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Sediment delivery in large prairie river basins, western Canada

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ABSTRACT Suspended sediment monitoring has been carried out on several large river systems in the Canadian prairies for the past 30 years,primarily for river engineering purposes. Mean annual specific yield increases downstream in many of these stream systems, contrary to the conventional model derived from small agricultural basins. In the Canadian prairies there are several reasons for this: basin size sufficient to incorporate contrasting physiographic regions and characterized by long geomorphic recovery times from glaciation; the wide-spread internal drainage and poorly-integrated stream systems (again at least partly a glacial legacy), which isolate the main streams from the land surface; extensive Quaternary deposits whose disposition is largely unrelated to fluvial processes but represent readily recruited sediment; and post-glacial incision of major streams into Quaternary deposits and erodible Cretaceous sediments. The Saskatchewan and Assiniboine Rivers both illustrate this tendency but each for slightly different reasons. One of the implications for this pattern of sediment delivery is that continued monitoring of main stem streams will not provide the information required to manage sediment-related environmental problems.

INTRODUCTION

The conventional model of declining mean annual suspended sediment yield (or sediment delivery ratio) with drainage basin area is derived from relatively small agricultural basins in fairly homogeneous terrain. The pattern for larger drainage basins, especially in largely undisturbed terrain, is much less well documented but evidence from large Canadian drainage basins (Ashmore & Day, 1988; Church & Slaymaker, 1989; Church et al., 1989) has shown that peak specific yields do not necessarily occur in the headwaters, but may actually increase downstream. In British Columbia, Church & Slaymaker (1989) and Church et al. (1989) demonstrated that this is due to the dominance of secondary remobilization by bank erosion and mass movement of Quaternary sediments along the degrading trunk streams. By comparison, the undisturbed upland surfaces yield very little sediment. Similar patterns in basins of the south-east U.S. have been explained by secondary remobilization of valley fill eroded from the uplands during earlier agricultural settlement (Trimble, 1975; Meade, 1982).

While, in general, the glacial legacy is also significant in the Canadian prairies, there are several differences from the British

Columbia case, not the least of which is that the land surface is largely disturbed yet riparian erosion still dominates because of the extent of internal drainage and the poorly-integrated drainage system, which is also largely a glacial legacy (Fig. 1) (Stichling & Blackwell, 1957). Thus, the small streams on the prairie surface function almost independently of the trunk streams, some of which are largely allogenic.

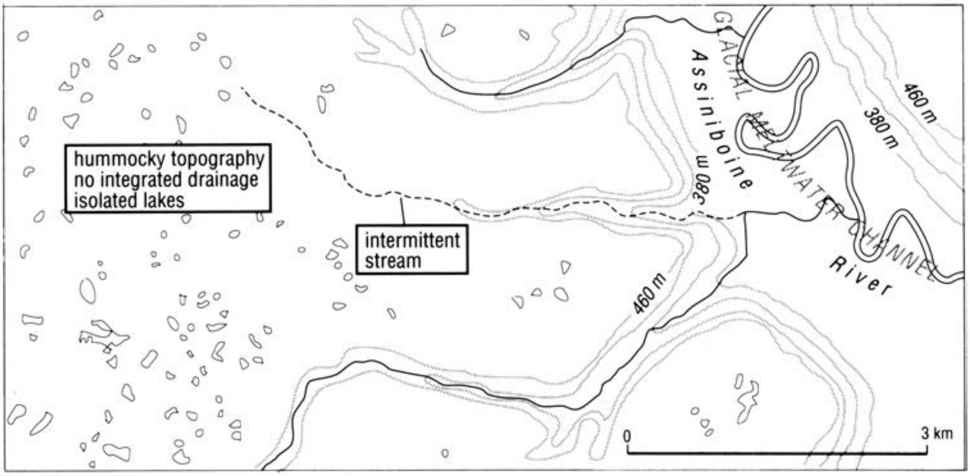

FIG. 1 Example of local drainage and topography adjacent to Assiniboine River, near Miniota, Manitoba.

The increase in sediment yield with basin area in the prairies is not solely the product of a prolonged 'paraglacial' cycle of sedimentation in undisturbed basins. As Church et al. (1989) indicate, there is no reason to suppose that the pattern of sediment yield observed in a particular natural landscape would be applicable elsewhere. The examples used in this paper illustrate that point and allow the factors that conspire to contradict the conventional basin area-sediment yield relationship in the Canadian prairies to be identified. It is apparent that not only the pattern of sediment yield, but also the causes of the pattern, may differ between regions or even between drainage basins.

