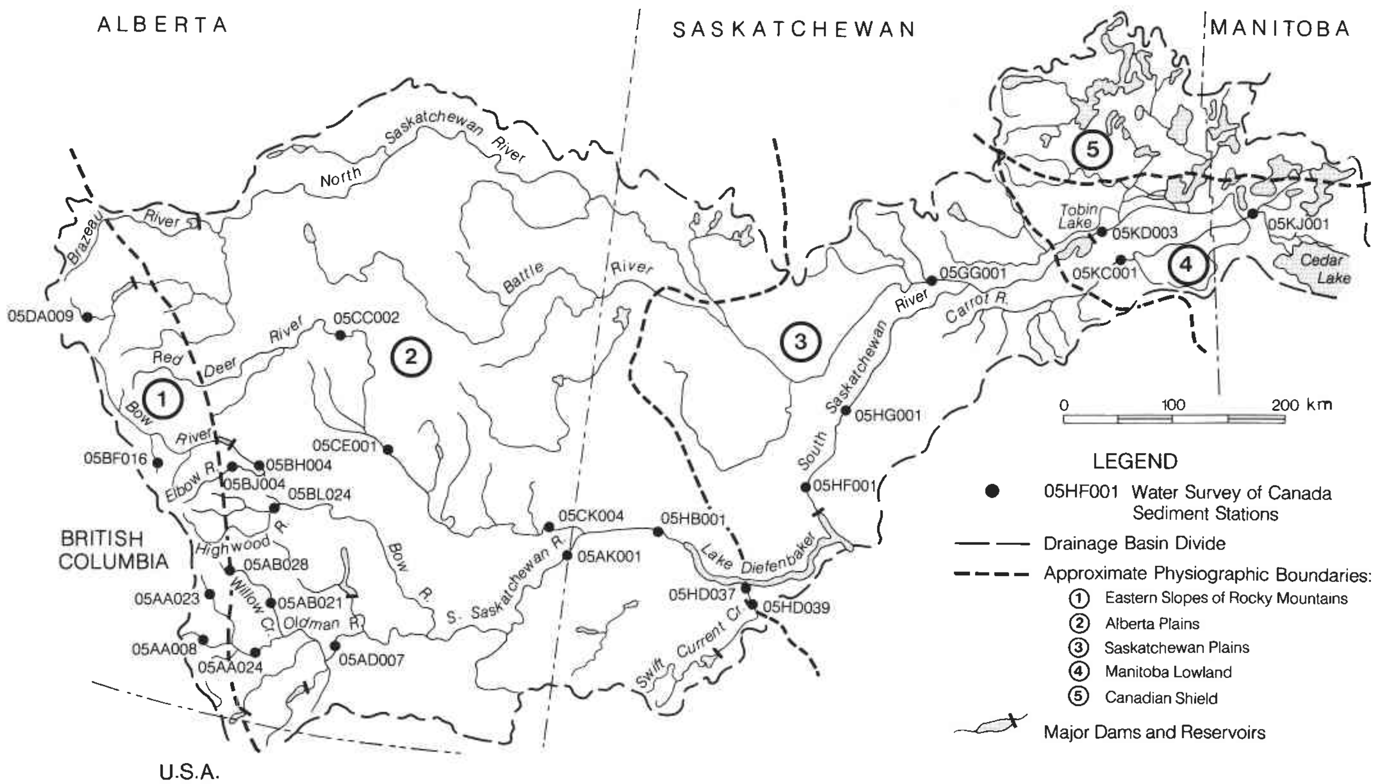

FIG. 1. Drainage system, physiographic regions, and the location of long-term Water Survey of Canada sediment stations.

glacial deposits and erodible Cretaceous sediments of the Plains. Although the general pattern of sediment yield in the region is known, the spatial and temporal variability of suspended-sediment transport has not previously been synthesized for the entire Saskatchewan River basin nor for any other major Canadian river system.

The Water Survey of Canada has operated a network of sediment stations in the Saskatchewan River basin for over 20 years. The present data base includes more stations and a longer period of record than was available for previous summaries such as Stichling's (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. Rigorous analysis of these patterns is hampered by the differing length and period of records between the various sediment stations. Reducing the records to a common period involves sacrificing large quantities of data, which would considerably reduce the accuracy and precision of the load estimates, and in some cases it is impossible because there is no overlap. Although the average annual load is sensitive to differences in the period and length of record, this is less true of the duration and magnitude–frequency characteristics, and in neither case are the consequences of the differences in period of record so severe as to alter the trends in sediment-transport regime described in the paper.

A further problem in analysis is that the station network was designed to monitor long-term sediment loads, not for the analysis and explanation of differences in sediment-transport regimes. Consequently, the sample consists of small basins in the Rocky Mountains and Foothills and much larger basins in the Prairies, making impossible the separation of the effect of drainage area from the effects of other environmental factors. Hence, this paper is largely devoted to describing the trends in sediment regime that can be identified within the 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 (Fig. 1). There are few natural lakes on the main streams of the basin except in the Cumberland Delta and the extreme northeastern 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.

The physiographic contrast between the Alberta–Saskatchewan plains and the Rocky Mountains – Foothills along the western margin of the basin is significant because of associated differences in precipitation and runoff (Figs. 2*a*–2*c*); the combined mean annual flow of the North Saskatchewan River, Red Deer River, Bow River, and Oldman River in western Alberta accounts for about 70% of the mean annual flow of the Saskatchewan River at The Pas, Manitoba. The rolling and hum-

