Recent (1999–2003) Canadian research on contemporary processes of river erosion and sedimentation, and river mechanics

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Abstract:
Contributions by Canadian fluvial geomorphologists between 1999 and 2003 are discussed under four major themes: sediment yield and sediment dynamics of large rivers; cohesive sediment transport; turbulent flow structure and sediment transport; and bed material transport and channel morphology. The paper concludes with a section on recent technical advances. During the review period, substantial progress has been made in investigating the details of fluvial processes at relatively small scales. Examples of this emphasis are the studies of flow structure, turbulence characteristics and bedload transport, which continue to form central themes in fluvial research in Canada. Translating the knowledge of small-scale, process-related research to an understanding of the behaviour of large-scale fluvial systems, however, continues to be a formidable challenge. Models play a prominent role in elucidating the link between small-scale processes and large-scale fluvial geomorphology, and, as a result, a number of papers describing models and modelling results have been published during the review period. In addition, a number of investigators are now approaching the problem by directly investigating changes in the system of interest at larger scales, e.g. a channel reach over tens of years, and attempting to infer what processes may have led to the result. It is to be expected that these complementary approaches will contribute to an increased understanding of fluvial systems at a variety of spatial and temporal scales. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS sediment yield; sediment dynamics; sediment transport; channel morphology; turbulent flow; Canada; river ice; bed material transport

INTRODUCTION
This review is part of the Canadian quadrennial report to the International Association of Hydrological Sciences (IAHS). Its focus is on Canadian scientific and applied studies of sediment dynamics in rivers and drainage basins published between 1999 and 2003. This review follows an earlier review by Ashmore et al. (2000) of research published between 1995 and 1998. The themes of this review relate to the research area of the International Commission on Continental Erosion (ICCE), a scientific commission of the IAHS. The themes were also chosen to represent a broad overview of the nature and directions of Canadian research in fluvial geomorphology.

Fluvial systems in Canada have a number of defining characteristics. Because Canada is a high-latitude country, spring snowmelt is a dominant feature of the discharge and sediment transport regimes in most basins. Furthermore, in the northern part of the country, the presence of permafrost directly affects hydrological processes and is an important factor in fluvial processes and landforms. The northern location of Canada is

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also important from a historical perspective, since much of Canada was covered by ice during the Quaternary glaciations. As a result, the landscape in most of Canada is relatively young, and rivers are still actively adjusting to the latest deglaciation, which occurred at the end of Pleistocene Epoch. The high latitude of the country also places it in that part of the world where atmospheric general circulation models (GCMs) suggest thermal impacts of global warming will be greatest.

Even though Canada is generally viewed as a comparatively pristine country, many of its rivers are affected significantly by human activity. A multitude of dams has resulted in modifications of the annual discharge regime, and has led to changes in sediment storage and channel characteristics to a degree that is unknown, but likely substantial. Furthermore, in parts of Canada, human activity has led to a substantial degradation of water and sediment quality—typically associated with urban, industrial, and agricultural areas—and mobilization of large quantities of sediment within the drainage basin, characteristically caused by forestry and agriculture. Sediment quality and quantity directly affect fish populations in streams and, consequently, studies of the effect of human activity on fish habitat and behaviour form an important, applied aspect of fluvial geomorphology research in Canada.

A large body of Canadian research is aimed at elucidating the historical process record, e.g. through the study of lake sediments that reflect the erosional history of the contributing basin. This review, however, primarily concerns contemporary processes. The major themes include sediment budgets and sediment yield; cohesive sediment transport; turbulent flow structure, sediment transport and bedforms; and bed material transport and channel morphology. These themes were selected because they have been the focus of substantial research in Canada. The review ends with a section on recent technical advances, which presents Canadian contributions to methods and techniques for research and monitoring.

SEDIMENT YIELD AND SEDIMENT DYNAMICS OF LARGE RIVERS

Sediment yield is a measure of the response of the fluvial system to processes taking place in the drainage basin. Despite a dramatic decrease in the number of monitoring stations in Canada, studies of sediment yield are still possible using previously collected data, and a number of investigators have taken this approach. Unfortunately, this valuable database will not be significantly expanded in the near future to cover the response of fluvial systems during a period when increased pressures on water resources, combined with climate change, will result in adjustments that are likely to be substantial. Projecting the current understanding of fluvial systems to the future will, therefore, be a significant challenge.

Spatial and temporal patterns in sediment yield

Church et al. (1999) examine fluvial clastic sediment yield in Canada, and present maps of regional sediment yield for standard areas of 1, 10² and 10⁴ km². The specific sediment yield, i.e. expressed per unit surface area, increases downstream in most regions, indicating regional degradation of river valleys. Aggradation on a regional basis, however, is taking place on the southern prairies, whereas specific sediment yields on average are similar at all scales in southern Ontario. The scale dependence of specific sediment yield means that sediment yields must be scaled to a standard area for comparison between basins and regions.

Church (2002a) reviews morphological transitions and thresholds associated with sediment and water transfer through riverine landscapes and discusses the influence of stream competence on the distribution of sediment and channel characteristics throughout the drainage basin. In a second paper, whilst addressing the question of sediment transfer in cold regions, Church, (2002b) suggests that sediment transfer within a drainage basin at long time scales (10²–10⁶ years) is mainly a matter of sediment storage. The glaciations of the Pleistocene Epoch are the most significant sedimentary disturbance event in geologically recent times in Canada (see also Church and Slaymaker (1989) and Church et al. (1999)), but sedimentary disturbance is also detectable in landscapes that recently have been extensively perturbed by human activities (Church, 2002b). That paper also presents a model of sediment movement and storage in a drainage basin as a cascade of linear
reservoirs, a hypothesis investigated by Lisle and Church (2002) by studying the transport–storage relations of natural sediment storage reservoirs such as valleys and channels. They propose a two-phase conceptual model: phase I, in which a reservoir, e.g. a channel segment, responds to variations in sediment supply by proportional changes in the volume of stored sediment (linear response); and phase II, in which the reservoir responds through armouring and changes in roughness (non-linear response).

Evans and Church (2000) address an issue that is crucial for studies involving lake-sediment-based reconstructions of sediment yield, i.e. how to derive error estimates of the estimated sediment yield. Their approach involves modelling the physically controlled, spatial variability of sedimentation using regression surfaces fitted to point values of sediment mass derived from multiple cores. Deviations from these surfaces are interpreted to represent the remaining, unstructured variance, which provides an error estimate. Because the majority of lake sediment studies are based on a small number of cores, the method proposed by Evans and Church (2000) will result in a significant increase in cost.

