Sediment and the Environment (Proceedings of the Baltimore Symposium, May 1989)
IAHS Publ. no. 184, 1989.

A case study of approaches for determining diffuse suspended sediment sources and processes

Henry R. Hudson
Resource Technologies Department, Alberta Research Council, Edmonton, Alberta, Canada T6H 5X2

ABSTRACT Methods of differentiating sources and processes governing suspended sediment transport in the 4400 km^2 Upper Oldman River basin, SW Alberta, are evaluated. Long term records show that the average annual suspended sediment yield of 275 000 tonnes is largely transported in a period of days during the spring freshet. The majority of this material is thought to be derived from channel and near channel (riparian) sources from a short reach of the river in the Cardston Plains. Sediment sources and process inferences were determined in a static approach by (a) reconnaissance survey of sediment sources (aerial photograph interpretation and site surveys); (b) quantification of sediment sources (sediment budgets for sub-basins and erosional volume estimates of selected sites from sequential aerial photos); and (c) examination of spatial variations in sediment attributes (size distribution, lithology, cesium content). A combination of these approaches is required to obtain a reasonable assessment of the sediment sources and processes.

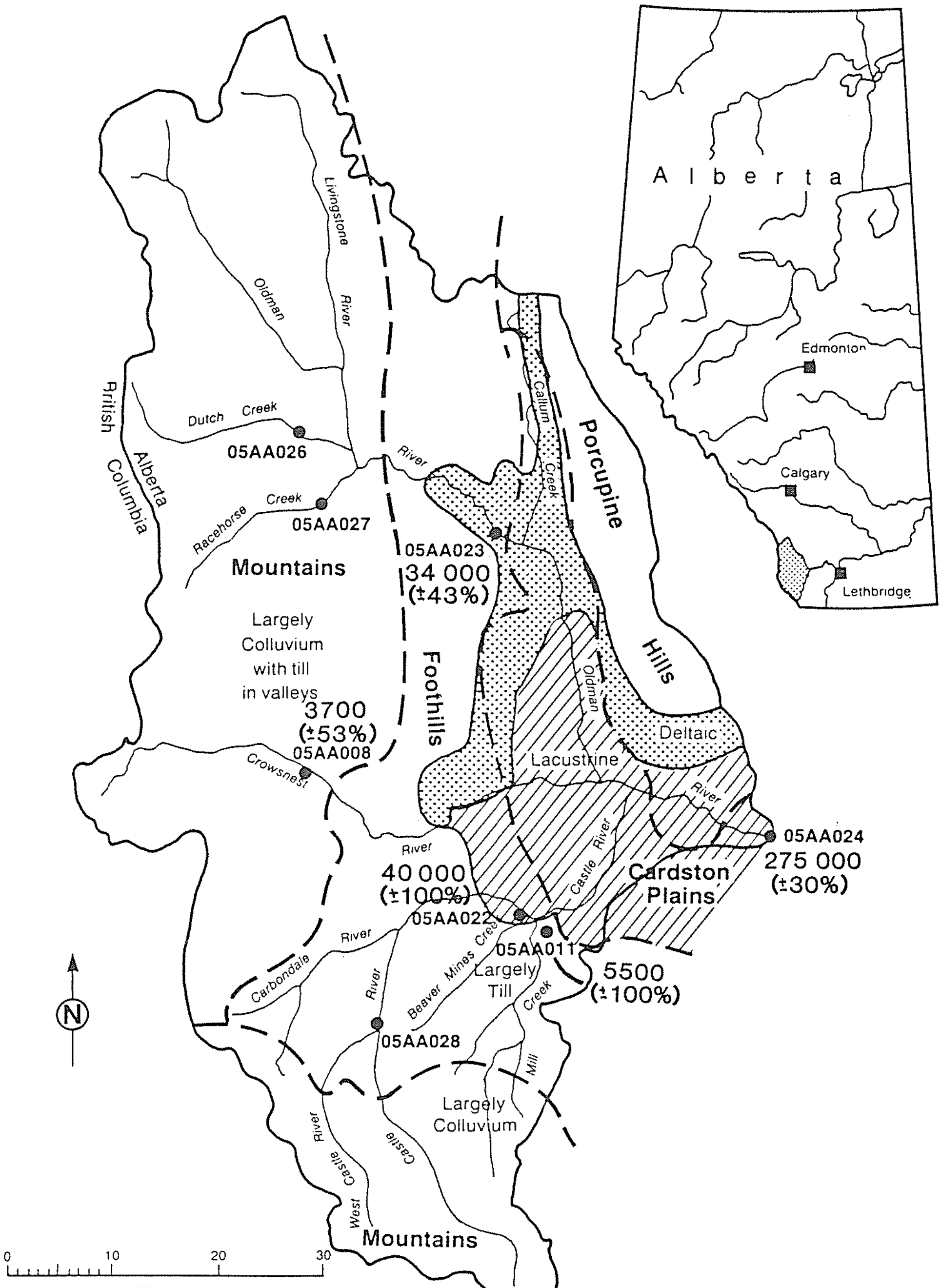
INTRODUCTION

Concerns have been raised about possible sediment associated contaminant cycling problems in the Oldman River basin. As well, upstream sediment control measures may have to be planned for the Three Rivers dam which is being constructed near Brocket (05AA024; Fig. 1). Both of these applications require knowledge of sediment sources and pathways, and factors controlling the sediment regime.

The objectives of this study were: (a) to examine sediment sources and controls on sediment transport in the Upper Oldman River basin; and (b) to relate knowledge of sediment sources and controls to the long term sediment regime. However, the methodology required to undertake such studies is not highly developed. Therefore, the final objective was (c) to develop and evaluate the utility of methodologies for sediment source-process studies.

APPROACHES

There are two major approaches for quantifying sediment yield: the black box and the distributive approach. The majority of sediment yield studies treat the contributory drainage basin as a 'lumped system' (Glymph, 1975), or



05AA024 Sediment station

3700 Load (tonnes/year)
(±53%) Standard error of estimate

Fig. 1 Location of the study area, sediment stations, geomorphic regions and annual suspended sediment loads.

'black box', in that they deal with the basin as a whole, rather than with its constituent parts, in deriving the quantity of sediment expected at a point downstream. Sediment yields from these studies are generally presented as a yield per unit area of the drainage basin, which implies that sediment is evenly derived from the whole of the basin. Although this approach does provide a broad regional picture of sediment yield, that is appropriate for suspended sediment transport estimates at the reservoir, it is not possible to identify the processes of sediment production (upland and channel erosion) and then link them to the sediment regime at the reservoir. This information is prerequisite for understanding sediment contaminant cycling and for the implementation of sediment control measures.