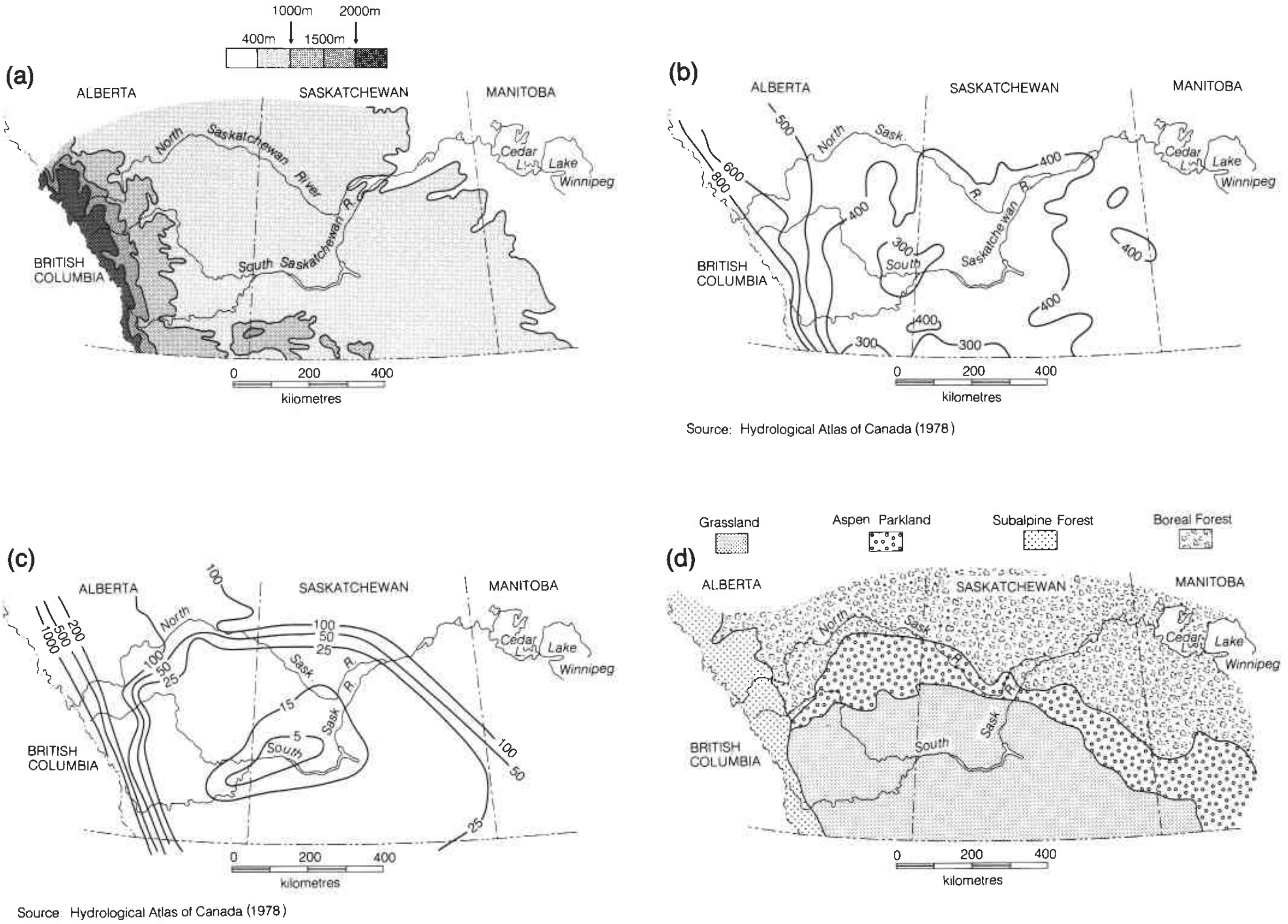

FIG. 2. Physical geography of the Saskatchewan River basin: (*a*) relief; (*b*) mean annual precipitation (mm); (*c*) mean annual runoff (mm); (*d*) natural vegetation.

mocky topography of the Prairies contains large areas that are internally drained and do not contribute sediment to the main river system.

The natural vegetation (Fig. 2*d*) is largely unaltered in the Rocky Mountains and Foothills and the northwestern portion of the Plains, but a large part of the natural grassland and parkland of the Prairie portion of the basin has been replaced by farm land.

Data

Since 1961 the Water Survey of Canada has routinely collected suspended-sediment samples at hydrometric stations in Canada. Samples are collected using standard United States Geological Survey 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, but only 20 or 30 of these may be active in any given year. At many of these stations sampling frequency is inadequate to enable long-term average concentration and load to be calculated. Consequently, this paper concentrates on 23 stations with long-term records, several of which were established at the inception of the national program in the early 1960's. These stations are listed in Table 1, and their location is shown in Fig. 1. Their drainage areas range from 10 to over 300 000 km^2.

Sampling at these stations covers either the entire year (''continuous'') or the open-water season from March or April to October (''seasonal''). Samples are collected every few days during average flow conditions and more frequently during flood events. A continuous plot of concentration is interpolated by hand between samples, and the daily mean concentration and load are then calculated. This method is different from the rating curve technique commonly used in sediment-yield studies.

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 that 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 reduced summer flows and consequently has increased the proportion of the annual load carried during winter. At these two stations the annual loads have been used.

It is not possible to compile a completely accurate picture of

TABLE 1. Drainage area, period of record, annual discharge, and annual sediment load for long-term stations in the Saskatchewan River basin

Station name	Station No.	Drainage area (km²)	Period of sediment record		Mean seasonal total discharge (dam³)	Seasonal sediment load		
			Continuous	Seasonal		Mean (t)	Std. error (%)	Skewness
Crowsnest River at Frank	05AA008	402	1978	1976–1977, 1979–1980	107 800	2 500	23.2	−0.41
Oldman River near Waldron's Corner	05AA023	1 440	1977–1978	1976, 1979–1983	307 000	17 000	46.1	1.33
Oldman River near Brocket	05AA024	4 400	1967–1978	1966, 1979–1983	1 129 000	260 000	28.5	1.66
Willow Creek near Claresholm	05AB021	1 100	1965–1974	1964	96 600	53 000	37.0	1.70
Willow Creek above Chain Lakes	05AB028	162	1967–1977	1965–1966	31 800	6 000	45.2	1.86
Oldman River near Lethbridge	05AD007	17 000	1973–1978	1972, 1979–1983	2 015 000	1 451 000	32.5	1.63
South Saskatchewan River at Highway 41	05AK001	66 000	1967–1978	1966, 1979–1983	4 492 000	2 786 000	18.3	0.94
Marmot Creek main stem near Seebe	05BF016	9	1964–1978	1963, 1979–1983	3 740	25	24.5	2.64
Bow River at Calgary	05BH004	7 860	1973–1978	1972, 1981	2 107 000	28 200	27.6	0.64
Elbow River at Bragg Creek	05BJ004	792	—	1968–1969, 1971–1975	226 000	23 300	36.7	0.90
Highwood River near the mouth	05BL024	3 390	1972–1978	1970–1971, 1979–1980	561 000	124 000	28.2	0.67
Red Deer River at Red Deer	05CC002	11 600	1972–1973, 1978	1971, 1974–1977, 1979–1983	1 129 000	213 000	27.4	1.39
Red Deer River at Drumheller	05CE001	24 800	1977–1978	1975–1976, 1979–1983	1 174 000	572 000	20.8	0.35
Red Deer River near Bindloss	05CK004	44 700	1967–1978	1966, 1979–1983	1 634 000	2 000 000	18.5	1.05
South Saskatchewan River near Lemsford	05HB001	119 000	1962–1970	1966	7 022 000	6 020 000	18.3	0.21
Swift Current Creek near the mouth	05HD037	3 910	—	1965–1972	80 000	67 000	52.2	1.41
South Saskatchewan River near Outlook	05HF001	136 000	—	1948–1952, 1955–1961	7 831 000	5 270 000	31.6	1.24
South Saskatchewan River at Saskatoon	05HG001	141 000	1962–1971	1961	(1962–1966) 6 924 000	2 700 000	19.3	0.18
					(1967–1971) 4 290 000	568 000	61.3	1.42
North Saskatchewan River at Whirlpool Point	05DA009	1 920	1973–1975, 1977–1978	1972, 1976, 1979–1981	1 480 000	235 000	6.1	−1.50
North Saskatchewan River at Prince Albert	05GG001	131 000	1963–1975, 1977–1978	1958, 1962, 1979–1983	6 455 000	3 070 000	20.6	1.33
Carrot River near Smoky Burn	05KC001	9 250	—	1972, 1974–1979	294 000	156 000	33.7	1.99
Saskatchewan River below Tobin Lake	05KD003	289 000	1966, 1969–1970	1965, 1967–1968	10 820 000	92 000	30.5	1.04
Saskatchewan River at The Pas	05KJ001	347 000	1963–1983	1954–1961, 1962	19 060 000	2 110 000	15.7	−0.10