Sediment and contaminant transport in the St Lawrence River

Several large Canadian rivers, such as the St Lawrence, the Fraser, and the Mackenzie, drain substantial parts of North America. The first two of these rivers have been the subjects of extensive investigation into their sediment transport characteristics. Rondeau et al. (2000) examine the budget and sources of suspended sediment for the reach of the St Lawrence River between Cornwall, Ontario—near Lake Ontario, where the river starts—and Quebec City, Quebec, for the period 1989–93. The results of this study indicate that Lake Ontario contributes less than 3% of the particulate load at Quebec City—estimated as 6.9 $\times 10^9$ t year$^{-1}$—whereas the tributaries on the south and north shores contribute 19% and 13%, respectively, of the sediment load. The remainder, nearly 65%, results from erosion of the bed and banks of the St Lawrence River. As a result, the specific sediment yield of the St Lawrence increases with drainage area, which is consistent with the results presented by Church et al. (1999).

The presence of fluvial or riverine lakes is a characteristic feature of the St Lawrence River. These lakes—from upstream to downstream, Lac Saint-François, Lac Saint-Louis and Lac Saint-Pierre—represent wide and shallow sections of the river rather than true lakes. To investigate the role of these riverine lakes in the transport and storage of sediment and associated contaminants, Carignan and Lorrain (2000) used $^{210}$Pb, $^{137}$Cs and $^7$Be to investigate the sediment dynamics, with the objective to evaluate accumulation rates and to characterize the mixed sediment layer. It was found that sediment retention in the lakes ranged from 1.5 (Lac Saint-Pierre) to 17% (Lac Saint-François) of the annual suspended sediment load. The relatively high mixing coefficient in the superficial sediments (14.9 $\pm$ 2.8 cm$^2$ year$^{-1}$) and the similarity between the annual particulate matter loading to the river and the mixed sediment inventory suggest that these lakes have a short memory of past conditions and can be expected to recover rapidly (within 2 to 5 years) following a decrease in contaminant influx. Lepage et al. (2000) investigated the sediment dynamics of the upstream portion of Lac Saint-François, and concluded that the suspended load on the northern side of the lake is mainly a function of the suspended load carried by the St. Lawrence River. In contrast, on the southern side of the lake, sediment resuspension and contributions of local tributaries constitute an important portion of the suspended load. Lepage et al. (2000) point out that wave action is likely to resuspend surficial sediments where the lake is shallower than 2 m, which encompasses a surface area estimated to be 32 to 35 km$^2$ between Cornwall Island and Thompson Basin. Resuspension of sediment by waves is also a factor in the other riverine lakes (Carignan and Lorrain, 2000).

The St Lawrence River system has been extensively modified for navigation and hydropower generation. Morin et al. (2000) applied a two-dimensional hydrodynamic model to simulate past flow conditions and to produce quantitative descriptors of morphological change in Lac Saint-François. A comparison of the pristine state, based on 1870 and 1900 measurements, with the present-day geometry indicates significant changes in the morphology of the lake. Hydrodynamic simulations for the pristine and present-day states indicate an increase in velocities over shoals and a decrease in velocities in deeper water for discharges less than
8800 m$^3$ s$^{-1}$. Dredging and straightening around Cornwall Island resulted in changes in the proportions of the discharge carried by the two channels around the island, with an increase in flow through the south channel from 64 to 71% of the total river flow and a corresponding decrease in flow in the north channel from 36 to 29%. Human activity in and around the St Lawrence likely also affects erosion and deposition elsewhere along the river (Rondeau et al., 2000).

Much of the sediment-related research on the St Lawrence River has been carried out because of concerns about contaminant transport. Lean (2000) presents an overview of these issues. Filion and Morin (2000) investigated the effect of local sources on metal concentrations in littoral sediments and aquatic macro-invertebrates of the St Lawrence River near Cornwall, and found that metal concentrations in sediment increased with the percentages of fines and organic matter, but were generally below the lowest effect level of the Ontario provincial sediment quality guidelines. They conclude from the spatial pattern of metal concentrations in littoral sediments that local sources of mercury and zinc contributed to the contamination. Chromium, iron, nickel and zinc concentrations in macro-invertebrates were similar to or exceeded concentrations reported for deeper sites in the Cornwall area, despite the much lower concentrations in littoral sediments, suggesting that bio-availability of these metals is greater in littoral than in deeper sediments. A comparison with the Ontario sediment quality guidelines and with other sites in the Great Lakes–St Lawrence system suggests that metal contamination of littoral sediments and invertebrates along the section of the river investigated was relatively low, despite the effect of local point sources. The fate of sediment in the St Lawrence River is not just affected by the flow in the river itself, but also by the flow conditions in the tributaries. Lepage et al. (2000) suggest that fluctuations in the winter discharge of the south-shore tributaries contribute to sediment resuspension and redistribution of contaminants such as mercury and polychlorinated biphenyls in Lac Saint-François.

**Sediment transport in the Fraser River**

On the other side of the continent, Sichingabula (1999) investigated the magnitude–frequency characteristics of effective discharge (Wolman and Miller, 1960) for suspended sediment transport in the Fraser River, British Columbia, using discharge and sediment concentration data for the period 1965 to 1988 that were collected and archived by the Water Survey of Canada. Sichingabula (1999) defines the effective discharge as the midpoint of the discharge class transporting the greatest portion of the suspended sediment load, and presents equations for predicting the class-based effective discharge in the Fraser River basin from bankfull discharge and drainage area. McLean et al. (1999) investigated sediment transport along the lower Fraser River using sediment transport data collected between 1966 and 1986, and found that the annual total suspended load at the three stations investigated (Hope, Agassiz, and Mission) was almost identical at $17 \times 10^6$ t year$^{-1}$. Over the long term, sand made up about one-third ($5.5 \times 10^6$ t year$^{-1}$) of the total suspended load at Hope and Agassiz. In any given year, however, some sand is stored within the channel reach and transported further downstream later.