Therefore, a distributive sediment yield approach had to be employed to answer the fundamental issues concerning contaminant cycling and sediment control approaches in the Upper Oldman River basin.

A distributive sediment yield study would ideally be met with a very detailed 'dynamic' sediment sampling program in which sediment loads from point and diffuse sources were monitored over a period of years. Concurrent observations of processes and rates of erosion would provide the descriptive and quantitative information to explain the sediment regime (e.g., Elbow River, Hudson, 1983). However, this type of information was not available, would take at least a few years to obtain, and would be relatively expensive to collect using conventional technologies. Therefore, a 'static' approach had to be employed in this study.

The objectives of the static approach are to: (1) establish distribution and relative magnitude of point and diffuse sources; (b) quantify sediment contributions from the major sources; (c) infer processes by post mortem; and (d) compare inferences with sediment records. The methodologies employed in this study are now described and discussed after the study area description.

STUDY AREA DESCRIPTION

Suspended sediment and streamflow has been measured at several sites in the 4 400 km^2 Oldman River system which flows through the mountains, foothills and plains of the Eastern Slopes of the Rocky Mountains in SW Alberta, Canada. The area has been described by Hudson (1987). With the exception of the fine textured plains tributaries, the system has steep, gravel and cobble bed rivers with a typical high latitude runoff regime. Winter discharges are low, and the river is frozen over a few months. The annual floods usually occur in May or June as the form of snowmelt, which may be enhanced by rainfall. Smaller annual floods tend to be generated by snowmelt, primarily from the foothills and mountains. As the magnitude of the flood increases, the rainfall component tends to increase and the proportion of runoff derived from the lower basin tends to increase. The annual flood rises and receeds rapidly. As a result, most of the annual discharge occurs in a few weeks in spring and the bulk of the suspended sediment transport occurs in a period of days.

RECONNAISSANCE SURVEY OF SEDIMENT SOURCES

Aerial photograph interpretation

Aerial photographs were examined to provide a qualitative overview of the distribution and relative magnitude of sediment sources. The study was deliberately undertaken independently of previously published work (Neill and Mollard, 1982) to compare results. The interpretation scheme outlined by Hudson (1983, 1987) was employed.