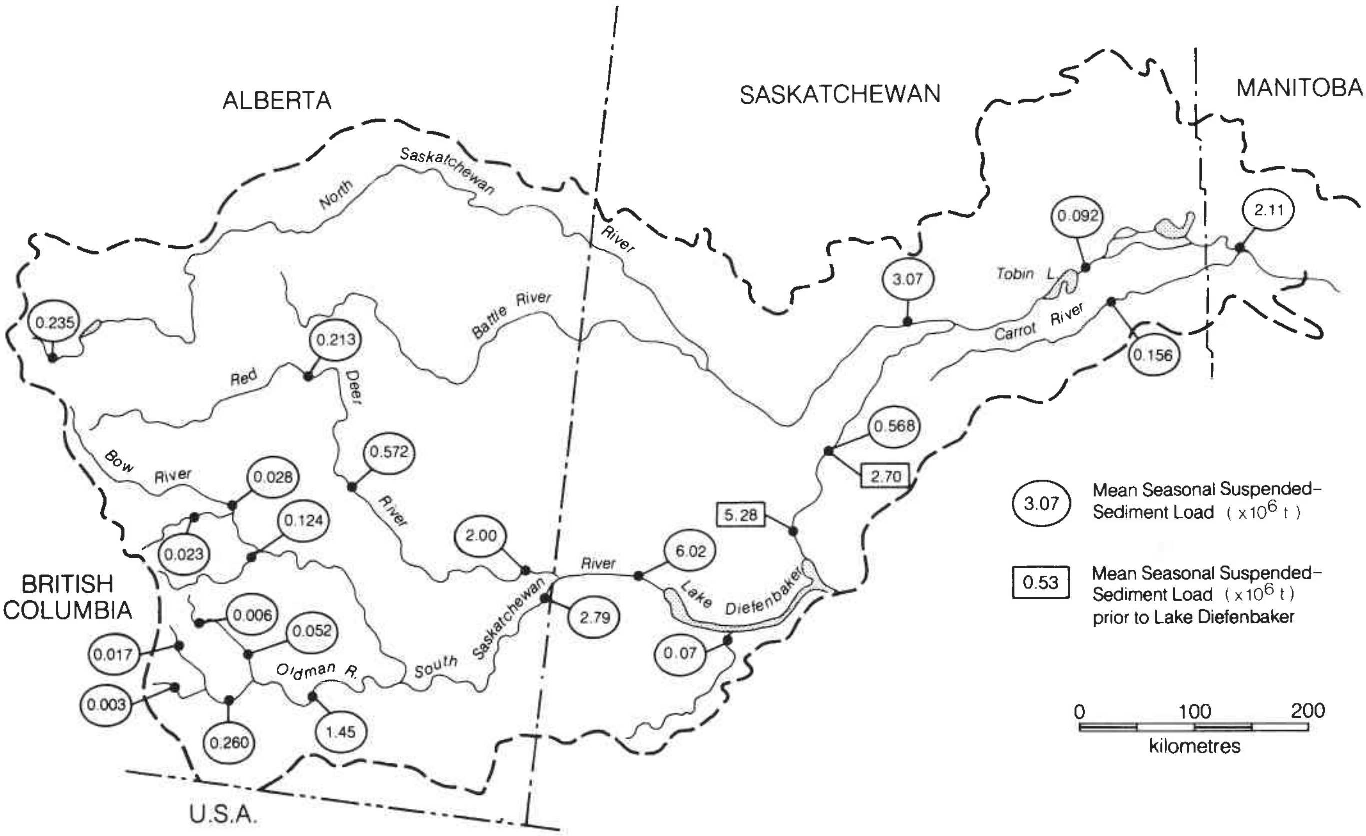

FIG. 3. Mean seasonal suspended-sediment load at Water Survey of Canada sediment stations.

the variation in annual sediment load because of discrepancies caused by differences in the period of record. Table 1 displays the seasonal suspended-sediment loads together with the standard error of the estimate of the mean and the skewness of the distribution of annual load. The standard error of the estimate of the mean 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. However, differences in the length of record are responsible for some of this variation. The mountain and Foothills streams, as well as the two Prairie-source streams, also have greater positive skewness of the annual load series than the large Prairie streams.

The variation of annual load within the Saskatchewan River basin is shown in Fig. 3. Much of the annual sediment 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 0.5×10^6 t (see also Rasid 1979), compared with an estimated 6×10^6 t prior to the dam construction.

Similarly, the trapping of sediment in Tobin Lake (Squaw Rapids Dam, 1962) has caused a reduction from 9×10^6 t per year to practically zero in the sediment load entering the Cumberland Delta area. Despite this, the Saskatchewan River at The Pas still transports a mean annual sediment load of 2×10^6 t (reduced from an estimated 4×10^6 t prior to dam construction (Northwest Hydraulic Consultants Limited 1986)). The load of tributaries such as the Carrot River cannot account for all of this load, and therefore it is possible that the Cumberland Delta is now an area of net erosion.

Plots of cumulative deviation from the mean seasonal load over the period of record show a similar pattern of variation in all cases (Fig. 4): a period of above average loads from the early 1960's to the mid 1970's followed by consistently small loads after 1975. The similar pattern of variation on all the major rivers of the drainage basin suggests that it is primarily the result of natural flow variation rather than regulation and abstraction.

Annual sediment yield

Calculation of the mean annual sediment yield (load per unit area) for many of the Prairie drainage basins is complicated by the presence of large areas of internal drainage, which makes it difficult to decide on an appropriate measure of drainage area. The areas of internal drainage include both large drainage systems of several thousand square kilometres as well as a myriad small hollows, depressions, and sloughs (Stichling and Blackwell 1957). The area of internally drained land (''dead'' drainage area) upstream of each Water Survey of Canada gauging station has been measured from 1 : 50 000 topographic maps by Prairie Farm Rehabilitation Administration (1983). 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. The yields from the Prairie basins are more comparable with data from basins without large areas of internal drainage when calculated by this