CASE STUDIES

Two examples will be used to illustrate the pattern of sediment yield in large prairie drainage basins. The Saskatchewan River case has been described elsewhere (Ashmore & Day, 1988) and only a brief summary is given here. The Assiniboine River data have not previously been reported. In each case the source of data are Water Survey of Canada sediment data collected at hydrometric stations and published annually.

1. Saskatchewan River Basin

Physiography The Saskatchewan River drains over 350 000 km^2 extending from the continental divide to Lake Winnipeg. There is a major physiographic divide near the western margin of the basin separating the Rocky Mountains and Foothills from the Alberta - Saskatchewan plains (Fig. 2). Over 70% of the mean flow of the Saskatchewan River at The Pas is derived from the extreme western portion of the basin and mean annual runoff changes from over 1000 mm to less than 5 mm between the two regions. This also represents the transition from predominantly carbonate rocks of the Mountains to the easily eroded Cretaceous sediments of the plains. Internal drainage accounts for about 120 000 km^2, (PFRA, 1989). In calculating sediment yields allowance has also to be made for the presence of several large reservoirs (Ashmore, 1986; Ashmore & Day, 1988). The prairie streams are usually incised into the surrounding prairie surface and valley sides are often characterized by mass movement and extensive gullying which is best developed in the extensive badlands along the Red Deer River (Campbell, 1977).

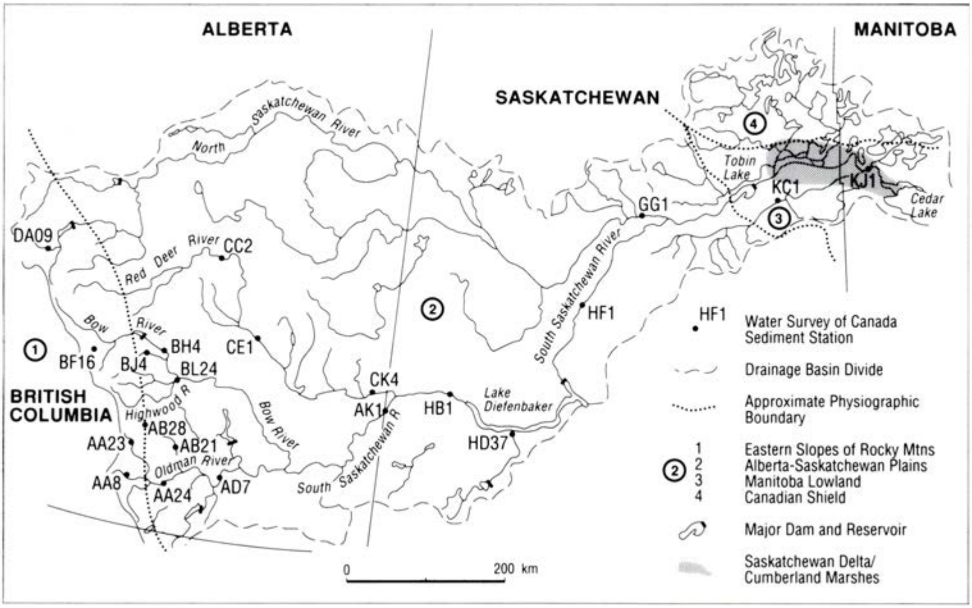

FIG. 2 Drainage system, physiographic regions, and the location of long-term Water Survey of Canada sediment stations, Saskatchewan River basin.

Sediment Yield Data are available from over 20 long-term (> 4 years) Water Survey of Canada sediment stations for the "seasonal" period April-October (which accounts for over 95% of the annual load at most stations). Their gross (including internal) drainage areas range from 10 to over 300 000 km^2. The differences in length of record and period of record undoubtedly are a source of error in estimates of the mean annual sediment load. Figure 3 shows the basin-wide trend in mean