**COHESIVE SEDIMENT TRANSPORT**

The transport of cohesive sediment in aquatic systems is characterized by interactions among fine-grained sediment particles that cause flocs to form. Flocs have relatively low densities, large pore spaces, and reactive surfaces that remove contaminants from the water column. Flocculation alters the transport characteristics of solids by changing the aggregate density, porosity, settling velocity and surface area, and is an important mechanism for removal of particulates in streams, lakes and oceans. Numerical models designed to simulate contaminant transport, fate and bioaccumulation in aquatic environments have begun to include a cohesive sediment transport component (Church and Krishnappan, 1998), but a better understanding of cohesive sediment transport processes (erosion, deposition, flocculation) is required to improve model predictions.
The following sections review recent Canadian studies that have advanced knowledge regarding the nature and transport of cohesive sediment in aquatic systems.

**Nature of cohesive sediment**

Cohesive materials represent variable proportions of the total annual sediment flux in many Canadian rivers (Droppo et al., 1998; Krishnappan, 2001) and urban storm water runoff (Krishnappan et al., 1999; Droppo et al., 2002). The morphology and settling characteristics of these materials vary in response to physical, chemical and biological attributes of individual rivers and sediment sources (Petticrew and Droppo, 2000). Cohesive suspended sediment is commonly transported in fluvial systems in a flocculated form, and many larger flocs do not settle within the Stokes region of Reynolds numbers (Droppo et al., 2000). In a study of river and lake sediment, Droppo et al. (1999) report that only flocs <100 µm (equivalent spherical diameter) settled within the Stokes region (Re < 0.2). The bulk densities of these flocculated materials ranged from 1 to 1.4 g cm⁻³, but the majority of flocs had densities of less than 1.1 g cm⁻³. Floc porosity increases with floc size, and low floc densities are caused by the high porosity of the flocs (Droppo et al., 2000).

Flocs consist of a complex matrix of microbial communities, organic particles, inorganic particles, interfloc pore spaces, and interstitial water (Droppo, 2001). Advances in understanding the structural components of a floc and of its individual properties have led to the development of a conceptual model that links the structural and behavioural components of flocs (Droppo, 2001). The model modifies the traditional view of suspended solids from discrete particles to a collection of compositionally diverse flocculated particles that behave as individual micro-ecosystems with complex physical, chemical and biological behaviours.

Fractal dimensions reflect the nature and mechanism of formation of particles. Particle properties, such as settling velocity and density, are a function of the fractal dimensions. De Boer and Stone (1999) examined the fractal dimensions of suspended solids in streams to compare settling and filtration sampling techniques for particle analysis. Systematic differences between the two methods were observed, the filtration method being more sensitive to indicating differences within and between the sites in two basins. De Boer et al. (2000) investigated the fractal dimensions of individual flocs and floc populations of suspended solids collected during snowmelt in southern Ontario streams with contrasting riparian buffer zones. Fractal dimensions of both individual flocs and floc populations provided similar information about temporal changes in sediment source contributions and about the contrasting effectiveness of the riparian buffer zones in the two basins.

Stone and Krishnappan (2003) examined the fractal dimensions of particle populations of cohesive river sediment in a rotating circular flume and used image analysis to evaluate the structure and size distribution of flocs formed during the deposition process at four conditions of steady state flow. As shear stress increased from 0.058 to 0.121 Pa, particle boundaries became more convoluted and shape irregularity of larger particles increased compared with the smaller ones. Micro-flocs were the building blocks of the larger flocs suspended in the water column, and the stability of larger flocs was a function of the shear stress at steady state.

An international symposium on ‘The Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer’ was held at the University of Waterloo in 2000. The published proceedings of the symposium advance knowledge of erosion and sediment transport processes in relation to the transfer of chemicals at a range of spatial and temporal scales (Stone, 2000). Ongley and Droppo (2000) provide guidance on sampling suspended solids for water quality investigations.

**Cohesive sediment transport**

Numerical models have been developed to predict the transport and fate of sediment and contaminants. These models require information on the transport characteristics of sediments as input parameters. For cohesive sediment, variables such as erosion rate and critical shear stress for erosion and deposition must be determined by direct measurement. The following sections review recent laboratory and field investigations that have advanced knowledge of cohesive sediment transport.
Laboratory studies. Flocculation of cohesive materials and settling of flocs on the riverbed result in the formation of surficial fine-grained laminae (SFGL) that represent a significant potential sink for contaminants bound to cohesive sediment (Droppo and Stone, 1994; Stone and Droppo, 1994). Several recent studies have advanced knowledge regarding the formation and erosional characteristics of SFGL. Droppo et al. (2001) conducted experiments in an annular flume using commercially available kaolinite clay and contaminated bed sediment from Hamilton harbour to assess the effect of depositional history on the stability of contaminated bed sediment. Results of the study demonstrate that bed erodibility depends on both the degree of bio-stabilization and the flow conditions under which the bed is deposited. In a related study, Lau and Droppo (2000) report that the critical shear stress for beds deposited under sheared flow was up to eight times larger than for beds deposited under quiescent conditions. In a series of sequential erosion–deposition experiments, Lau et al. (2001) demonstrate the effects of depositional history on erosion and show how the rate of erosion and the amount of sediment eroded reflect the structure of the bed and flocs that formed it. That research shows that layers of sediment deposited under different conditions will not have the same shear strength, and similar flow conditions, therefore, do not necessarily produce the same erosion rates.

Using a rotating circular flume, Krishnappan and Marsalek (2002a) measured the transport characteristics of cohesive sediment deposited in an on-stream storm water management pond. The critical shear stresses for deposition (0.050 N m\(^{-2}\)) and erosion (0.12 N m\(^{-2}\)) of pond sediment were determined and used to develop empirical relationships to estimate sediment deposition and erosion as a function of shear stress. A new model to predict transport characteristics of sediment from an on-stream storm water management pond was developed by Krishnappan and Marsalek (2002b). Skafel and Krishnappan (1999) investigated the depositional characteristics of mud from Port Stanley harbour using a rotating annular flume, and showed that duration of sample storage, presence of bacteria, and textural composition of the sediment affected depositional behaviour.

Milburn and Krishnappan (2003) carried out an intensive field programme before river-ice break up and conducted controlled experiments in a rotating annular flume to determine the critical shear stress for erosion and deposition of Hay River sediment. They proposed a modelling strategy for analysing the under-ice transport of cohesive sediments in the Hay River. Krishnappan (2000a) developed a new algorithm for the transport and deposition of Hay River sediment. They proposed a modelling strategy for analysing the under-ice transport of cohesive sediments in the Hay River. Krishnappan (2000a) developed a new algorithm for the transport and deposition of Hay River sediment. It was incorporated into and improved the performance of the contaminant transport model WASP5. These algorithms have also been used to improve accuracy of the sediment transport models RIVFLOC and FINSED (Krishnappan, 1991; Krishnappan, 1997).