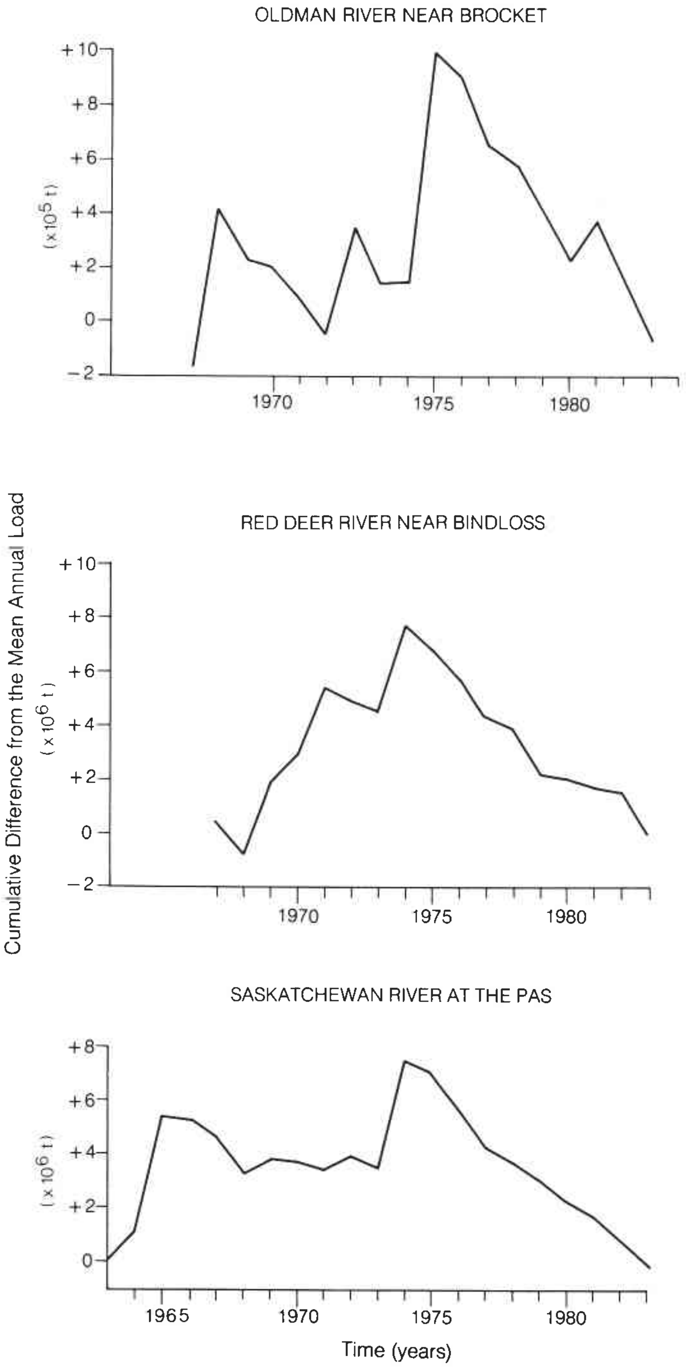

FIG. 4. Cumulative deviation from the mean annual sediment load from 1963 to 1983 at selected stations.

method than if they were calculated from the total drainage area. Note that the absence of sediment data for the North Saskatchewan River between Whirlpool Point (05DA009) and Prince Albert (05GG001) means that much of the discussion of the variation in sediment yield applies to only the South Saskatchewan River basin.

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 larger basins of the Alberta Plains (Fig. 5). This can be seen clearly by examining the trend along rivers such as the Red Deer or the Oldman − South Saskatchewan. The high yield from the glacierized upper North Saskatchewan River basin (at Whirlpool Point, 05DA009) is an exception. Annual sediment yield declines again along the large rivers in the eastern portion of the basin.

The consequence of high yields combined with the large drainage area of most of the Prairie rivers in the sample is that sediment yield shows a positive correlation with drainage area (although the correlation coefficient is 0.302, which is not significant at the 0.1 significance level) (Fig. 6). Hudson (1983) described a similar pattern for the Elbow River as it flows from the Rocky Mountains through the Foothills into the Alberta Plains, as did Campbell (1977) for the Red Deer River. Very high annual yields have also been measured from rating curve calculations in the High Plains tributaries of the Oldman River, such as the Belly River (190 t km^{-2} $year^{-1}$) and Waterton River (90 t km^{-2} $year^{-1}$), which, along with erosion along the main stem, accounts for the large yield from the Oldman River basin between Brocket and Lethbridge (Ashmore 1986). In both the Elbow and Red Deer river basins, and presumably also in the Oldman River basin, riparian sediment sources on the Prairies are the dominant factor accounting for the increase in annual yield downstream.

Existing data on the relationship between drainage area and sediment delivery ratio, mainly derived from small (<1000 km^2) agricultural basins (see, for example, Walling and Webb 1983, Fig. 4.8), demonstrate that sediment yield declines downstream through a drainage basin because of gentler hillslope gradients and storage of sediment in the lower reaches. However, in very large drainage basins within which there may be pronounced contrasts in geology, relief, and land use this model is likely to be inapplicable. A better alternative in such cases would be to consider the variation in sediment yield downstream through the drainage network as being strongly dependent on the juxtaposition of major sediment source areas and sinks within the drainage basin. Sediment load and yield would fluctuate downstream in response to the arrangement of these sources and sinks. In the Saskatchewan River basin 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.

The dominance of the Prairie region as a sediment source for these rivers becomes more apparent when the mean annual sediment yield for the portions of each drainage basin between adjacent sediment stations on the same river is calculated. The result of doing so (Fig. 7) is that the relationship between yield and drainage area is less apparent (the correlation coefficient is less than 0.1); instead there is a distinction between a group of stations with yields less than 40 t km^{-2} $year^{-1}$, which are mainly mountain and Foothills basins, and a second group with yields over 50 t km^{-2} $year^{-1}$, which are primarily larger Plains basins. 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 standardizing 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.

The contrast between relatively low concentrations in the

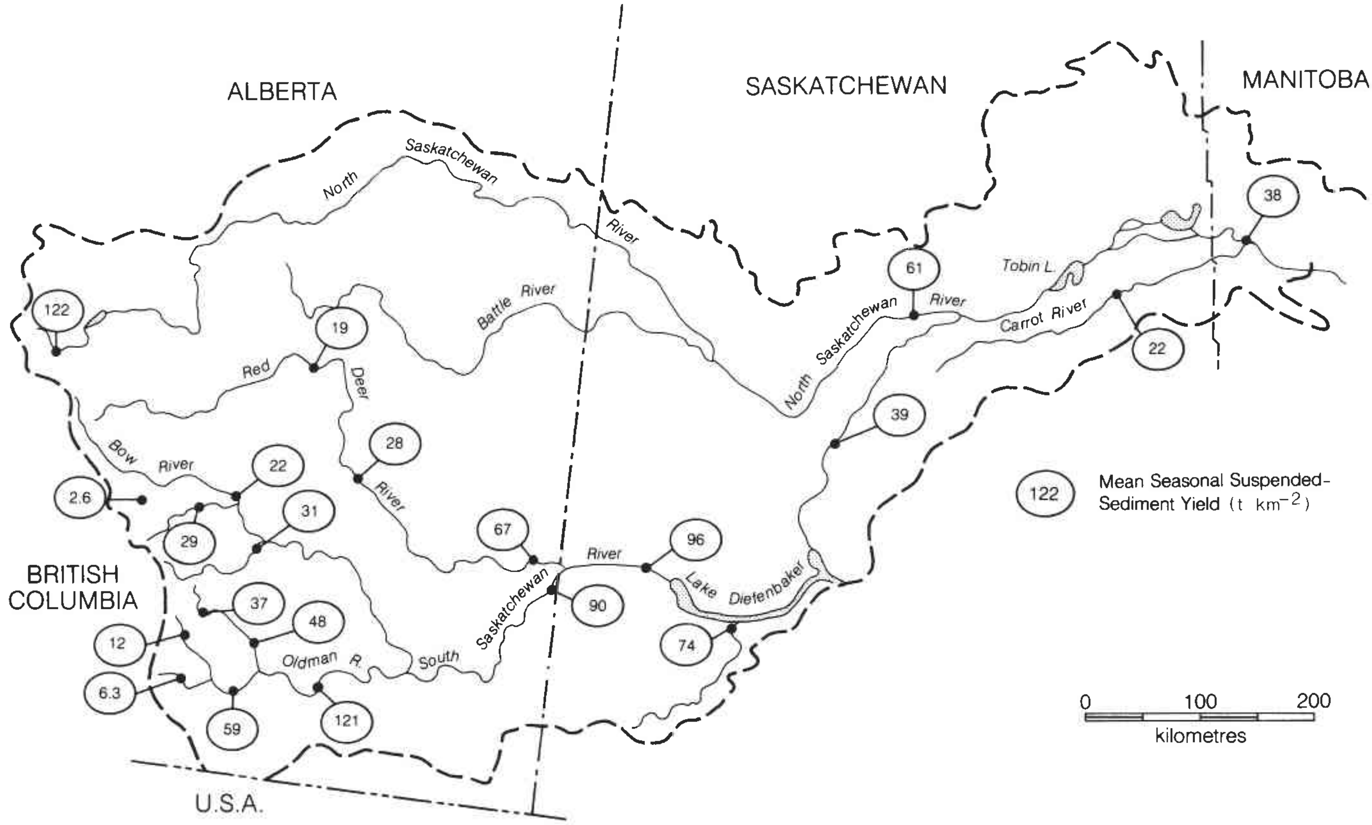

FIG. 5. Mean seasonal suspended–sediment yield at Water Survey of Canada sediment stations.