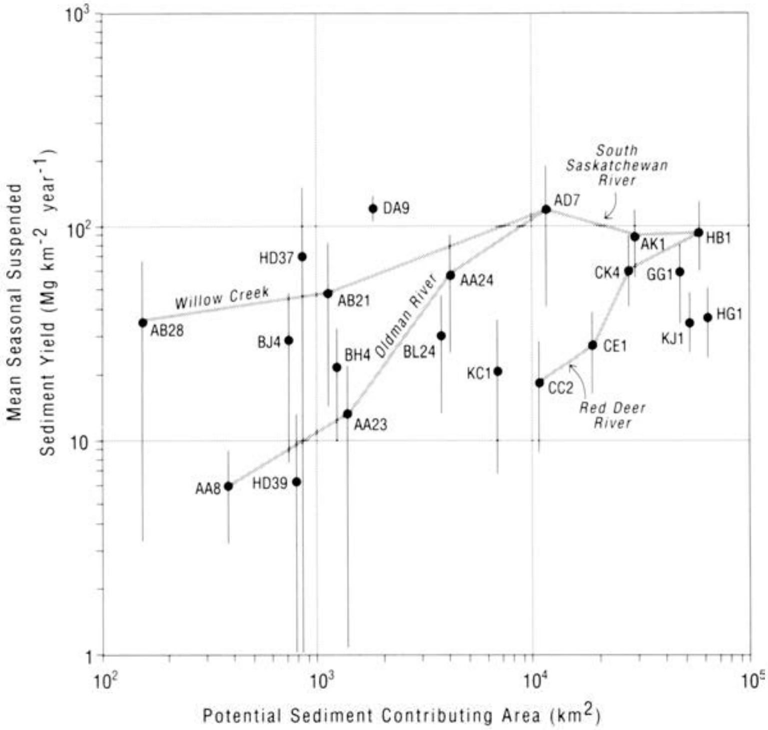

FIG. 3a Mean seasonal suspended-sediment yield versus potential sediment-contributing area, Saskatchewan River basin. Bars represent ±2 standard deviations about the mean.

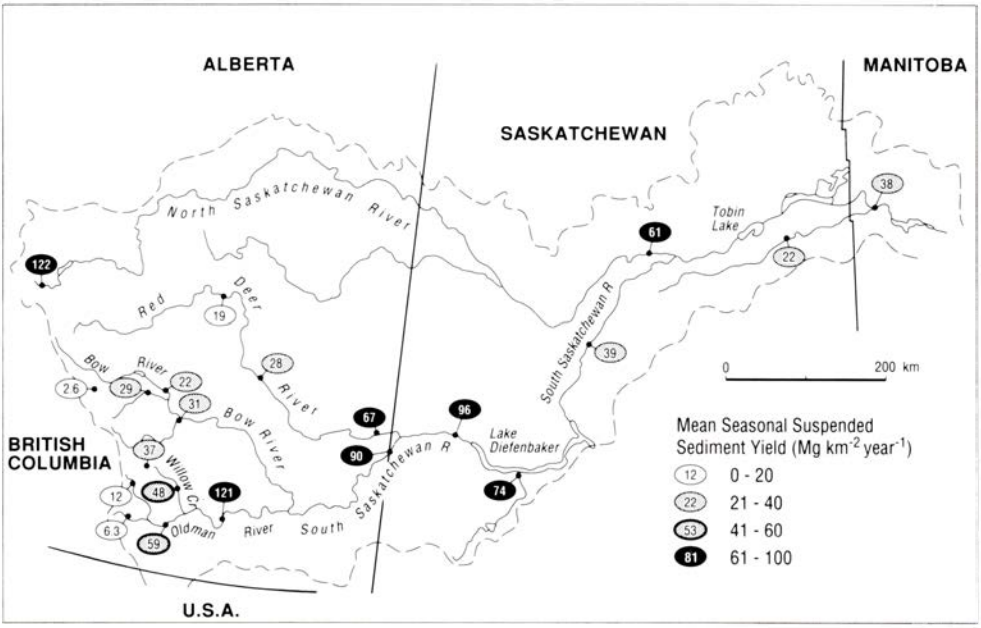

FIG. 3b Mean seasonal suspended-sediment yield at Water Survey of Canada sediment stations, Saskatchewan.

annual specific yield along with the relationship between yield and drainage basin area. There is a general tendency for the smaller headwater basins in the Rocky Mountains and Foothills to have low yields and for yields to increase downstream across the plains. This is clearly apparent on the South Saskatchewan/Red Deer/Oldman river system. The upper North Saskatchewan River is extensively glacierized and does not obey this trend of increasing yield downstream. The extreme downstream portions of the basin show a slight decline in sediment yield particularly in the extreme eastern portion of the basin where alluviation is occurring in the Saskatchewan Delta.