Aerial photograph analysis suggested that the dominant fluvial sediment contributions in the Upper Oldman River basin are derived from lateral channel erosion and mass movements of the relatively high river valley walls, and upland erosion with gully development on the Cardston Plain (Fig. 1). The major sediment sources in the foothills are channel and riparian erosion of floodplain, till and recessive bedrock exposures. In the mountains the major sediment sources were thought to be from local lateral river erosion of riparian till sections and from surface wash processes and mass movements of the coarse textured, barren colluvial slopes.

Aerial photograph analysis provided an overview of the distribution of sediment sources with a high degree of consistency between investigators. However, subsequent analysis showed that there were difficulties in interpreting the relative rate of contribution of specific sediment sources, and there were errors in inferring sedimentation processes. It was concluded that aerial photographs were very useful in isolating points of interest for the field inspections, but that field inspection was an absolute necessity for inferring sedimentation processes and assessing the rates of contribution of sediment.

Site Surveys

Aerial survey (by fixed wing aircraft) and visits to the sites identified in the aerial photograph reconnaissance revealed that, with localized exceptions, bedrock control was prevalent throughout the river channel system. The major zone of channel and valley wall sediment contribution was found to be along the Oldman River between the confluence with the Crowsnest River and the gauge at Waldron's Corner (05AA023, Fig. 1). This reach, through the Cardston Plain, is controlled to some degree by incompetent shales and sandstones. Where the bedrock dips below river level, till faces are exposed to the river. As well, there are three very large landslides which have moved significant quantities of overburden to the river channel. In the foothills and mountains of the Castle River several reaches have actively eroding alluvium or till river valley walls.

The gully networks of the Cardston Plain and Porcupine Hills appear to be inactive much of the time. The gullies are generally well vegetated and the major activity appears to be deposition from wind blown soil on the walls, and channel erosion of the gully bottoms. There was little other evidence of upland erosion, probably because farming activities obliterated these features.

The site surveys provided information for process inference as well as illustrating scale and interpretation difficulties in the 1:15 000 and 1:30 000 aerial photographs. Details of small scale processes (such as seepage control of slumping), and features such as sediment storages at various elevations, and lag deposit and bedrock control of lateral erosion, were revealed. However, sediment contributions are qualified not quantified.

QUANTIFICATION OF SEDIMENT CONTRIBUTIONS

Sub-basin sediment budgets

A sediment budget is a quantitative description of the input, storage and export of sediment within a given area and time. The budget is constructed from suspended sediment data at several hydrometric stations (Fig. 1). However, the records were not of equal length or quality, so they were standardized, and the relevance and reliability of the records described (Hudson, 1987).

The sediment stations were fortuitiously located in terms of the physiographic regions. The Brocket station (05AA024) represents the integrated effect of basin scale processes and provides the downstream control with long term, high quality sediment data. The estimated average annual suspended sediment load of the Upper Oldman River (05AA024) is over 275 000 tonnes, with a standard error of estimate of 30 percent. Over two-thirds of this load is derived from the lower part of the drainage basin, which was the area identified as the major sediment contribution zone in the reconnaissance analysis.

The sediment budget quantified the average sediment loads at a sub-basin scale within relatively favourable error bands. However, the quantities of sediment from point (e.g., the major landslides along the Oldman River) and diffuse sources (e.g., upland erosion in the Cardston Plain) of sediment are not defined. Therefore, erosional volumes of select sites were estimated.

Erosional volume estimates

Sediment supply areas identified in the aerial photograph analysis were examined in the field, and six of the apparently more important sources along the Oldman River in the Cardston Plain were selected for volumetric analysis from sequential aerial photographs. Volume estimates from these sources were determined from 1 m contour interval 1:5 000 scale topographic maps (with an accuracy of ±0.5 m in the horizontal and vertical) produced from 1965 and 1985 aerial photographs, using a Wild automatic stereo plotter and ground control. Changes in net volume over the 20-year period 1965 to 1985 were estimated by calculating the area-elevation relationship for each site, using a digitizer. In addition, the net volumetric change of specific areas within the site (e.g., gully systems) were estimated in the same manner. Rates of bank retreat and erosional volumes were estimated from changes in the position of the bank, bank height and representative length, from the cross sections through the deposits.