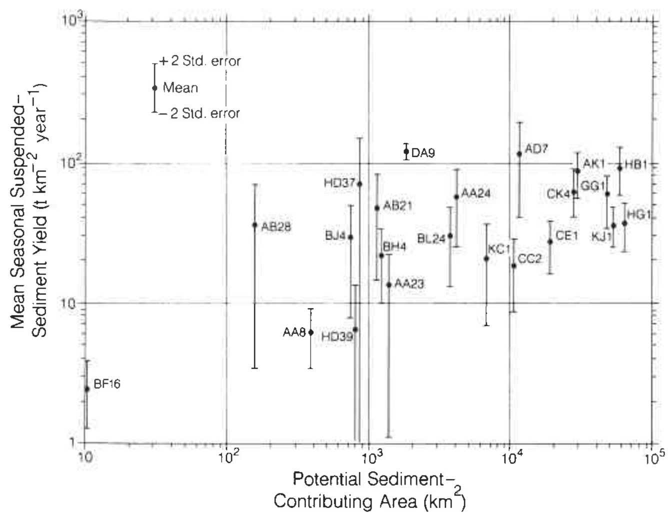

FIG. 6. Mean seasonal suspended-sediment yield versus potential sediment-contributing area. Stations are identified by abbreviated Water Survey of Canada station numbers.

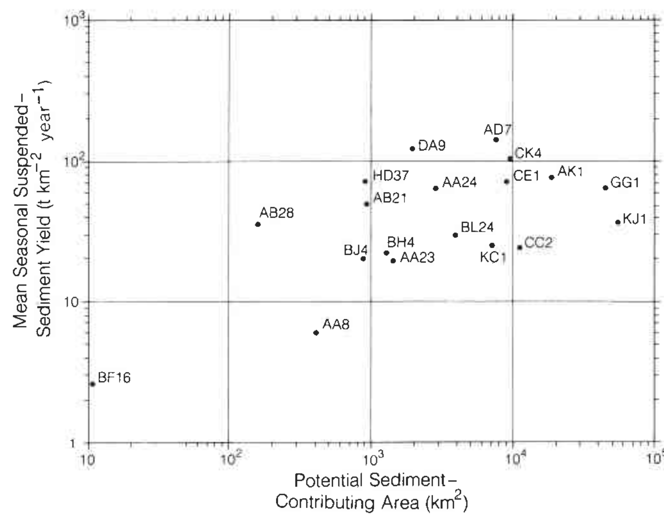

FIG. 7. Mean seasonal suspended-sediment yield versus potential sediment-contributing area for subbasins. Stations are identified by abbreviated Water Survey of Canada station numbers.

mountain and Foothills streams and the high concentrations in the Alberta Plains portion of the basin parallels the pattern of variation of sediment yield (Fig. 8). 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 Saskatchewan River downstream of Tobin Lake (05KD003) is also apparent.

The concentration is relatively low in the upper North Saskatchewan River at Whirlpool Point, in contrast to the high yield recorded at this site. This is a consequence of the glacially dominated flow regime at this station.

These results do not differ greatly from the only previous regional summary of annual concentrations (Stichling 1973), although further detail is now available showing that annual concentration over 1000 mg L^{-1} occurs only in the portion of the Red Deer River downstream of Drumheller. Concentra-

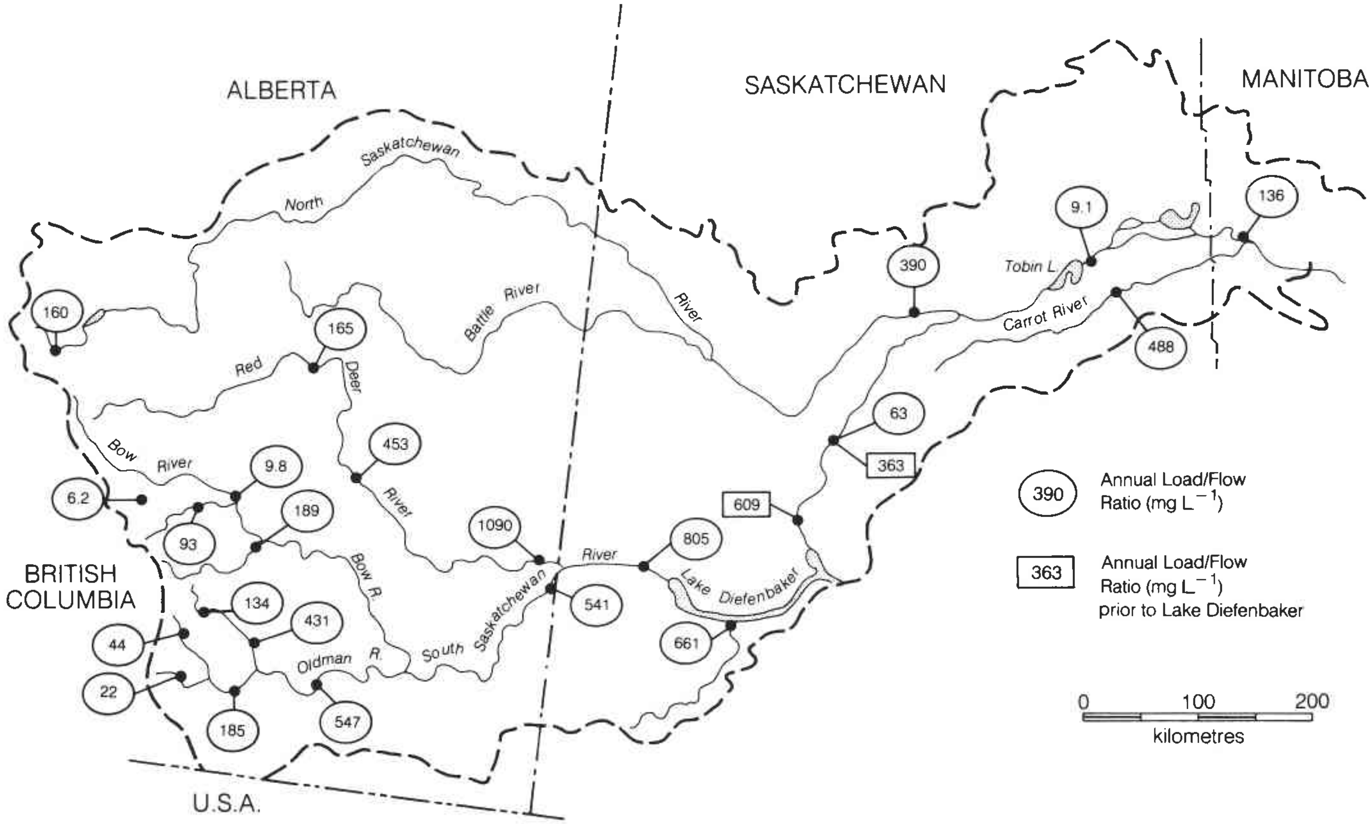

FIG. 8. Annual load/flow ratio at Water Survey of Canada sediment stations.

tions along the Oldman River also differ slightly from those mapped by Stichling from more limited data.