This pattern of increasing sediment yield downstream reflects the dominance of riparian sources, especially badlands erosion (rather than entirely glacial sediments), along the streams in southern Alberta (Campbell, 1977). However the rate of increase of sediment yield with basin area is lower than that of the British Columbia data (Church & Slaymaker (1989); Church *et al.,* 1989).

2. Assiniboine River Basin

Physiography The Assiniboine River drains 153 000 km^2 of south-east Saskatchewan and south-west Manitoba (Fig. 4). Of this, 110 000

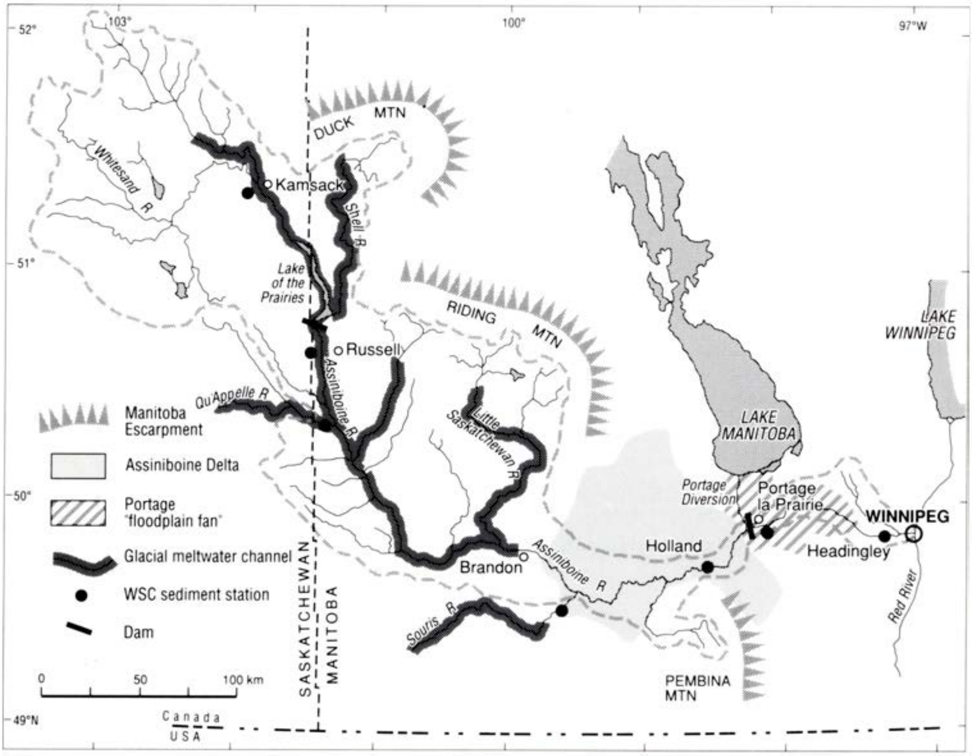

FIG. 4 Geomorphic features and location of Water Survey of Canada sediment stations, Assiniboine River basin.

km^2 is drained by the two major tributaries, the Souris and Qu-Appelle rivers. The flow of the Assiniboine River is entirely dependent on prairie runoff, unlike the S.Saskatchewan River which is almost allogenic in the prairies. Internal drainage reduces the 'effective' drainage area to about 40% of the total (PFRA, 1989). Mean annual runoff increases eastward across the basin from much less than 25 mm in the Saskatchewan plains, to 50-100 mm over the uplands of the Manitoba Escarpment in the eastern portion of the basin (Hydrological Atlas of Canada, 1978; Rannie et al., 1989).

For much of its course the Assiniboine River is tortuous, underfit and confined to a large glacial meltwater channel up to 85 m deep and 800 m wide with stable valley sides. However, downstream of Brandon (Fig. 4) the post-glacial Assiniboine has incised a deep valley into the Pleistocene Assiniboine Delta (formed on the western shore of Glacial Lake Agassiz). The silt and sand of the delta deposits are exposed in many places along the valley, and the stream itself contains numerous unvegetated sand bars and vegetated islands. East of the Manitoba Escarpment the river flows initially over the Portage la Prairie 'floodplain fan' (Rannie et al., 1989) and then the Lake Agassiz plain where it is confined by artificial levees. The channel gradient averages about 0.0001 upstream of Brandon, increases to about 0.0004 through the Assiniboine Delta and then declines to 0.0003 east of the Escarpment. The major tributaries are predominantly tortuous channels confined in glacial spillways like the upper Assiniboine. Often they become steeper and more deeply incised near their confluence with the Assiniboine.