The six sites, which were identified as the primary sediment sources in the Upper Oldman River basin, contributed about 480 000 m^3 of material to the river over the 20-year period to July 1985. This represents a total load of about 860 000 tonnes (assuming a weight of 1 800 kg/m^3) or 43 000 t/y (±12 500 t/y) of largely suspended sediment sized material, but includes friable bedrock, and morainic material ranging from clay to boulder size.

Of the total sediment contribution from the six sites, 65 percent is derived from erosion of the toe of the deposits by lateral migration of the river or by impingement of the deposit into the channel. The remainder is derived from entrenchment of tributary streams and gully development. These upland contributions are derived from a total area of 0.33 km^2 from a total mapped area of 3.75 km^2. This suggests that significant upland erosion may occur over the long term from unmapped diffuse sources of the Cardston Plain.

The sequential aerial photograph analysis provided an accurate quantification of point and diffuse source long term contributions of sediment. As well, erosional processes could be inferred from the morphometry of the sites. However, this type of analysis may be too costly to undertake for large geographic areas.

SEDIMENT ATTRIBUTES

Sediment attributes, such as sediment size distributions, lithology and cesium-137 content, may be used to differentiate sediment sources (Hudson, 1987). Sediment samples were obtained from channel deposits and from sediment sources. Two types of channel deposit samples were obtained: gravel samples and fine sediment samples. Gravel samples were obtained by bulk sampling the distal ends of bar deposits. The objective was to obtain a gravel sample for petrographic analysis. To minimize sample variance caused by the pronounced variation in gravel deposits, a standard location was sampled (the downstream end of bars) and only the gravel size fraction was petrographically analysed. A bulk sample was obtained by shovelling several kilograms of gravel into a bag.

Fine sediment is very difficult to sample in clean, gravel bed streams and the hydraulic relevance is difficult to ascertain (Hudson, 1987). Samples were obtained by scraping mud from lee deposits in the river channel or from drapes in slack water areas. There was no lack of fine material in the tributary streams or sediment source areas in the Cardston Plain. Samples were obtained by shovelling about a kilogram of fine material into a sample bag.

Particle size distribution

In order to construct a sediment budget from the particle size distribution variations, it would be necessary to describe the size distribution variations of the stream inputs (notably, the Oldman River at Waldron's Corner, the Corwsnest River and the Castle River), the stream output (i.e., Brocket), and the sediment sources. Although this was possible in the Elbow River (Hudston, 1983), there is limited size data available for the suspended sediment in transport and the major erosion sites were generally extremely heterogeneous. The presence of several overlying tills in the typical valley wall requires that numerous samples, and the stratigraphic relevance of these samples, would have to be obtained in order to adequately describe the representative size distribution. This was not possible in this study.

The mud drape and lee deposits from the river channel tend to be somewhat coarser textured than the suspended sediment load at Brocket. This may reflect the fact that the deposits are derived from deposition during waning stages of high flows when the suspended sediment load tends to be coarser (see Day and Spitzer, 1985). The Cardston Plain tributary streams and lacustrine covered benchlands tend to be finer textured than the channel deposits but similar to the bulk of the suspended sediment samples at Brocket (05AA024).

A possible explanation of the increase in silts and clays during large floods is that the finer textured surficial deposits of the Cardston Plain were carried into the river. For example, in 1975, the maximum daily discharge from the plains area was 220 m^3/s. The expansion of gullies and tributary channel erosion during this rare high flow event from the Plains are possible source areas for large quantities of this finer textured suspended sediment.

Petrographic analysis

Spatial variation in bedrock and surficial material characteristics, present the opportunity to differentiate sediment sources on the basis of the petrology of the gravel fraction. Local tills are characterized by Cordilleran rock lithologies, whereas Laurentide tills are characterized by pebbles of Shield and Alberta Plains provenance.

Results of the analysis were inconclusive because of the complexity of the stratigraphy (hence petrology) and the variety of sediment sources. But, it was evident that there are locally important additions of valley wall and channel bedrock to the gravel bars of the lower Crowsnest and Castle Rivers. In the Oldman River reach between the Corwsnest and Waldron's Corner, contributions of overburden and bedrock strongly influence the petrographic composition of the channel deposits locally. This indicates that significant gravel size sediment is contributed to the system in that reach. However, the contribution could be quantified only if the relative abundances of lithologies and size distribution of the source deposits were defined.