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. Figure 9 illustrates some of the variation in annual discharge and sediment regimes within the Saskatchewan River basin.

At high elevation in the Rocky Mountains (e.g., Marmot Creek) both discharge and sediment load have a single peak in June. This June peak also occurs in the larger Foothills and western Plains basins (e.g., Highwood River), where runoff from lower altitudes is responsible for significant flow and sediment load in May and to a lesser extent in April. In contrast, the glacial regime of the upper North Saskatchewan River has a broad summer peak extending from May to September, with a maximum in July.

The Mountain snowmelt (and rain-on-snow) peak also prevails further downstream along the larger rivers, but it is delayed until late June or early July in the eastern portions of the basin (e.g., North Saskatchewan River at Prince Albert), where there is a second smaller peak in April, contributed by Prairie snowmelt. However, regulation has altered the regime at these stations. For example, at Prince Albert, upstream storage of the July flows for power generation has resulted in the April peak becoming the dominant sediment-transporting event (Ashmore 1987).

The Prairie-source streams (e.g., Swift Current Creek) have a single peak in April caused by Prairie snowmelt and negligible load throughout the remainder of the year. Note that soil-erosion studies (Wall *et al.* 1983) suggest that the climatic indices of soil-erosion potential are very low during snowmelt and reach a peak in mid-summer. This difference in timing between peak soil erosion and peak stream sediment loads demonstrates that sediment routing from the field to the stream system is indirect and involves a considerable amount of storage. Indeed, if sediment loads are derived primarily from riparian sources there is very little connection between the magnitude and timing of soil erosion and stream loads. For this reason there may be large discrepancies between stream-borne sediment yields and field-scale soil-erosion rates calculated for the same area (Coote 1984).

Seasonal clockwise hysteresis in the relationship between load and discharge is common. However, flow regulation of the larger rivers, in which large winter releases with very low sediment concentrations occur, has resulted in more complicated hysteresis patterns at some stations.

Duration curves of daily concentration and yield

Selected examples of daily concentration–duration and yield–duration curves are shown in Figs. 10 and 11. Table 2 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 for all stations.

Apart from the differences in average yield discussed earlier, some trends in the shapes of the duration curves can also be seen. The general trend downstream through the drainage system is for skewness and dispersion to be relatively low in the small mountain streams, to increase at the western margin

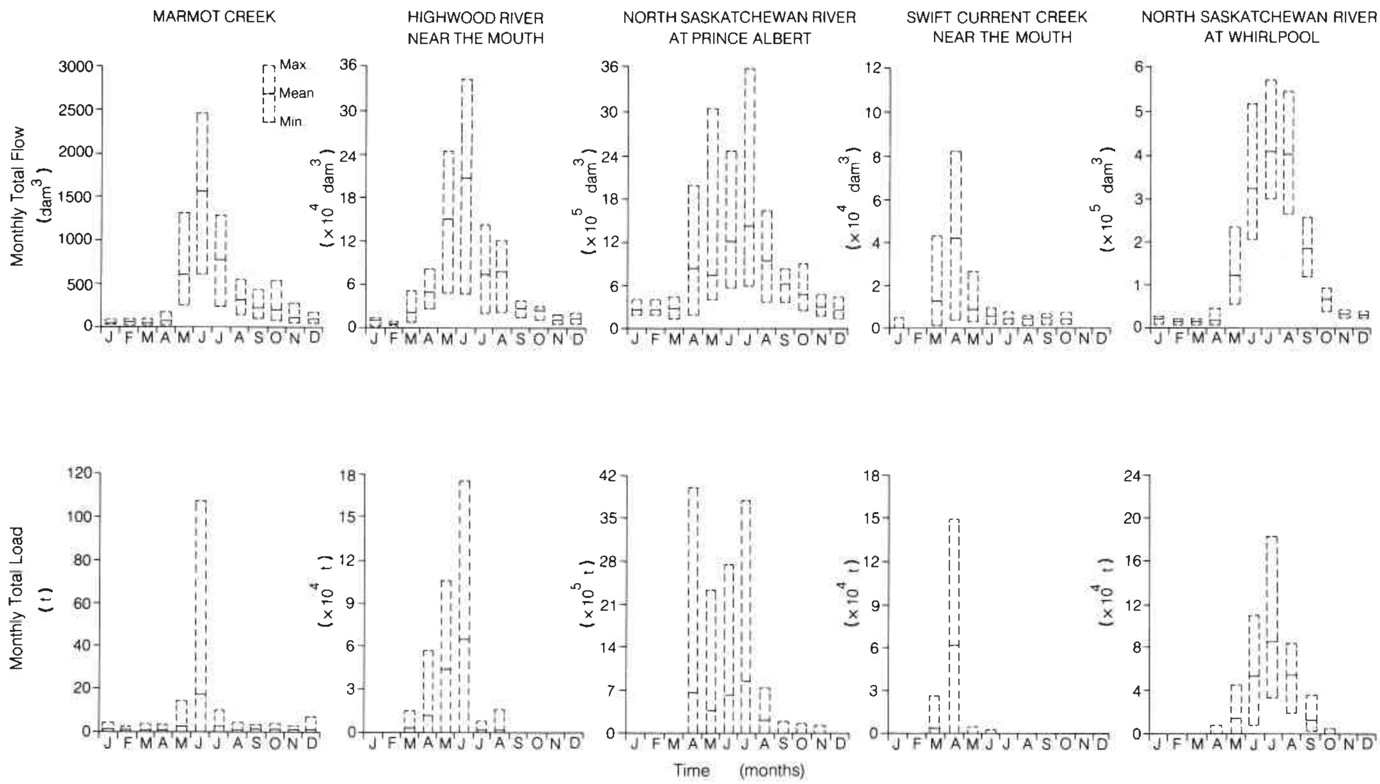

FIG. 9. Annual flow and load regimes for selected stations.

of the Plains, and then to decrease downstream. Skewness and dispersion are also high in the small Prairie-source streams (e.g., Swift Current Creek).

In two cases the duration curves are negatively skewed: the glacially fed North Saskatchewan River at Whirlpool Point and the Saskatchewan River at The Pas, in which flow is strongly regulated by lakes and by reservoirs.

A spatial pattern of variation in dispersion and skewness very similar to that described for the daily yield–duration curves can be seen for the daily concentration–duration curves (Fig. 11).

Without an understanding of the sediment delivery processes and properties of the major sediment sources it is difficult to explain the observed pattern of variability of the duration curves. The maintenance of relatively high concentration at low discharge in the Prairie rivers may be aided by the supply of fine-grained wash-load-calibre sediment from badlands areas. It is conceivable that discharge regime may also influence the form of the yield–duration and concentration–duration curves.

Magnitude and frequency characteristics

Table 3 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 4 consecutive-day load ranges from 4 to 40% of the seasonal total load 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-day load accounts for 25–90% of the seasonal total load and in some years approaches 100% in Swift Current Creek and the Carrot River.

The highest proportional 4 and 36 consecutive-day loads occur in the streams on the western margin of the Alberta Plains and also in the two Prairie-source streams (Swift Current Creek and the Carrot River). The larger Prairie rivers, as well as those strongly influenced by upstream flow regulation, have much lower proportions of the total load transported during short time periods, as does the glacier-fed North Saskatchewan River at Whirlpool Point. Hudson (1983) showed that there is a downstream increase from the Foothills to the Plains in the proportion of the annual load transported by the largest events in the Elbow River basin. However, in the mountain headwaters of the Elbow River, a lower proportion of the total load is transported during large events than downstream in the Foothills portion of the basin. This is also true of the headwaters of the Oldman River (compare Crowsnest River at Frank, Oldman River at Waldron's Corner, and Oldman River at Brocket in Table 3).