Much of the landscape of the western part of the drainage basin consists of hummocky or corrugated moraine, till plains, limited areas of till veneer over Cretaceous bedrock and glaciofluvial and glaciolacustrine deposits (Klassen, 1975, 1979; Manitoba Department of Energy and Mines, 1981, 1987), all with slopes of only a few degrees. Much of the land is agricultural.

Sediment Regime Suspended sediment data are available from 5 Water Survey of Canada stations on the mainstem of the Assiniboine River (Fig. 4) beginning in 1962 at Headingley, 1963 at Portage la Prairie and in the late 1960s at the remaining stations. Details of the data collection and sediment regime at each of these stations can be found in Ashmore (1990). There are also sediment data for the Souris and Qu'Appelle near their confluence with the Assiniboine River.

This nival flood in April and May is responsible for the bulk (over 75% under natural flow conditions) of the annual sediment yield under natural flow. Flow regulation has reduced the relative contribution of this event by 5-10%. Thus, much of the sediment yield pattern is really the pattern of sediment production for this major annual runoff event.

Annual Load Mean annual load for the common period 1970-1979 is shown in Fig. 5. The most striking feature of Figure 5 is the dramatic increase in mean annual suspended sediment load between Russell and Holland (from 16 000 Mg to 950 000 Mg). Very little of this increase in load is due to tributary inputs since neither the Qu'Appelle nor the Souris rivers contribute more than a small percentage of the increase, and the remaining tributaries have considerably lower discharges. This

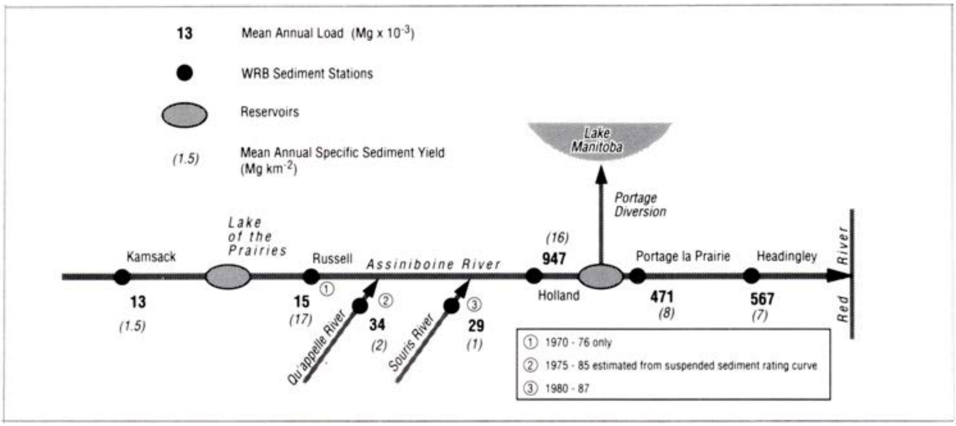

FIG. 5 Mean annual suspended sediment load and specific yield, Assiniboine River.

suggests that the increase in load is accounted for by riparian sources along the Assiniboine mainstem. Between Russell and Holland mean annual load increases by a factor of 40, while mean annual discharge increases by only a factor of 4. The Souris River, which is incised into Assiniboine Delta deposits in its lower course, also shows a similar increase in load downstream.

The difference in load between Holland and Portage is the result of the operation of the Portage flood control diversion. Mean annual loads at Portage and Headingley differ by only 10-15%, and therefore this section is neither a significant source nor a significant sink for suspended sediment (presumably the result of the artificial confinement).

Specific Yield The sediment yields calculated for the Assiniboine basin (Ashmore, 1990) are generally less than 15 Mg km^{-2} $year^{-1}$ which is very low, even compared with other prairie drainage basins, where yields are typically 10 - 100 Mg km^{-2} $year^{-1}$ (Ashmore & Day, 1988). They are also at the low end of the range for other regions of Canada (Dickinson & Green, 1988; Church et al. ,1989). Presumably the very low annual runoff values are a major influence here. The yields are lowest in the upper portion of the basin (1-2 Mg km^{-2} $year^{-1}$), peak in the central area between Russell and Holland (17 Mg km^{-2} $year^{-1}$), and decline again downstream (7-8 Mg km^{-2} $year^{-1}$). The relatively high yield at Russell is probably derived from bank erosion along the river between the Shellmouth Dam and Russell and almost certainly includes some after effects of construction.