Cesium content

Cesium-137 is a product of atmospheric thermonuclear testing since 1945, and there has been significant global fallout since late 1952. Once on the ground surface, cesium is firmly absorbed to the fine fraction of the soil, predominantly in the upper five centimeters. McHenry, Ritchie and Gill (1973) indicated that if cesium is deposited uniformly over a watershed, soils and existing sediments should receive equal amounts of fallout. However, if erosion occurs, some soil containing absorbed cesium will be removed and deposited as sediment. The resulting sediment will be enriched in cesium and the remaining soil will contain relatively less cesium.

Cesium appears to offer the possibility of differentiating upland erosion from channel erosion. The cesium content of the upland sources would be expected to be large when a veneer of cesium rich top soil is removed, whereas lateral channel erosion would be expected to produce sediment with little cesium. The ratio of the upland cesium content and suspended sediment load cesium content would reveal the magnitude of the sediment sources.

Several samples from sediment sources and the river channel deposits were analysed for cesium-137 content. The high cesium content of sediment from a small plains tributary is thought to represent the effects of preferential accumulation of wind blown material, snow and runoff from the adjacent cultivated plains as well as direct atmospheric fallout. There is little evidence of significant channel or upland erosion in the creek. Sediment contributions from this tributary appears to occur primarily from minor channel erosion.

The extremely low cesium content of fluvial deposits at the mouth of Callum Creek (Fig. 1) suggests that upland sediment contributions are minimal in this basin relative to the contribution from channel sources. The basin is primarily grazing land, and channel incision is a feature.

The cesium content of the Oldman River near 05AA023, and the mounts of the Crowsnest and Castle River reflect primarily wind erosion redistribution of soil and perhaps gully erosion. The Castle River mouth area has lower cesium contents because there is little cultivation in the windward part of the basin. The area of land which is cultivated is greater in the case of the Castle and Crowsnest sites, resulting in a greater cesium content in the channel deposits.

The low cesium content of channel deposits at Brocket (05AA024) suggest that relatively low cesium content materials are added to the system between the upstream points and the Oldman River at Brocket gauge. This material is probably derived from lateral channel erosion and from continued gully erosion, rather than extensive surface wash processes of the cultivated lands.

The analysis of sediment attributes such as particle size distributions, cesium-137 content, and petrographic variations of sediment sources, channel deposits and sediment yield from the basin, may be able to be used in their own right to provide estimates of sediment contributions from a drainage basin. However, in complex basins, such as the Upper Oldman River basin, evidence from these approaches are used to confirm independently derived interpretations based on the approaches described previously.

CONCLUSIONS

It is necessary to employ a distributive sediment yield approach to provide the information required to understand sediment associated contaminant cycling, and to provide information for upstream sediment control. This study demonstrates that in complex environments, a combination of approaches have to be employed in order to define sediment sources, pathways and controlling processes.

ACKNOWLEDGEMENTS This study was undertaken as a joint venture with Water Survey of Canada. Their cooperation, and the review comments by David Andres of the Alberta Research Council, are greatly appreciated.

REFERENCES

Day, T. J. & Spitzer, M. O. (1985) Sediment station analysis, Oldman River near Brocket, 05AA024. Sediment Section, Water Survey of Canada, Water Resources Branch, Environment Canada.

Glymph, L. M. (1975) Evolving emphasis in sediment yield predictions. In Present and prospective technology for predicting sediment yields and sources. US Department of Agriculture, Agricultural Research

Service, ARS-S-40, page 5-9.
Hudson, H. R. (1983) Hydrology and sediment transport in the Elbow River basin, Southwestern Alberta. Ph.D. thesis, Department of Geography, University of Alberta, 322 pages.
Hudson, H. R. (1987) An interpretative study of the Upper Oldman River sediment regime. Sediment Survey Section, Water Resources Branch, Inland Waters Directorate, Environment Canada, IWD-WNR(A)-WRB-SS-87-3, 172 pages.
McHenry, J. R., Ritchie, J. C. & Gill, A. C. (1973) Accumulation of fallout cesium-137 in soils and sediments in selected watersheds. Water Resources Research Volume 9, No. 3, page 676-686.
Neill, C. R. & Mollard, J.D. (1982) Erosional processes and sediment yield in the Upper Oldman River basin, Alberta, Canada. In Recent Developments in the explanation and prediction of erosion and sediment yield, IAHS Pub. 137, pages 183-191.