Field studies. A series of field studies has been conducted with portable flumes to determine the in situ transport properties of cohesive sediment in lakes and rivers. Droppo and Amos (2001) used an in situ annular flume to assess the effect of shear stress on the structure and stability of bottom sediments in Hamilton harbour. They developed a general three-layer model that depicts organic flocs of the fine-grained surficial layer (layer 1), which are compressed within the collapse zone (layer 2) to form a consolidated bed (layer 3). The structure of the eroded materials evolved from low-density flocs eroded from the fine-grained surface layer to dense aggregates derived from the consolidated bed. In a related study, Amos et al. (2003) compared three methods to estimate the threshold shear stress \(\tau_c\) of lakebed sediment using the benthic flume Sea Carousel. The method, which extrapolates a regression of suspended sediment concentration and fluid-transmitted shear stress, is recommended for evaluation of the erosion threshold.

Krishnappan (2000b) used a submersible laser particle-size analyser to show that suspended solids in the Fraser River downstream of a pulp mill outfall were transported as flocs. The fibrous organic material in the effluent promoted flocculation of inorganic solids suspended in the water column, which increased the deposition rate of sediment. Biickert (1999) carried out a 1 year study of the structure and composition of suspended sediment upstream and downstream of a pulp mill discharging effluent into the Fraser River (see also Petticrew and Biickert (1998)). That study indicated no significant differences between the upstream and downstream sites in the total amount, size and deposition rate of fine sediment collected in gravel traps.
addition, there were no significant differences in the fractal dimensions of suspended sediment upstream and downstream of the effluent source, and only a very small increase in the $d_{84}$ of the suspended flocs at the downstream site. The significant seasonal variation in floc size far exceeded the near-field effects of the pulp mill effluent. The differences between the findings of Krishnappan (2000b) and Biickert (1999) are due to the use of different sampling techniques and scales at which the effluent effect was evaluated. Krishnappan (2000b) tracked the plume downstream using a Malvern *in situ* laser particle size analyser, whereas Biickert (1999) used laboratory microscopy and image analysis, and sampled at stationary sites approximately 300 and 600 m downstream of the effluent pipe. Grain size distributions from the *in situ* Malvern particle analyser are typically coarser than those from the image analysis method because the Malvern has a higher cut off.

Subsurface drainage represents a relatively unknown component of sediment transport in low-order streams, and little is known about the effect of soil texture, land use and moisture conditions on the properties and transport characteristics of sediment in tile drains. Stone and Krishnappan (2002) examined the effects of irrigation on tile sediment transport in tile drains in a headwater drainage basin. The sediment yield during a controlled irrigation event was 4.6 kg ha$^{-1}$ and tile sediments were fine-grained ($d_{50} \approx 5 \mu m$).

Stone and Haight (2000) used a field-based water elutriation system to investigate the occurrence and distribution of dioxins and furans in separated size fractions of suspended sediment during a spring storm event in Canagagigue Creek near Elmira, Ontario. Several furan and dioxin compounds, including 2,3,7,8-T$_4$CDD and 2,3,7,8-T$_4$CDF, were detected in suspended solids at levels comparable to those reported in previous investigations of creek bed and floodplain sediments. There was no significant relationship between grain size and organic contaminants in suspended solids because of the highly flocculated and bio-stabilized nature of river-bottom sediment eroded from the study site.

In a study of suspended solids, trace metals and polycyclic aromatic hydrocarbon (PAH) concentrations from coal pile runoff to Hamilton harbour, Curran *et al*. (2000) found that trace metal concentrations often exceeded the Canadian Water Quality Guidelines for the Protection of Aquatic Life and concentrations of some PAHs exceeded the provincial ‘Severe Effect Level’. They recommend treatment of coal pile discharge as a component of remedial action for the harbour. Lévesque and De Boer (2000) investigated the trace element chemistry of SFGL in the South Saskatchewan River. Concentrations of copper, zinc, cadmium, lead and uranium in SFGL samples downstream of the city of Saskatoon were significantly greater than upstream samples collected on days when the flow velocities were low.

**Turbulent Flow Structure and Sediment Transport**

Flow provides the impetus for sediment transport and the development of bedforms in river environments. The study of flow turbulence has become increasingly relevant over the last few years for two reasons. First, sediment transport has been found to be highly variable at small space and time scales (e.g. Nelson *et al*., 1995). As a consequence, the flow parameters relevant to the study of sediment transport must also be investigated at small scales, and it becomes necessary to look beyond mean parameter values. Second, continued investigations into the structure of turbulent flow have revealed organization at a variety of scales (e.g. Roy *et al*., 1996; Buffle-Bélanger *et al*., 2000a). There exists a strong potential for feedback mechanisms between the structure of flow and the organization of the bed. Recent research in Canada has contributed to the study of the character of turbulent flow in rivers and of the interaction of turbulence with sediment transport and bedforms.

*Flow structure in gravel-bed rivers*

Progress in the understanding of flow structure in gravel-bed rivers has been made through a combination of flume experiments, field studies, and computer simulations. Lawless and Robert (2001a) constructed pebble clusters for a series of flume experiments, and obtained high-resolution, three-dimensional measurements of the surrounding flow fields. They found high lateral variance of flow properties, but they were unable to
confirm the hypothesis of a standing horseshoe vortex. Instead, the results suggested an intermittent structure that converges in the upwelling zone downstream of a cluster. In a second paper, Lawless and Robert (2001b) address the effects of pebble clusters on local and average velocity profiles. The increase in the scale of roughness induced pressure gradients that changed the shape of the velocity profiles and increased the average shear stress in the outer region by 100% relative to plane bed conditions.