Despite some uncertainty about the accuracy of the specific yield data it is clear that there is no consistent relationship between drainage area and sediment yield. The peak yields come from the central portions of the drainage basin upstream of Holland. Several lines of evidence point to the incised section through the Assiniboine Delta as the major source of sediment for the river. The load estimates for the Souris and Qu'Appelle rivers indicate that tributary inputs are not a major source of sediment for the main stem Assiniboine River. The upland surfaces, although widely cultivated, are low relief, hummocky topography with very low soil erosion potential (Eilers et al., 1987) except locally on steep valley sides. In addition, the drainage network is poorly integrated and the main stream system is isolated from potential sediment sources on the prairie surface above the entrenched main stem and tributaries, especially in the upper section where it is confined to the glacial meltwater channel.

Downstream of Brandon the river becomes much steeper with large unvegetated point bars, mid-channel islands and erosional bluffs along the valley walls cut into the Assiniboine Delta deposits. Wolowich and Tamburi (1975) report active slumping and spring sapping along the valley walls. The bed material along this section is predominantly medium sand, which probably reflects the supply of sediment from the Delta deposits. The steepening and incision of the Assiniboine has elicited a similar response in the downstream sections of the tributaries, notably the Souris.

All the evidence points to the Assiniboine Delta deposits as the dominant source of suspended sediment in the Assiniboine River system. The decline in yield in the downstream portion of the basin east of Portage la Prairie is attributable to the flat terrain of the Lake Agassiz plain and the tendency for the river to be slightly topographically higher than the surrounding land surface (Rannie et al., 1989). In fact, this portion of the river appears to be simply conveying the load from upstream and not adding any new sediment. Therefore, the Quaternary history and deposits in the Assiniboine River basin are the dominant influence on the disposition of sediment sources and the pattern of sediment yield. However, the isolation of the river from the prairie surface because of the poorly-integrated drainage system and confinement of the main stem to a pre-existing meltwater channel are also important contributing factors.

DISCUSSION

Both the Saskatchewan and Assiniboine river basins show sediment yield increasing downstream, which contradicts the classical model from small, agricultural drainage basins. They provide further examples of the extended relaxation time from Quaternary glaciation in large drainage basins and the dominance of secondary remobilization of Quaternary sediments recognized in British Columbia (Church et al., 1989; Church & Slaymaker, 1989). However, different physiographic settings (alpine versus continental glaciation) and glacial history have resulted in differences in detail between the western Cordillera and prairie sediment yield patterns, as well as differences in the causative factors. Furthermore, the prairie landscape is essentially a disturbed one. There are also differences between the two prairie basins. In the Saskatchewan River basin the dominant influence is extensive badlands erosion in southern Alberta (aided by post-glacial fluvial incision) which reflects bedrock lithology as much as the disposition of Quaternary valley fills, while in the Assiniboine River the presence of the extensive Assiniboine Delta sediments is the dominant influence. In both cases the poorly-integrated post-glacial drainage pattern is also significant. Thus, it is impossible to generalize about the pattern of suspended sediment yield in drainage basins of this type where riparian sediment sources dominate and their disposition is a product of glacial history unrelated to the present fluvial regime.

The major practical implication of this situation is that the sediment load of these large prairie river systems is largely insensitive to the off-farm impacts of sediment pollution and land-use activities in general. Conversely, long-term monitoring of stream sediment loads on the main stem will reveal little of the impact of such changes. This has important implications for the utility of the present data set in addressing problems of soil erosion and other environmental problems within the basin, as well as design of future sediment monitoring networks to address problems other than those of river engineering. Paradoxically, the data are required to provide the information on sediment sources that demonstrates the inadequacy of the data. This highlights the more general point that in many cases some prior knowledge of the sediment sources and sediment cascade of a particular basin is required before a sediment monitoring network can be designed to address particular problems. At the very least this implies that the information acquired by such a network needs to be continually evaluated and the network modified accordingly.