Figure 12 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 3. The pattern of variation between stations is similar to that for the 4 and 36 consecutive-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; Red Deer River near Bindloss), the glacier-fed upper North Saskatchewan River, and some other mountain headwaters. The consequence is that the proportion of the total load transported in a given percentage of the time decreases downstream along the main rivers from the

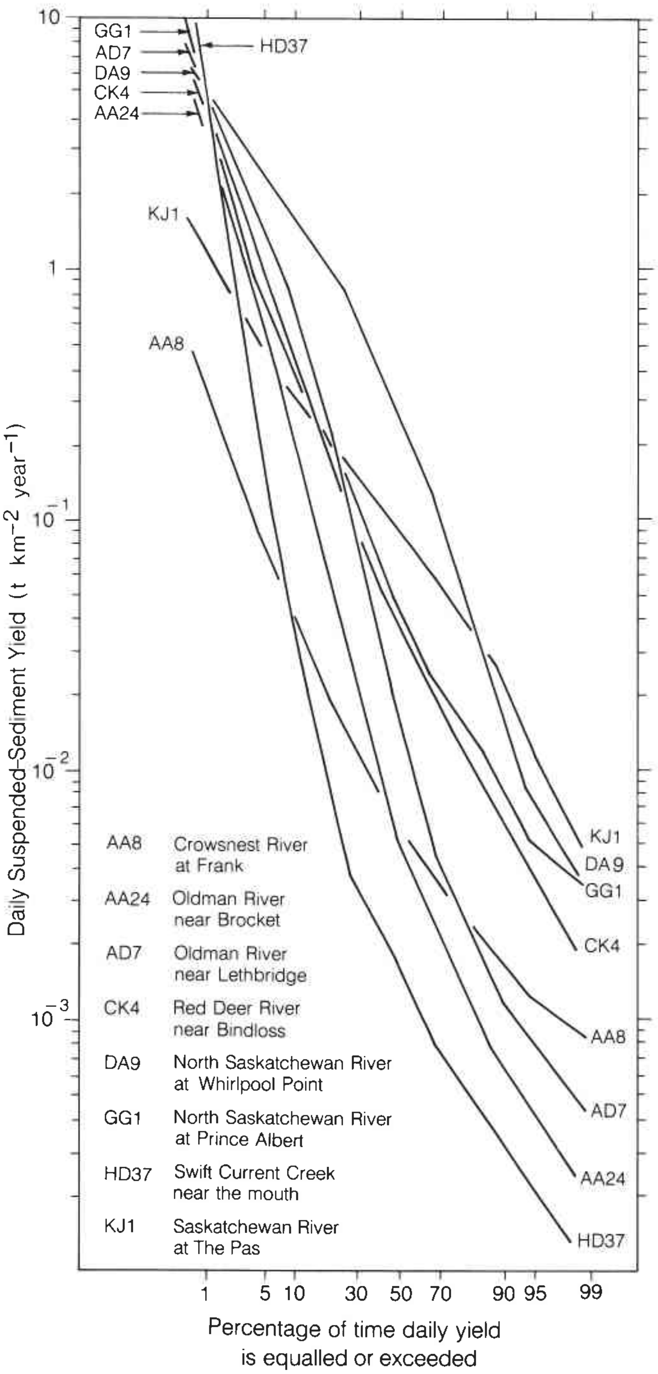

FIG. 10. Daily suspended-sediment yield – duration curves for selected stations.

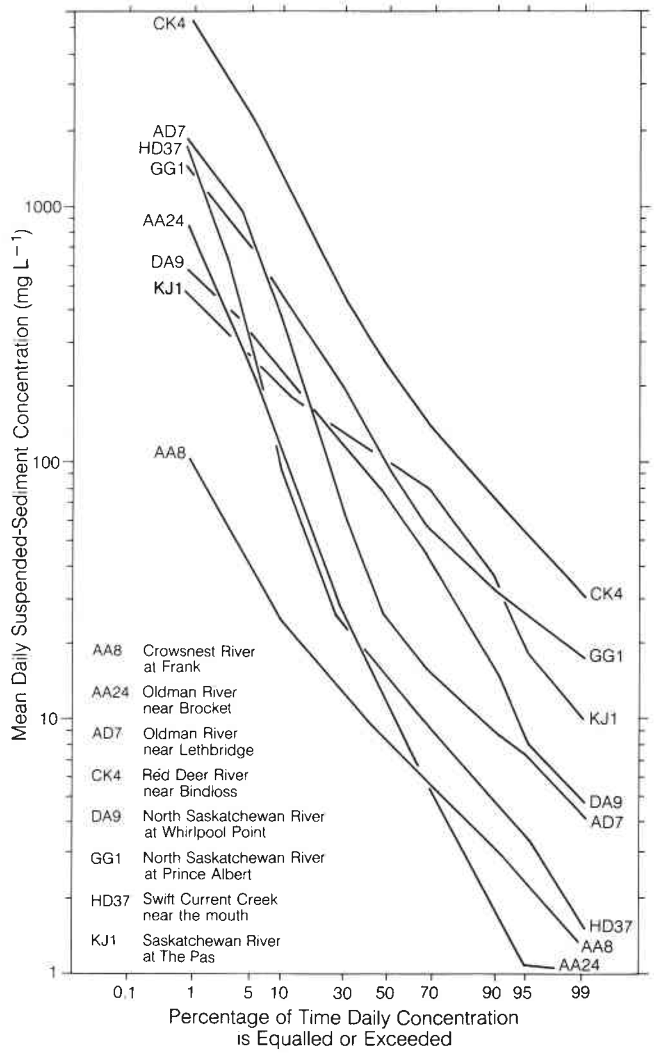

FIG. 11. Daily suspended-sediment concentration – duration curves for selected stations.

Foothills to the Plains. 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, to 8% at Highway 41, to 4% near Lemsford, and to 2% at Outlook.

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; 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 Robinson (1972) and Dickinson and Wall (1977). Dickinson and Wall's Fig. 6, showing regional contrasts in cumulative load versus percentage time, is very similar to our Fig. 12 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 Fig. 12. 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 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, in contrast to the relatively small basins of Carrot River and Swift Current Creek.

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 in 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.

TABLE 2. Graphical dispersion and skewness of daily sediment yield–duration and concentration–duration curves

Station name	Station No.	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 near the mouth	05HD037	292.6	2.42	37.6	1.12
South Saskatchewan River at Saskatoon	05HG001 (1962–1963)	44.0	0.57	13.2	0.28
	(1967–1971)	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

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 Fig. 13. Here the percentage of the seasonal total load transported in 1% of the time 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 discharge-duration curve (correlation coefficients are 0.787 and 0.605, respectively; both exceed the 0.01 significance level). However, there is a danger of spurious correlation because discharge is used in computing sediment load. Presumably these differences in flow regime and discharge duration may in turn be related to drainage area (e.g., downstream attenuation of flood waves from the mountains to the Saskatchewan Plains), topography, and other physical properties of the drainage basins as well as differences in the precipitation and snowmelt inputs to the streams. However, sediment delivery and source area characteristics also need to be considered. Explanation of the differences in temporal patterns of sediment transport in these terms is beyond the scope of this paper but is an important future step.