Buffin-Bélanger et al. (2000a) measured and visualized large-scale flow structures in a natural gravel-bed river and developed a new technique based on time–space velocity matrices for their presentation. Velocities were measured using an array of electromagnetic current meters (ECMs) sampling at a frequency of 20 Hz. Large-scale flow structures were shown to consist of low- and high-speed wedges that occupied the full depth of flow. The new presentation technique was used to demonstrate a clear association of the high-speed wedges with large peaks in bed shear stress. In an effort to integrate recent advances of the understanding of turbulence in gravel-bed rivers, Buffin-Bélanger et al. (2000b) developed a conceptual model of the interactions between bursts (as classically defined in the literature on boundary-layer dynamics), surface boils, shedding motions from clusters and protruding particles, and large-scale flow structures. These schematics, while speculative, highlight the range of scales in coherent turbulent structures and their complex interactive potential. Buffin-Bélanger et al. (2001), again using an array of ECMs operated at 20 Hz, applied correlation and flow visualization techniques to explore further the interactive nature of shedding motions and large-scale structures. Strong downstream velocities at the crest of a protruding particle or cluster were followed, after a small lag, by strong upstream velocities in the separation zone. The visual analysis suggested a relation between the passage of large-scale structures and the shedding of eddies from the separation zone.

Millar (1999) examined the modification of energy dissipation due to bedform development in gravel-bed rivers. Using data from a number of sources, he demonstrated that overall roughness can deviate strongly from widely used relations with grain size due to roughness generated by bedforms. Zimmermann and Church (2001), in a study of stability of step–pool structures in the upstream part of the Shatford Creek basin in British Columbia, found an empirical relation between step height and the depth of the downstream pool. This suggests that flow turbulence was playing at least a modifying role, as the dissipation of momentum in the pools caused sediment to be moved out and deposited downstream. Woollridge and Hickin (2002) tested different methods for the identification of individual step–pool bedforms in Mosquito Creek, a small steep stream in British Columbia. The visual identification method provided more information about the bedform geometry than the other methods, and the power spectral method identified periodic wavelength in the both reaches examined.

Flow structure over dunes

The understanding of flow structure in sand-bedded rivers has advanced due to laboratory experiments and a series of field experiments conducted in the Fraser River of British Columbia. Robert and Uhlman (2001) undertook a comparative study of flow turbulence above three bed types in a flume. The beds were fixed positive casts of fluvial forms, and represented the transition from a ripple to a dune-dominated morphology. An acoustic Doppler velocimeter (ADV) was used to measure velocities in three dimensions at 10 Hz. A gradual increase in overall turbulence intensity was observed through the transition, and the spatial variability of turbulence increased in a non-linear fashion, with dunes inducing very high Reynolds stresses on the bed at some locations.

Villard and Kostaschuk (1998) compared the effect of symmetric and asymmetric dunes on the relation between shear velocity and suspended sediment concentration over large dunes in the estuary of the Fraser River in British Columbia. They found that the roughness length for asymmetric dunes was much larger than for symmetric dunes, and that asymmetric dunes were relatively inactive remnants of symmetric forms developed during high flows. Kostaschuk (2000) continued the investigation by combining measurements, taken at 1 Hz, of velocity with an ECM and of turbidity with an optical backscatter (OBS) sensor. On the stoss side of the dunes, the near-bed velocity and sand concentration increased, whereas in the leeside
separation zone the intensity of turbulence increased and reversed mean flow was observed. Wake-flapping and eddy shedding from the separation zone were found to be the dominant generators of turbulence. Both processes advected eddy structures into the ambient flow at an angle of 23–25° from the horizontal.

Villard and Church (2003) investigated the importance of the dune structure for sediment transport. They repeatedly surveyed the bathymetry through the middle of a navigation channel in the Fraser River and found dune dimensions to increase in height and length in response to increases in flow, though lags between flow and dune dimension peaks were commonly observed. The study confirmed that dune-associated transport corresponds with overall bedload transport in the channel, highlighting the importance of understanding dune mechanics.

Bedform mechanics in sand-bed environments are also active areas of research in other Earth science fields. Recent progress in aeolian sand transport and dune formation is reviewed by Walker and Nickling (2002), and Crawford and Hay (2003) present the results of an investigation into ripple migration in near-shore ocean environments. These fields offer ample opportunity for sharing results, as the forms being studied are similar, though each environment presents unique challenges.

Flow structure at river confluences

Recent research into the flow dynamics at river confluences has emphasized the role of turbulence and the advantages of numerical modelling. De Serres et al. (1999) conducted a field investigation into the three-dimensional flow structure at the Bayonne–Berthier confluence in Quebec. Velocity measurements in three dimensions were obtained at 20 Hz using ECMS, though limitations of the technology meant that only two dimensions could be measured simultaneously. The study documented the flow structure at the confluence over a range of flow stages and bed conditions. The results illustrate the feedback from bed morphology to flow structure, and the dominant role of mixing layer vortices in controlling bed morphology and sediment transport. Biron et al. (2002) conducted a field-based study to obtain accurate measurements of variations in water surface elevation at the Bayonne–Berthier confluence. They were able to document coherent patterns of super-elevation and depression, including super-elevation of the mixing layer. Incorporating this information into a numerical model increased the accuracy of the simulations.

Lane et al. (1999) began a critique of the manner in which secondary flow circulation is typically defined at channel confluences. They argue that secondary flow can appear mathematically where, due to flow convergence and the downstream transfer of water, no secondary circulation occurs. These arguments were developed more fully in Lane et al. (2000) and the dangers demonstrated of using numerical simulations. The simulations resolved larger scale eddies using the Navier–Stokes equations, and sub-grid-scale turbulence was resolved using the SIMPLE algorithm of Patankar and Spalding (1970). The results were verified by comparisons with flume and field data. One of the main problems found was the requirement of data rotation for secondary flow identification. The results were shown to be radically different depending on the rotation used. The research also showed the dangers of working with mean flow values, as instantaneous values indicated the dominance of periodic eddy shedding events rather than a closed secondary circulation cell. Further simulation work (Bradbrook et al., 2000, 2001) investigated the roles of bed discordance, junction angle, and velocity ratio at river confluences. Flow separation as a result of bed discordance was found to result in upwelling into the separation zone and significantly reduced mixing lengths compared with confluences without bed discordance.

Interaction of turbulence and sediment transport

The initiation of sediment transport by turbulence has been examined by a number of investigators in the last decade. Nevertheless, feedback mechanisms such as the modification of turbulence by entrained sediment remain poorly understood. Recent flume studies have aimed to address this problem. Li and Gust (2000) examined drag reduction due to the introduction of cohesive sediments. They designed a series of flume experiments in which kaolinite was fed at different concentrations into flows over a smooth bed. Skin
friction shear velocities and velocity profiles were measured using an array of hot-film sensors. They found that shear velocity was reduced by up to 70% as a result of the presence of sediment. The decrease in shear velocity was attributed to a thickening of the inner wall layer and turbulence damping.