CONCLUSIONS

The suspended sediment yield of large prairie drainage basins does not follow the conventional model of declining yield downstream. In this respect they follow a pattern of increasing yield downstream similar to that identified for streams in British Columbia. However, the relationship between sediment yield and drainage area is not the same as in B.C and, although the secondary remobilization of Quaternary sediments along degrading trunk streams is generally a significant effect, there are additional factors at work in the two prairie basins described here:

1. Low yields from the land surface (despite extensive agricultural disturbance) are largely a product of isolation of the main streams from the surrounding land surface because of a poorly-integrated drainage system, itself largely a legacy of glaciation.
2. Holocene incision of the main streams which has steepened the distal sections of tributaries and provided sites for extensive badlands development where Cretaceous bedrock is exposed, or rapid erosion of Quaternary sediments.
3. The disposition of particular deposits, such as the Assiniboine Delta.

The importance of local Quaternary history and surficial geology suggests that it is impossible to generalize about the patterns of suspended sediment yield in basins such as these. Furthermore, from a practical point of view, it is clear that monitoring of loads in the trunk streams in such drainage basins will provide little, if any, information on the environmental effects of land-use. The sediment monitoring network must be designed in the light of knowledge of the dominant sediment sources rather than supposed patterns of suspended sediment yield.

REFERENCES

Ashmore, P.E. (1986) Suspended sediment transport in the Saskatchewan River basin. Inland Waters Directorate, Water Survey of Canada, Sediment Survey Section, Report IWD-HQ-WRB-SS-86-9.

Ashmore, P.E. (1990) Analysis and interpretation of Assiniboine River sediment station data. Inland Waters Directorate, Water Resources Branch, Western and Northern Region.

Ashmore, P.E. & Day, T.J. (1988) Spatial and temporal patterns of suspended sediment yield in the Saskatchewan River basin. Can. J. Earth Sci. 25, 1450-1463.

Campbell, I.A. (1977) Stream discharge, suspended sediment and erosion rates in the Red Deer River basin, Alberta, Canada. In: Erosion and Solid Matter Transport in Inland Waters (Proc. Paris Symp., July 1977), 244-259. IAHS Publ. no. 122.

Church, M., Kellerhals, R. & Day, T.J. (1989) Regional clastic sediment yield in British Columbia. Can. J. Earth Sci. 26, 31-45.

Church, M. & Slaymaker, O. (1989) Disequilibrium of Holocene sediment yield in glaciated British Columbia. Nature 337(6206), 452-454.

Department of Fisheries and Oceans, Canada (1978) Hydrological Atlas of Canada.

Dickinson, W.T. & Green, D.R. (1988) Characteristics of sediment loads in Ontario streams. Can. J. Civ. Eng. 15, 1067-1079.

Eilers, R.G., Langman, M.N. & Coote, D.R. (1987) Water Erosion Risk, Manitoba. Agriculture Canada Publication 5259/B.

Klassen, R.W. (1975) Quaternary geology and geomorphology of Assiniboine and Qu'Appelle valleys of Manitoba and Saskatchewan. Geological Survey of Canada, Bull. 228.

Klassen, R.W. (1979) Pleistocene geology and geomorphology of the Riding Mountain and Duck Mountain areas, Manitoba and Saskatchewan. Geological Survey of Canada, Memoir 396.

Manitoba Department of Energy and Mines (1981) Surficial Geological Map of Manitoba. Manitoba Mineral Resources Division, Map 81-1.

Meade, R.H. (1982) Sources, sinks and storage of river sediment in the Atlantic drainage of the United States. J. Geol. 90, 235-252.

Prairie Farm Rehabilitation Administration, Agriculture Canada (1989) The Determination of Gross and Effective Drainage Areas in the Prairie Provinces. Addendum #4, Hydrology Report #104.

Rannie, W., Thorliefson, L.H. & Teller, J.T. (1989) Holocene evolution of the Assiniboine River paleochannels and Portage la Prairie alluvial fan. Can. J. Earth Sci. 26, 1834-1841.

Stichling, W. & Blackwell, S.R. (1957) Drainage area as a hydrologic factor on the glaciated Canadian Prairies. In: General Assembly of Toronto, vol. 3, Surface Water, Prevision, Evaporation, 365-376. IAHS Publ. no. 45.

Trimble, S.W. (1975) Denudation studies: Can we assume stream steady state? Science 188, 1207-1208.

Wolowich, E.A. & Tamburi, A.J. (1985) Sediment dynamics on the Assiniboine River. In: Proc. Can. Soc. for Civ. Eng. Annual Conference (Saskatoon, May 1985), 127-147.