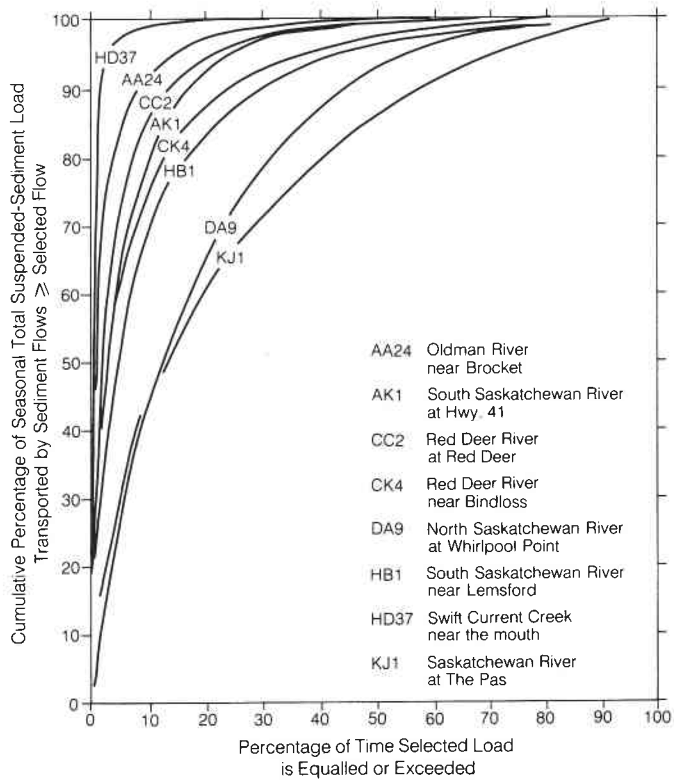

FIG. 12. Cumulative load – duration curves for selected stations.

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.

Mean annual sediment yield increases downstream along the major rivers between the Rocky Mountains and the Saskatchewan Plains. Thus, sediment yield tends to increase with drainage area in these streams, contrary to the pattern widely

TABLE 3. Proportion of seasonal load transported by extreme events

Station name	Station No.	Mean percentage of seasonal load transported during highest 4 consecutive days	Mean percentage of seasonal load transported during highest 36 consecutive days	Seasonal load transported in percentage of time		
				0.1%	1%	5%
Crowsnest River at Frank	05AA008	13.7	26.7	5	30	60
Oldman River near Waldron's Corner	05AA023	22.5	65.3	18	62	82
Oldman River near Brocket	05AA024	28.3	65.8	20	55	81
Willow Creek near Claresholm	05AB021	33.4	67.9	15	55	82
Willow Creek above Chain Lakes	05AB028	39.8	70.2	20	74	91
Oldman River near Lethbridge	05AD007	22.7	66.2	18	48	78
South Saskatchewan River at Highway 41	05AK001	19.6	63.7	8	35	62
Marmot Creek main stem near Seebe	05BF016	22.0	64.5	15	45	65
Bow River at Calgary	05BH004	10.2	44.1	5	30	55
Elbow River at Bragg Creek	05BJ004	34.8	87.1	8	48	82
Highwood River near the mouth	05BL024	32.4	70.8	11	42	78
Red Deer River at Red Deer	05CC002	24.3	56.6	12	42	73
Red Deer River at Drumheller	05CE001	19.6	45.2	5	28	61
Red Deer River near Bindloss	05CK004	15.6	48.9	6	32	63
South Saskatchewan River near Lemsford	05HB001	15.7	48.5	4	23	52
Swift Current near the mouth	05HD037	36.7	90.2	15	70	95
South Saskatchewan River near Outlook	05HF001	10.2	41.2	2	15	40
South Saskatchewan River at Saskatoon	05HG001 (1962–1963)	10.0	47.9	3	30	60
	(1967–1971)			10	50	73
North Saskatchewan River at Whirlpool Point	05DA009	10.6	33.1	2	12	30
North Saskatchewan River at Prince Albert	05GG001	11.7	45.7	5	25	52
Carrot River near Smoky Burn	05KC001	24.5	84.8	5	50	85
Saskatchewan River below Tobin Lake	05KD003	3.9	24.4	1	10	30
Saskatchewan River at The Pas	05KJ001	7.2	35.2	2	12	32

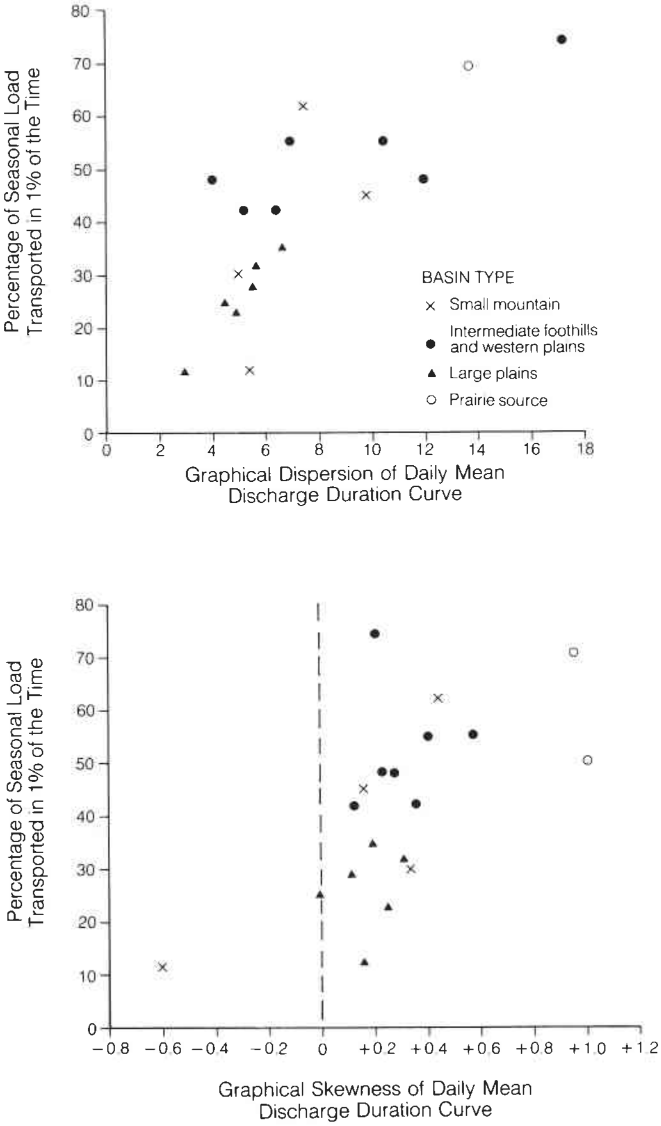

FIG. 13. Relationship between the cumulative proportion of the total load transported in 1% of the time and the dispersion and skewness of the daily discharge–duration curve.

observed in many small basins, because of the overriding influence of the differences in geology and physiography between the Plains and the mountains.

The dispersion and skewness of the daily yield–duration and concentration–duration curves are greatest in the basins close to the Rocky Mountains and in the two small Prairie-source streams. These are also the basins that have the most skewed cumulative load–duration curves and have sediment-transport regimes dominated by high-magnitude events. Thorough explanation of the differences in temporal and spatial characteristics of the sediment yield awaits better understanding of the hydrological contrasts within the basin but, more importantly, improved understanding of the link between stream-borne sediment and the source areas and delivery processes.

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