Bergeron and Carbonneau (1999) investigated the effect of sediment load on flow properties by feeding sediment into a flume with a fixed rough bed and maintaining flow conditions above the entrainment threshold. Velocity profiles were measured, and shear velocity, roughness length, and resistance to flow were calculated. It was found that mean flow velocity decreased with an increase in sediment concentration, whereas shear velocity, roughness length and resistance to flow increased. A shear velocity plateau was reached that appeared to be associated with the sediment transport capacity of the flow. In a continuation of the work, Carbonneau and Bergeron (2000) found that, under some conditions, the introduction of sediment resulted in higher mean velocities. These conditions corresponded to situations in which flow turbulence decreased. The authors argue that the effect of sediment load on roughness is difficult to predict because parameters such as roughness are representative of energy dissipation at a large scale. The incorporation of greater spatial and temporal variability through the study of turbulent kinetic energy and turbulent dissipation is necessary to identify the active physical mechanisms.

BED MATERIAL TRANSPORT AND CHANNEL MORPHOLOGY

Channel morphology is governed by the volume and distribution of water flow, the magnitude and other characteristics of the sediment load, the properties of the bed and bank material, and the characteristics of the riparian vegetation. Recent Canadian research has addressed four major issues: sediment transport and bed surface structures; morphological methods for estimating sediment transport; response of channel morphology to changes in the controlling factors; and modelling of channel dynamics.

Sediment transport and bed surface structures

Bed material transport in gravel-bed rivers commonly occurs at near-threshold rates. Under these conditions, the bed is only partially mobilized, and most of the bed material remains immobile for extended periods of time. Hassan and Church (2000) continued earlier work by Church et al. (1998) by conducting flume experiments to examine the development of surface structures and to explore their influence on channel stability. Zero-feed experiments show that such structures developed simultaneously with the armour (Church et al., 1998). Under varying feeding conditions, the bed surface structures remained intact, but the bed surface composition fined with increasing sediment transport rate (Hassan and Church, 2000).

Hassan and Church (2001) examined the sensitivity of bedload flux to variations in flow strength using trap-specific rating curves obtained in Harris Creek, British Columbia. All the rating curves were very sensitive, indicating that bedload flux remained in the partial transport regime. The ratings also exhibited seasonal hysteresis, and varied from trap to trap. Church and Hassan (2002) found that fractional transport rates in Harris Creek would plot up to three orders of magnitude below the reference transport rate corresponding to the threshold of movement suggested in the literature. Sediment mobility was largely controlled by bed surface structures that stabilize the bed and reduce the transport rate by orders of magnitude.

Zimmermann and Church (2001) identified three distinct populations of gravel in the upstream part of the Shatford Creek basin in British Columbia. Each population exhibited a characteristic degree of stability: the immobile boulders that form the step keystones; loose cobble population in the pools; and fine pocket deposits. They concluded that the keystones are delivered to the channel by mass wasting. As a result, the keystone location is semi-random, and aspects of the channel morphology, such as step–pool wavelength and step height, display a large variability.

Scour and fill, and fish habitat

Haschenburger (1999) described the spatial variation of scour and fill in Carnation Creek, a small gravel-bed river on Vancouver Island, British Columbia. She fitted an exponential density function to the frequency
distributions of scour and fill depths and the model parameters were related to the dimensionless shear stress. Paige and Hickin (2000) examined the annual patterns of scour and fill in the Squamish River by using sonar cross-sectional surveys. The analysis indicates that there is no simple relation between mean bed elevation and discharge. The bed-elevation regime is dominated by the variation in sediment transport rate, which in turn depends on the sediment supply. Fassnacht and Conly (2000) used bathymetric evidence to examine the spatial and temporal stability of a scour hole in the East Channel of the Mackenzie delta. The study shows that the hole remained stable even during the record event of 1988. Nevertheless, some lateral erosion and sedimentation has been recorded.

A gravel-bed river represents a heterogeneous habitat for fish. Local-scale variations in turbulence and sediment transport have strong implications for fish energetics and reproduction success. Several recent studies have addressed the spatial variability of scour and its impact on redds. Lapointe et al. (2000) delineated potential spawning areas in a river and then completed high-resolution topographic surveys to determine the impacts of three significant floods on scour and fill. The data suggested that the probability of scour ranges from under 5% for a typical spring flood, to approximately 20% for a rare event with a recurrence period measured in centuries. Rennie and Millar (2000) used a spatially dense (monitor density of 0.059 m⁻²) array of scour chains in a short spawning reach of Kanaka Creek, British Columbia, to determine whether there was a difference in scour depth between redds and the surrounding bed. They found that the spatial variability of scour was greater than the density of their measurements, so that there was no statistically significant difference between redds and the adjacent bed. None of the four egg pockets instrumented, however, was scoured to the critical depth during a typical spring flood, whereas scour was much greater in the redd tailspill areas.

Morphological methods for estimating sediment transfer

In several recent studies, estimates of sediment transfer in rivers have been made using observed changes in channel morphology (Ashmore and Church, 1998). McLean and Church (1999) investigated sediment transport along the lower Fraser River using data collected between 1966 and 1986 in combination with channel surveys conducted 32 years apart. The study indicates that within-reach variations in transport are substantial, so that the results from a single cross-section may not be representative for the entire reach. Furthermore, the authors conclude that the bed material fraction of the sediment load often is far less than the hydraulic capacity would indicate, and that approaches based on morphological change seem to be the most cost effective and can best take advantage of available historical information.

Ham and Schwab (1998) examined erosional and depositional trends along the wandering gravel-bed channel of the Kitimat River, British Columbia, and Ham and Church (2000) examined the relation between planimetric channel changes and bed-material transport along the gravel-bed channel of the Chilliwack River, British Columbia. Morphologic change and sediment transport in these systems is dominated by the passage of large floods that cause extensive bank erosion and introduce much of the supply of available bed material to the channel. Eaton and Lapointe (2001) used the morphologic method and the Meyer-Peter and Müller formula to estimate sediment transport during two extreme floods on the cobble-bed Sainte Marguerite River, Quebec. They attribute channel instability to changes in channel pattern and the initiation of bed degradation following channel rectification during the 1960s. Using data collected during flume experiments, Lindsay and Ashmore (2002) examined the magnitude of bias associated with estimates of scour and fill that are derived by differentiating topographic surfaces. Their analysis shows an inverse relationship between survey interval and the measured cumulative volumes of scour and fill.

Channel morphology and adjustment

Halwas and Church (2002) present a classification of channel units in 17 first-order, high-gradient mountain channels on Vancouver Island, British Columbia. Channel units are classified based on their bed slope and
dominant bed material texture and organization. They found that the channel units in these small, first-order channels occurred at higher gradients than apparently similar units in larger channels farther downstream.

The characteristics of bedforms in sand-bed rivers were studied by Prent and Hickin (2001), who examined the links between discharge, flow resistance, and channel morphology of the Lillooet River in British Columbia and described the statistical character of bedforms. Chew and Ashmore (2001) examined historical downstream changes in channel geometry, grain size, and gradient of the Sunwapta River, a proglacial stream in Alberta. The analysis was used to test empirical hydraulic geometry relations and rational regime predictions of channel adjustment. Êkes and Hickin (2001) undertook the first application of ground-penetrating radar (GPR) to examine the complex sedimentary architecture of alluvial fans, and identified 10 radar facies in the Cheekye Fan in southwestern British Columbia.

A number of investigations have addressed the impact of disturbances on channel morphology. Channel steps, most commonly formed by boulders and woody debris, are significant geomorphic units that affect the stability and sediment transport capacity in low-order channels. Gomi et al. (2001) investigated the distribution of woody debris and sediment in 15 steep headwater channels under five management and disturbance regimes. The number of pieces of woody debris was significantly correlated with the volume of sediment stored in the channels. The timing of forest clear cutting and mass movement modified recruitment of woody debris, which altered the distribution of channel steps along the channels (Gomi et al., 2001, 2003). Millar (2000) investigated the influence of bank vegetation on alluvial channel pattern, and developed a planform stability diagram to determine the sensitivity of gravel-bed rivers to changes in bank vegetation.

In July 1996, a severe rainstorm caused widespread, catastrophic flooding along many rivers in southern Quebec, but especially along the tributaries of the Saguenay River in the Chicoutimi and Lac-Saint-Jean region. Brooks and Lawrence (2001) documented the geomorphic effects of these floods. Along some reaches, channel widening and floodplain erosion resulted in a transformation of the river from meandering to braided. The most significant geomorphic effects along some of the study reaches occurred at run-of-the-river dams. Four of these dams were overtopped by the floodwaters, resulting in rapid and deep erosion into the unconsolidated sediments next to the dams and the formation of new channels that captured the flow of the river. Floodwaters also overtopped a fifth dam within an urban subdivision, causing scour of the overburden and roadbeds, and damaging and destroying buildings.

Talbot and Lapointe (2002b) investigated the multiple response to large-scale meander rectification of the Saint-Marguerite River in the Saguenay region of Quebec. In terms of re-establishing sediment transport equilibrium along the river, the two most important responses were vertical repolishing and coarsening of the bed. Makaske et al. (2002) investigated floodplain sedimentation rate, channel avulsion and evolution of the anastomosing reach of the upper Columbia River. The study confirms Makaske’s (2001) characterization of the river as an internally dynamic, anastomosing system.

Finally, the impact of climatic changes on rivers and river processes in Canada has been discussed in an extensive monograph by Ashmore and Church (2001).

Models

Models can play a prominent role in elucidating the link between small-scale processes and large-scale fluvial geomorphology, as they do in other fields, such as climatology and oceanography. Canadian fluvial geomorphologists have recognized this role and, as a result, a number of papers describing models and modelling results have been published during the review period.

Tribe and Church (1999) developed a simulation model of stone structures based on mutual interactions between particles on a streambed. Simulating individual grain displacements by designing rules and statistical functions for the entrainment, movement and entrapment of stones, they succeeded in reproducing the ‘stone cells’ pattern observed in Harris Creek, British Columbia. In the Tribe and Church (1999) model, particles interact only when directly in contact with each other, and local flow dynamics do not play a role. A somewhat different approach was taken by Malmaeus and Hassan (2002), who developed a two-dimensional stochastic
model that simulates the movement of individual particles on a bed. The model of Malmaeus and Hassan (2002) is based on the concept of a resistance field around particles. As no direct contact is required for particle interaction, this concept implicitly represents the modification of turbulent flow properties around protruding clasts and particle clusters. The studies by Tribe and Church (1999) and Malmaeus and Hassan (2002) show that two-dimensional sediment transport models based on particle interaction can reproduce the bedforms and surface structures of gravel-bed channels.

Several one-dimensional models of fractional sediment transport and deposition have been developed in the last few years for predicting changes in channel morphology over to larger spatial and temporal scales. Ferguson et al. (2001) used the SEDROUT model to study the development of channel longitudinal profile and sediment fining along the Vedder River, British Columbia. Talbot and Lapointe (2002a) applied the same model to the Sainte-Marguerite River to simulate the response to meander straightening over a 32 year period. The study shows that pavement coarsening after rectification buffers the system against extreme degradation, which appears to limit the extent of degradation upstream of the straightened reach. Rice and Church (2001) tested mathematical models for the description of longitudinal profiles in simple alluvial systems, and found quadratic approximations to be the most flexible descriptor for linked longitudinal profiles. On the basis of dimensional analysis, Martin and Church (2000) developed a rational form of the Bagnold bedload transport equation, and also calibrated an empirical representation using a wide range of data from various sources.

RECENT TECHNICAL ADVANCES

Progress in the study of turbulence and sediment transport is limited by our ability to measure and analyse the active processes. It is not surprising, therefore, that advances in our understanding of these processes are often predicated on advances in technology that enable measurements of greater accuracy and detail. Recent technical advances have improved our ability to characterize bed surface sediments at a local scale, to measure sediment transport, to correlate measured velocity signals with images of mixing flows, and to generate and manipulate digital elevation models (DEMs).

Latulippe et al. (2001) developed a visual technique to increase our current capability to characterize the spatial variability of bed sediment calibre. The technique consists of a 2 to 3 day training period during which operators visually estimate size percentiles and then compare these estimates with measurements from established techniques to correct biases immediately. Trained operators were found to be capable of estimating the $d_{50}$ to within 15% and the $d_{84}$ to within 11%. A calibration relation was found to be independent of individual operators.

The Helley–Smith sampler is the most commonly used sampler for bedload. Nevertheless, the best technique for obtaining true sediment transport rates in gravel-bed rivers is unknown. Sterling and Church (2002) compared the magnitude and size distribution of sediment samples collected in a pit trap and a Helley–Smith sampler during 22 sampling events in a coarse cobble–gravel-bed river. The pit trap yielded consistent results with near 100% trapping efficiency for material larger than 2-8 mm. The Helley–Smith was more variable: the sampler exhibited a low efficiency for material between 0-71 and 16 mm, and a high efficiency for finer material.

Tunnicliffe et al. (2000) tackled the problem of high-resolution bedload transport measurement by installing a series of magnetic sensors in a stream bed. The sensors detect the distortion of the surrounding magnetic field due to the passage of clasts. A total of 82 sensors were used to give a spatial resolution of 10 cm transverse to the flow. The bedload movement detector was installed in a small stream in the northern headwaters of the Fraser River. Bedload moved only on 2 days during the field season, during the snowmelt discharge peak in May 1998. During this event, the bedload transport record showed an abrupt start of bed movement with a gradual decrease in activity, a variable, pulsating pattern of activity that appeared to be independent of stage, and a shift of the active zone laterally across the channel.
Rennie et al. (2002) developed a non-intrusive technique to measure bedload transport with an acoustic Doppler profiler (ADP), an instrument more typically applied to measuring flow velocities. Bedload transport was calculated by attributing biases in the bottom-tracking feature of the instrument to bedload velocity. Results from the ADP corresponded well with results from conventional techniques in the gravel-bed reaches of the Fraser River (Rennie et al., 2002) as well as in the sand-bed reaches (Rennie and Villard, 2003), indicating that the ADP technique is suitable for large rivers in an assumed state of carpet flow transport. Since Einstein’s classical work, tracing has become a standard technique in studying sediment transport in gravel-bed rivers. Hassan and Ergenzinger (2003) reviewed major available techniques for sediment tracing and developed a conceptual model for their use.

Characterizing turbulence in rivers is problematic, because it is difficult to associate point measurements with specific coherent structures. Roy et al. (1999) present two examples in which visual and quantitative techniques are combined to overcome this difficulty. The first example involved taking advantage of the natural turbidity contrast between the two rivers at the Bayonne–Berthier confluence, and consisted of filming the water surface downstream from the confluence simultaneously with measurements from two ECMs in the mixing layer and a Helley–Smith bedload sampler. The combined approach was essential for confirming the role of turbulent structures in mixing and sediment transport. The second example entailed filming a vertical profile of the river from underwater in combination with measurements from three ECMs. For visual contrast, milk powder was added to the flow behind a pebble cluster, which allowed observation of eddy shedding concurrently with flow velocity measurements. The authors conclude that the shedding process was closely associated with the passage of large-scale flow structures.

Developments in the application of photogrammetrical techniques may lead to new insights into the timing and magnitude of morphological changes at the scale of a channel reach. Stojic et al. (1998) used automated DEM acquisition methods to generate a time series of dense elevation models of a braided stream developed in a 2.9 m by 11.5 m laboratory flume. Following calibration, the DEMs were compared to assess sediment transport rates. Stojic et al. (1998) conclude that quantification of morphological change in theory may lead to accurate estimates of sediment transport. In practice, however, datum errors between DEMs and systematic errors in the DEMs resulting from the camera system make accurate estimates difficult to achieve. Chandler et al. (2002) took a similar approach to monitoring morphological change in the gravel-bed channel of the Sunwapta River in the Rocky Mountains, and demonstrated the value of combining terrestrial oblique digital imagery and automated digital photogrammetry for deriving high-resolution data on channel morphology that can be used for two-dimensional flow modelling. McLean and Church (1999) used a combination of Laplacian and spline interpolation to derive DEMs from bathymetric survey data from 1952 and 1984. Subsequently, the DEMs were used to derive a sediment budget for the section of the Fraser River between Agassiz and Mission, British Columbia.

CONCLUDING REMARKS

Some of the characteristics of Canadian fluvial systems are reflected in the directions of research, e.g. in the many investigations of bedload transport in gravel-bed rivers in the mountains of British Columbia and Alberta. In other cases, however, Canadian researchers have not yet taken up important challenges. Few studies, for example, have addressed the sediment dynamics of arctic rivers. Another topic that has received comparatively little attention is the effect of ice on sediment transport and channel morphology. Some progress, however, has been made in this area. Prowse (2001) provides an extensive review of the hydrological, geomorphological and water quality effects of river ice. Prowse and Culp (2003) present an extensive survey of the impacts of ice break-up, which possibly is the major cause of flooding of high-latitude rivers. Beltaos and Burrell (2003) review the impacts of climate change on the break up of river ice, and point out that changes in the timing of freeze-up and break-up events are unlikely to affect channel geomorphology. Changes to the magnitude of break-up events, however, may have an impact on fluvial processes and, hence, on channel
morphology. Smith and Pearce (2002) investigated gullies and bowl-shaped, closed scour holes eroded into the flood plain of the Milk River in southern Alberta and northern Montana, and concluded that the two anomalous fluvial landforms are caused by ice jams that reroute the water across the floodplain. Milburn and Prowse (2002) studied the movement of cohesive sediment under ice prior to break up in the Hay River, Northwest Territories, and found that a suspended sediment plume developed during the pre-break-up period. Milburn and Prowse (2002) infer that the under-ice plume results from the remobilization of fine-grained bed material that has accumulated during the winter, and suggest that this plume may have an ecological effect because of contaminants associated with the fine-grained sediment. Beltaos and Burrell (1998, 2000) measured extremely high peaks in sediment concentration during flow surges released from ice jams. Logistical and safety problems of fieldwork on ice-covered streams have limited the number of studies in this area and, as a result, many issues remain to be examined.

Overall, Canadian research in fluvial geomorphology during the period of this review (1999–2003) continues in the directions established in earlier work and summarized by Ashmore et al. (2000). This consistent direction reflects the presence of several established research groups that have well-defined areas of interest. As a result, fluvial geomorphology is a very active field of the geosciences in Canada. The current challenge is to build upon this foundation, and to advance our understanding of the poorly examined aspects of fluvial systems further.

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